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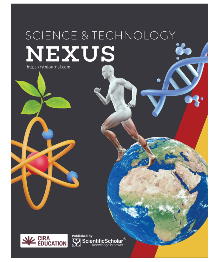

Review Article

Green-Synthesised Gold Nanoparticles: A Sustainable Technological Platform for Cancer Theranostics and Biomedical Innovation

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ABSTRACT

This review article focuses on the biological synthesis, characterisations and mechanism of action of gold nanoparticles (AuNPs) as an anticancer agent. The article explores various aspects, such as reactive oxygen species, cytotoxicity, and targeted delivery. Several research reports illustrate that green-synthesised AuNPs act as a reducing and stabilising agent. Biosynthesised AuNPs were characterised by various techniques like UV–Vis spectroscopy, SEM, TEM, and FTIR to determine attributes of nanoparticles. Cytotoxicity and anticancer activity were evaluated against cancer cell lines. This article summarises several research reports where AuNPs showed lower toxicity towards normal cell lines than cancer cells via ROS, disruption in physiological and metabolic processes, and apoptosis. AuNPs provide a versatile and efficient approach for cancer due to their ability to target specific sites and biocompatibility. Nanotechnology, by using green synthesis of AuNPs, holds promise for creating advanced and personalised treatment against cancer in the future.

Keywords: Cancer therapy, Gold nanoparticles, Green synthesis, Plant extract, Theranostics

1. INTRODUCTION

Gold nanoparticles (AuNPs) based biomedical applications have emerged as a growing field of study in recent years. Numerous potential biomedical uses have been investigated, including the transport of drugs and genes, and also the detection of proteins and pathogens, the labelling of deoxyribonucleic acid and fluorescence, tissue engineering, photo thermal ablation, and the usage of contrast compounds for the magnetic resonance imaging and the other imaging modalities. The synthesis, stabilisation, and functionalisation of AuNPs are the main subjects of research.[1] Palladium, platinum, silver, and gold are the metals utilised to create nanoparticles with great potential. The highest ionic conductivity of all three common metals is possessed by gold, and its size, shape, and surface state can all be modified while synthesising artificial AuNPs.[2] Commonly, the most common chemical processes for creating nanoparticles (NPs) are called wet synthetic, when NPs are created by a reduction or co-precipitation process. The primary limitations of this synthetic method include the synthesis and functionalisation of nanoparticles, which create hazardous residues during the synthesis process.[3] Hence, alternative (green/biological) technologies have been developed during the last two decades or so to produce diverse types of NPs.[3] Various approaches are devised to synthesise the nanoparticles of noble metals with precise dimensions, shapes, and forms based on the requirement. The increasing need to develop ecologically friendly methods in material syntheses has brought attention to the junction of nanotechnology and biotechnology, with biosynthesis of nanoparticles emerging as a prominent process.[4] Researchers in the areas of biology, chemistry, and materials science are engaged in developing environmentally acceptable and economically viable processes for the synthesis of nanoparticles, particularly in the context of efforts to discover "greener" ways to synthesise inorganic materials.[5] The use of plant extracts in the biosynthesis of gold nanoparticles has become increasingly interesting due to the improved chemical, physical, biological, and optoelectronic properties of the particles produced by the environmentally friendly methods.[6] The fastest growing area of research today is nanotechnology, enabling the production, visualisation, and use of resources at the nanoscale, which results in desirable structural changes.[7] Many physicochemical techniques are used to synthesise nanoparticles. The two commonly used methods, bottom-up and top-down, possess contrasting approaches for synthesis. Synthesis of nanoparticles occurs from nano-scope substances, like atoms and molecules, through the bottom-up approaches using oxidation and reduction. By using different physicochemical methods in the top-down synthesis, a size reduction method is used to synthesise nanoparticles[8] [Figure 1]. Generally, gold in the bulk form has been an inactive catalyst. However, nanoparticles of gold have considerable catalytic action due to their reduction property.[9] The secondary metabolites, such as phenols, alkaloids, and flavonoids, are different bioactive compounds found in the plants along with the proteins and vitamins. These also include antioxidants with reducing characteristics as well as coating agents that assure the strength of metal nanoparticles that transform metals into their equivalent nanoparticles.[8,10] The gold nanoparticles preparation occurs by using the plant extract, which acts as a reducing and stabilising agent. The gold nanoparticles apply to imaging and drug delivery within the human body because of their strength and biocompatibility.[10] Nanoparticles also function as drug carriers, changing the pharmacokinetic properties of the drugs and increasing their effectiveness with few side effects, controlling the drug release process in the body, improving encapsulation and solubilisation, and shielding pharmaceutical molecules. Because these are smaller than cells, they can pass through biological barriers and deliver the drug to a specific location, extending the duration of the drug in the bloodstream, and finally delivering it to a specific target.[11] The negative charge present on the hyaluronic acid plays an important role in the delivery of gold nanoparticles into the vitreous humour of the eye.[12] So, green-synthesised gold nanoparticles have the ability to minimise side effects common with conventional chemotherapy as they are selective in causing cell death of tumour cells with minimum damage to normal organs. Moreover, the size and operation characteristics of their surfaces make them good at loading up drugs, distributing them to the target area, and application in photothermal therapy that increases precision in therapeutic application. Green-synthesised nanoparticles are thus a practical, effective, and patient-friendly method of next-generation treatment of cancer.

1.1. Application of plant-based materials in cancer treatment

The plant compounds have shown antibacterial properties towards both Gram-negative and Gram-positive bacteria. Nanoparticles of gold, synthesised from plant sources, possess

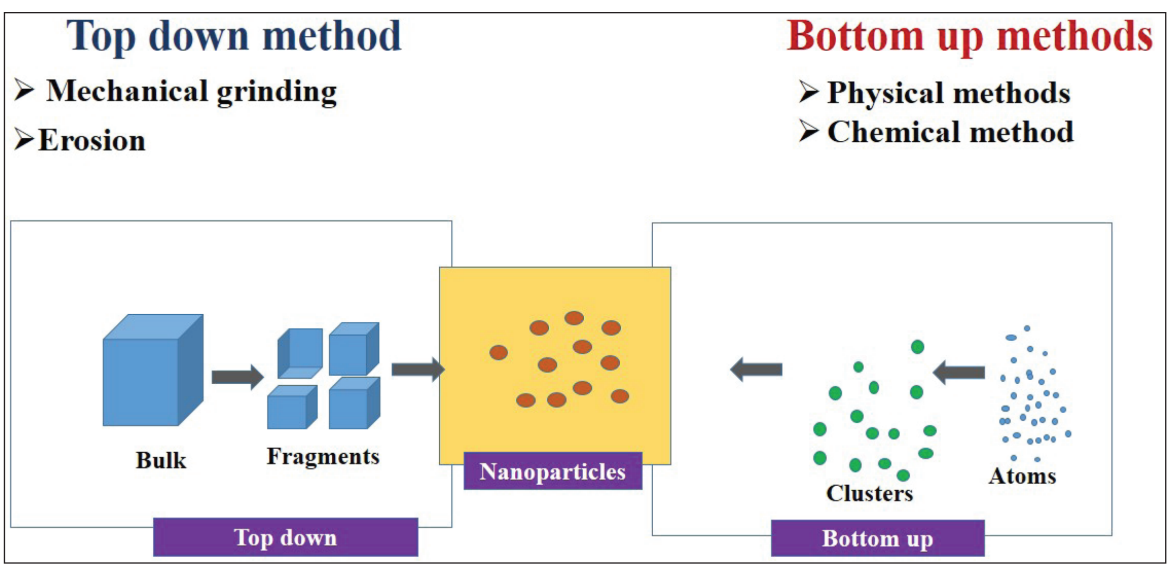

Figure 1: Nanoparticle synthesis using different screening methods. Two approaches to synthesising nanoparticles are top-down and bottom-up.

a considerable quantity of characteristic biomolecules, which also possess antioxidant potential.[7] The extracts of plants are a rich source of bioactive molecules, promoting the formation of gold nanoparticles.[10] This green method of gold particle synthesis from plants has been reported as quick, reproducible, and environmentally friendly with multiple potential applications [Figure 2].

1.2. Green synthesis of gold nanoparticles

Plant-derived nanoparticles have potential industrial and medicinal properties, and these particles have unique properties like a high surface area relative to their volume ratio.[8] The distinct characteristics of gold nanoparticles are examined based on their shape, dimensions, and surface properties.[10] Major active ingredients for the green synthesis are polyphenols and flavonoids, which are found in appreciable quantities in plants. AuNPs exist in a diversity of shapes, such as spherical, triangular, and also octahedral.[13] The non-hazardous nature and lack of immune response of gold nanoparticles, and owing to their properties of high permeability and retention effects, make these further advantageous for being useful for preparations to target the tumour site. In recent developments, the usage of gold nanoparticles for analysis and treatment of cancer, drug transport, imaging, photo-thermal, and photodynamic treatment.[14] Reduction of the gold ions through the plant extract does not require extra stabilisers and the capping agents to prevent accumulation of gold nanoparticles, and the stabilised gold nanoparticles are optimised by checking the effects of environmental factors such as change in temperature, pH, time, external appearance, dimension, etc.[15] Gold nanoparticles have expanded the biomedical applications of gold for the treatment of rheumatoid arthritis, rapid COVID-19 test, in vivo imaging, therapeutics, etc.[16]

1.3. In vitro characterisation of gold nanoparticles

The formation of gold nanoparticles can be accomplished by characteristic visual observation, a change in the reactants from pale yellow to dark brown, as a result of the characteristic colour shift which takes place when the nanoparticles of gold develop in reaction, which is caused by their unique surface plasmon resonance.[17] The nanoparticles of gold generated in laboratory conditions are characterised by using various analytical techniques such as the UV-Vis spectroscopy and the transmission electron microscopy (TEM). At around 550 nm, the UV-Vis spectra shows a surface plasmon peak.[18] According to TEM micrograph pictures, samples may exhibit structural morphology, including spherical morphology with distinct particle sizes: smaller particles are 10–30 nm in size, and larger particles are 80–150 nm.[19] At different pH ranges, gold nanoparticles exhibit varying zeta potential, with the lowest amount observed at high acidic pH. Reduced reaction pH causes the resultant nanoparticles to enlarge to between 50 and 250 nm in size. Particle size might be readily influenced

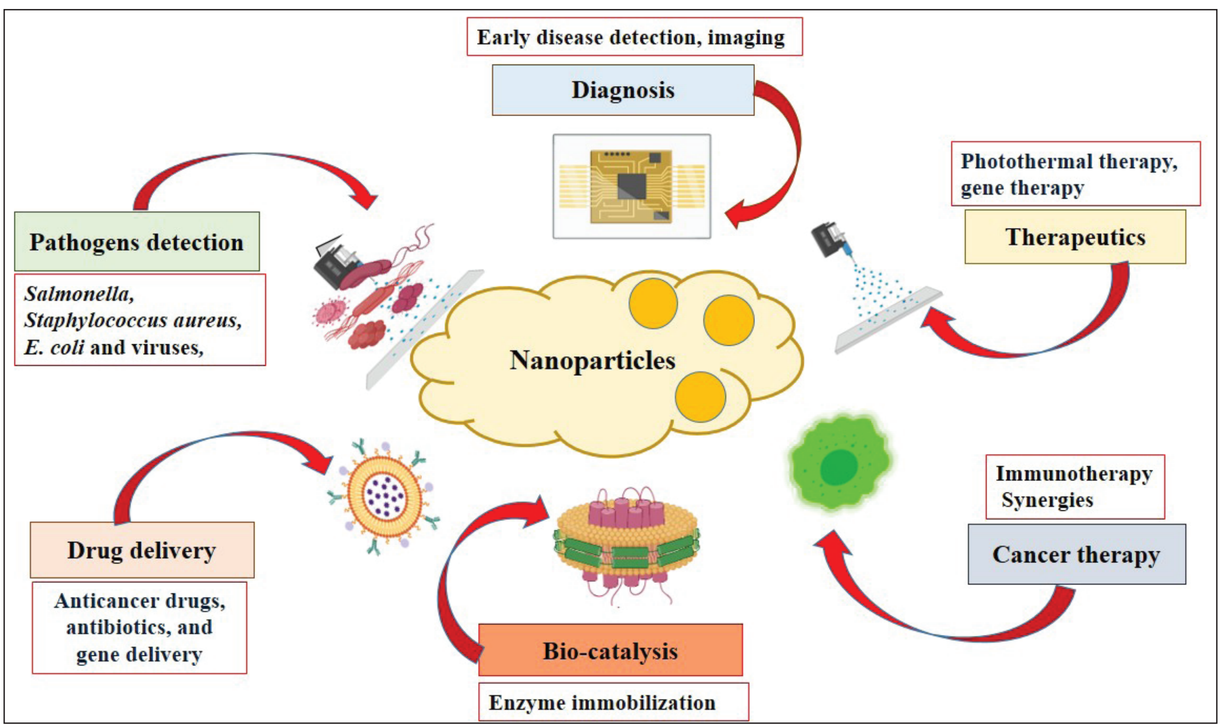

Figure 2: Multifunctional application of gold nanoparticles. Gold nanoparticles are working in cancer therapy, biocatalysts, drug delivery therapeutics, diagnosis, and pathogen detection.

by the prevailing reaction factors and conditions, such as pH, temperature, and extract composition and amounts. By adjusting the reaction conditions and reaction parameters, nanoparticles of gold of different sizes, even reaching within 10 to 30 nm in size, could be produced.[20,21] The observation of peaks through advanced analytical techniques such as X-ray diffraction, light stripes in high resolution transmission electron microscopy (HRTEM) lattice images, and the bright spots in the circular pattern of selected area electron diffraction (SAED) pattern, all confirm that structure and crystalline nature of nanoparticles and also use to study the morphology, distribution, and purity of synthesised gold nanoparticles as well as the plane of nanoparticles is confirmed by this technique. Determining the polycrystalline character and high crystallinity of the obtained AuNPs.[13,20] The biomolecules from the plants that caps the nanoparticles possess a variety of functional groups, which can be derived from the relevant Fourier transform infrared spectroscopy (FTIR) spectrum.[21] The one-pot method of biosynthesising AuNPs from the plant sources is a simple methodology and requires a single-step process. Different parts of the plant, such as leaves, fruits, bark, flowers, peels, seeds, rhizome roots, etc., are abundant in natural substances such as tannins, steroids, alkaloids, and flavonoids, which contribute to the NP synthesis process. Several secondary metabolites are found in various plant parts and serve as reducing agents and stabilising agents during the biogenesis of NPs.[1] Although the production of AuNPs has been described in many plant parts, leaves are usually the most commonly employed tissues compared to other tissue parts.[8] The number of metabolites present in various plant parts, as well as variations among plants, are significant factors that influence how NPs are shaped with reference to morphology.[22] Several methods, such as dynamic light scattering, X-ray diffraction, FTIR, transmission electron microscopy (TEM), and UV-visible spectroscopy, are routinely used to analyse the bio-generated NPs[23] [Figure 3]. FTIR data detected flavonoids, phenols, anthocyanins, and benzophenones, which indicate that these are involved in the reaction as the reducing agent with reducing properties. The negatively charged phosphate groups may also cap the produced nanoparticles of gold, according to FTIR data, which increases their stability in the aqueous media. According to FTIR data, the reduction of Au^{3+} to Au^{0} and the stabilisation of produced AuNPs, occur due to the presence of the phenolic group in the plant extract.[24] The normal size range of the AuNPs, as shown by TEM pictures, is 5 nm to 50 nm, which is highly capable for the majority of biological applications.[19] At higher pH levels, i.e., more than10, on the other hand, quasi-spherical and small-sized NPs, i.e., nearly 13 nm, were reported.[25]

2. SEARCH STRATEGY: INCLUSION/EXCLUSION CRITERIA

This review was developed using a structured literature search to ensure comprehensive and unbiased coverage of the anticancer applications of AuNPs. Relevant studies were identified from PubMed, Scopus, Web of Science, ScienceDirect, and the Indian Citation Index between 2007 and 2025, using the keywords "gold nanoparticles," “anticancer activity," and "ROS-mediated apoptosis", "green synthesis”. Both international and Indian research studies were screened to incorporate a globally diverse perspective.

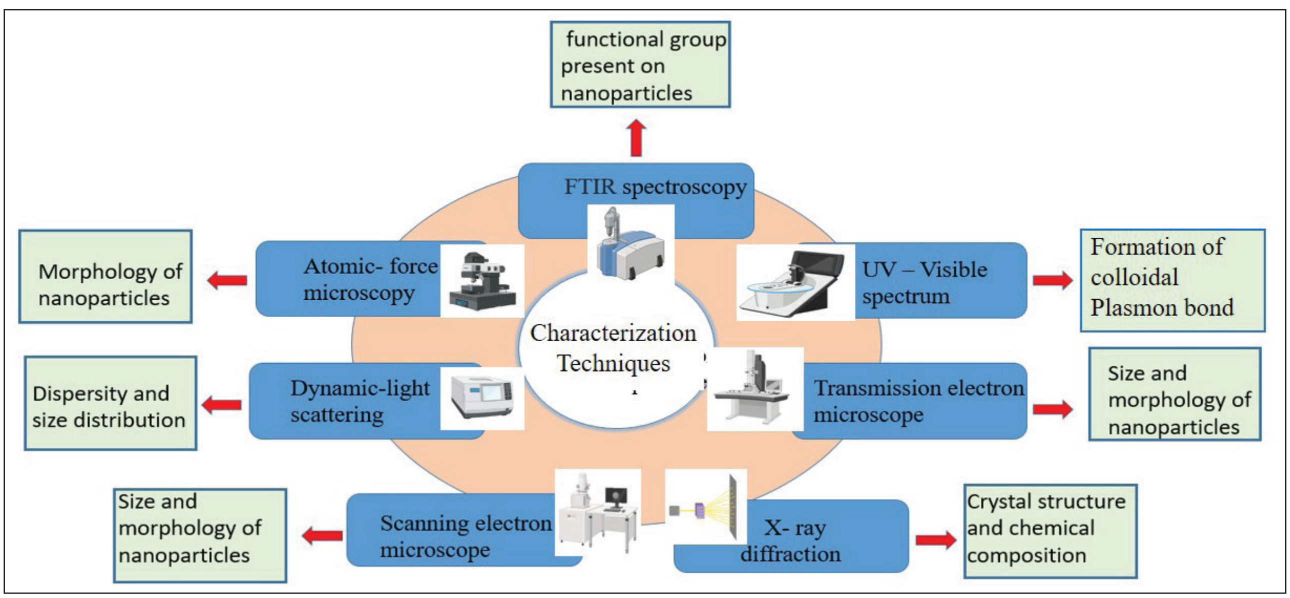

Figure 3: Overview of different techniques used for nanoparticle characterisation. FTIR: Fourier transform infrared spectroscopy, UV Visible: Ultra violet visible

Articles were included if they reported mechanistic, *in vitro*, or *in vivo* evidence of AuNPs anticancer activity. Non-cancer studies and non-nanoparticle gold compounds were excluded. Nearby 200 relevant articles formed the evidence base for this review, ensuring a balanced synthesis of mechanistic, therapeutic, and translational insights from global and Indian literature.

3. APPLICATION OF GOLD NANOPARTICLES IN CANCER THERANOSTICS

According to World Health Organization reports, cancer continues to be the biggest cause of death globally, with major effects on health, psychology, human life, and the economy.[26,27] Despite being the most widely used treatment approach, chemotherapy does not always produce good therapeutic results. Because of the frequent use of single drugs, the survival of a small population of cancer stem cells, low bioavailability, and severe, lethal side effects from a few organic anti-cancer agents, most patients experience a low therapeutic index, recurrence, or metastasis.[27] The potential medical benefit of the recently produced gold nanoparticles is being investigated.[6] Their antileukemic cancer activity has been investigated.[28] One common malignancy that affects a significant proportion of the population, particularly children, is leukaemia.[29] Unfortunately, several drawbacks concerning adverse effects and the emergence of developing resistance to drugs characterise existing treatments.[14] As a result, in addition to needing to be more potent and have fewer adverse effects, the new therapeutic agents also need to function *via* a different mechanism than the cytotoxic drugs currently in use. The modern research in the development of plant-based anti-cancerous treatments has been devoted to examining the molecular process *via* an agent that causes apoptosis and cytotoxicity in the majority of cancerous cells[26] [Figure 4]. This review offers important information for creating nano-therapeutics to combat cancer.[3] The aggressive neoplasm limits the effectiveness of the successful and life-saving treatment for pancreatic cancer. On the other hand, research indicates that pancreatic cancer cells have a high degree of resistance.[30,31] Globally, the prevalence of pancreatic cancer is rising annually. Globally, pancreatic cancer is the fourth most common cause of cancer-related mortality.[32] Since most pancreatic cancer patients receive their diagnosis late in the course of disease progression, there is little opportunity to consider all available treatment choices.[29,33-35] A lot of studies have gone into a deeper comprehension of the molecular pathways underlying the development of pancreatic cancer in humans.[33] Chemotherapy, radiation, and medications made from substances that may have serious adverse effects are the current therapeutic choices.[27] As a result, studies have been conducted to find novel therapeutic approaches and alternative treatments for pancreatic cancer, for which green-synthesised gold nanoparticles offer great potential.[34] Nanoparticle-based theranostic systems transfer anticancer drugs, improve their solubility, drug stability, and their accumulation in the tumour.[35] Photothermal therapy is a

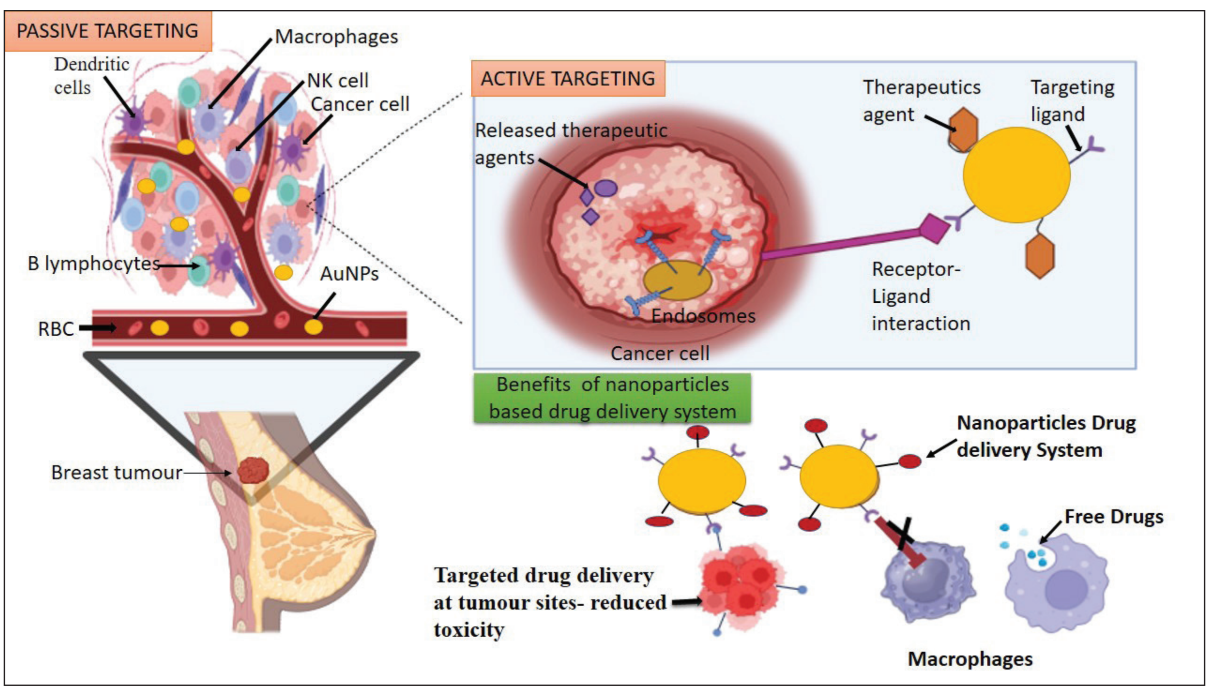

Figure 4: Schematic representation of a nanoparticle-based drug delivery method for cancer treatment. NK cell: Natural killer cell, AuNPs: Gold nanoparticles. RBC: Red blood cells, B lymphocytes.

minimally invasive treatment approach that utilises tumour ablation, so AuNPs are especially valuable photothermal sources owing to the tremendous plasmonic absorption.[36] Early and accurate diagnosis is required so as to have cancer managed effectively, so theranostic systems also combine custom nanomaterials and advanced imaging modes to enhance the accuracy of the diagnosis. Gold nanoparticles (AuNPs) can be excellent contrast agents in CT imaging due to their large atomic number and great X-ray attenuation coefficient.[37]

3.1. Pancreatic cancer

Pancreatic cancer has been increasing yearly throughout the world. In the world currently, the fourth most common cause of cancer-related deaths is pancreatic cancer.[32] Recent studies evaluated plant-derived synthetic gold nanoparticles for their potential as anticancer agents.[4] PANC-1 pancreatic cancer cell lines were effectively treated through the produced AuNPs, demonstrating that they have potent anticancerous activity. Therefore, more studies on this plant and approach could result in the creation of cutting-edge anticancer medications.[34] The antitumor effect of AuNPs against PANC-1 pancreatic cancer cells was evaluated. As a result, the 3-(4,5-dimethylthiazol-2-yl)-2,5-diphenyl tetrazolium bromide (MTT) cytotoxicity experiment was used to examine the anticancer potential of the AuNPs.[31] Plant extract-derived synthetic AuNPs exhibited strong anticancer properties. 1). Reactive oxygen species (ROS) that are intracellularly generated in a biological and cellular system cause oxidative stress, which in turn causes cell death.[38] In order to investigate AuNPs-mediated ROS generation, the DCFH-DA fluorescent assay was used. Thus, the synthesis of AuNPs from pancreatic PANC-1 cells stimulates the creation of ROS. Furthermore, excess ROS generation causes mitochondrial depolarisation and nuclear fragmentation, which result in oxidative stress-mediated death[39] [Figure 5]. The plausible potential of the AuNPs biosynthesised using *Scutellaria barbata* was excellent against pancreatic cell lines. The fluorescent staining method involved was applied with 25 ug/mL and 50 ug/mL concentrations of AuNPs, in order to determine the cytotoxic effects and the cancer cell mode of death. Possible apoptotic pathways were postulated to be the production of ROS, a small downregulation of Bcl-2, and the increase in the amount of proteins Bax, caspase-9, and caspase-3.[40]

3.2. Lung cancer

The report on the clonogenic experiment demonstrated that green-generated AuNPs effectively controlled the growth of lung cancerous cells.[41] Meanwhile, the size of the reactive oxygen species (ROS) formation confirmed that the green produced AuNPs caused cancerous cells to

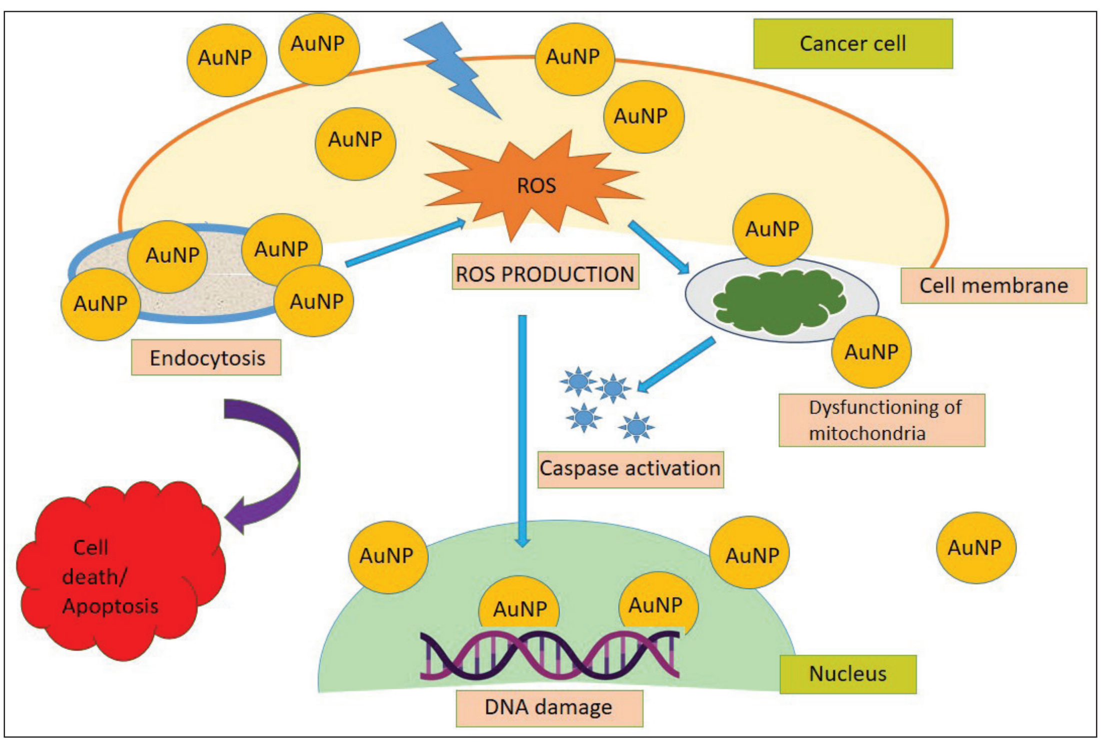

Figure 5: Systematic representation of the mechanism of action of gold nanoparticles in anticancer activity, ROS: Reactive oxygen species, AuNPs: Gold nanoparticles.

undergo apoptosis.[38] Consequently, the special biologically produced AuNPs may be used in a variety of other biomedical applications and have anticancer properties.[15] Based on the dosage-dependent growth suppression of A549 cells, the AuNPs cause toxicity. In A549 cells, treatment with AuNPs downregulates the production of the anti-apoptotic protein and activates caspase expression, so the plant extract of AuNPs are suitable stabilising agents that works well against A549 cell lines of lung cancer as an anticancer agent. The extract of the leaf and seed of *Moringa oleifera* is effective in the treatment of lung cancer. To check the inhibitory concentration (IC50) value, the MTT assay was used, which found 50 µg/mL. These nanoparticles induce the caspase-mediated apoptosis and dysfunction of mitochondria [Table 1].[38]

3.3. Cervical cancer

Studies have been performed on the anti-proliferative and cytotoxic effects of gold nanoparticles derived from green sources on the cervical (HeLa) and melanoma (A375) cancer cells.[42] Tannic acid, green tea extract, lemongrass extract, and sodium citrate were used in the synthesis of these nanoparticles in order to consider the results of various reducing agents on the capacity to alter cancer cell survival.[43] The apoptosis induction was detected in both the A375cells and A375 HeLa cells when treated with the tannic acid AuNPs nanoparticles, along with A375 cells when treated with the gold nanoparticles of the green tea, demonstrating that the impacts on the cell survivability were mediated by this process. The extract of the leaves of the medicinal plant *Catharanthus roseus* is the source of vinblastine and vincristine. To check the IC50 value, the MTT assay was used, which found 5 µg/mL. These nanoparticles induce the caspase-mediated apoptosis and dysfunction of mitochondria [Table 1].[44]

3.4. Glioblastoma cancer

About 10 million deaths globally are attributed to cancer, a disease that affects people with high incidence rates.[26,45] As per the World Health Organization (WHO), glioblastoma

Table 1: Green material-based AuNPs, anticancer efficacy against different types of cancer.

S No.	Plant (Extract parts)	AuNPs size	Cancer cell lines	Anticancer mechanism	Reference
1.	*Catharanthus roseus* (leaf extract)	~20–60 nm	HeLa (cervical)	Induced caspase-mediated apoptosis, mitochondrial dysfunction.	[64]
2.	*Azadirachta indica* (leaf extract)	~10–30 nm	HepG2, A549	ROS generation, dose-dependent cytotoxicity, and caspase activation	[65]
3.	*Moringa oleifera* (leaf, seed)	~15–50 nm	Dalton's lymphoma, A549 (lung), MCF-7 (breast)	Apoptosis induction (increases Bax, decreases Bcl-2, cytochrome-c release, caspase-3 activation), cell-cycle effects, ROS, and mitochondrial damage.	[6]
4.	*Curcuma long* (rhizome)	~20–60 nm	HT-29 (colon)	DNA fragmentation, ROS-mediated apoptosis.	[66]
5.	*Punica granatum* (leaf extract)	~10-15 nm	MCF-7, HepG2, A549	Antiproliferative activity, ROS and mitochondrial pathways commonly reported.	[1]
6.	*Camellia sinensis* (leaf extract)	~20-30 nm	Human HL-60/vcr, 32D-FLT3-ITD, and Murine C1498 cell lines	Anti-inflammatory Detoxifying, antibacterial properties, immunological, haematological.	[66]
7.	*Terminalia arjuna* (Bark extract)	~20-40 nm	Cardiomyocytes cell line (H9C2) Human breast cancer cell line (MCF7)	Cyto-protective property against ROS, antioxidant and cytoprotective.	[31]
8.	*Panax ginseng* (root extract)	~10-13 nm	Human breast cancer cells (MCF7)	NF-κB activation in macrophages, Anti-inflamatory	[67]
9.	*Ocimum sanctum* (leaf extract)	~200 nm	T-cell dalton's lymphoma (DL) cells	Reduced cell viability, altered nuclear morphology	[68]
10.	*Aloe vera* (leaf extract)	~20-50 nm	MCF7 and MDA-MB-231 cells	Antioxidant, oxidative stress-mediated cell death	[67]
11.	*Hibiscus rosa-sinensis* (Flower extract)	~ 13 nm	Human colorectal carcinoma cells (HCT-116) and breast cancer cells (MCF-7)	Apoptosis, caspase activation, anti-proliferative effects	[69]

ROS: Reactive oxygen species; NF-κB: Nuclear Factor kappa-light-chain-enhancer of activated B cells.

multiforme (GBM) is classified as a rank 4 cancer, which has the potential to aggressively kill the central nervous system (CNS) astrocyte cells and the brain.[46] According to data, the median survival rate for GBM carriers under standard methods is only 14.6 months.[47] Studies have documented that the anticancer effects of AuNPs, one of the most thoroughly studied nanoparticles, are on cells.[4] When cancer cell lines such as U-251 and U-87 were treated with AuNPs, their capacity to proliferate and migrate was significantly inhibited, and apoptosis was markedly induced.[16]

3.5. Liver cancer

The Global Cancer Statistics 2021 report states that while the incidence of liver cancer in men has stabilised, it is steadily increasing (by 2% per year) in women, primarily as a result of hepatitis B and C viruses, and other factors.[45,26,46] *Dendrobium officinale* (DO) water extracts were effectively used to create a new gold nanoparticle without the need for additional chemicals or reagents.[48] The survival rate of L02 cells and inhibitory rate of HepG2 cells were assessed *in vitro,* and the immunohistochemical analysis of H&E, Ki-67, and TUNEL staining was carried out *in vivo* to assess the anti-tumour efficacy and biosafety.[49] Following research, the rate of liver cancer incidence was ranked second in mortality and fifth in malignant tumours in China in 2020.[26] The conventional treatment procedures rely mostly on chemotherapy, radiation, and surgical removal as the major forms of treating tumour diseases.[27] Apoptosis, on the contrary, is not the primary role of killing cancer cells, and chemotherapeutic drugs tend to lack proper water solubility, and their use will be very limited due to low targeting properties.[50] The cytotoxicity of gold nanoparticles was examined by the MTT test, which was inhibited by pomegranate extract. Organic product strips of *Punica granatum* (Punicaceae) are rich in the polyphenolic class of antioxidants that contain flavonoids and tannins. Because they contain polyphenols, such as tannins, ellagic acid, and gallic acid, pomegranate strips exhibit potential effects on malignant cells.[51] Using the HepG-2 liver cancer cell line, the anticancer effects of gold nanoparticles mediated by pomegranate strip extract were evaluated. The anticancer effect of gold nanoparticles against the HepG-2 liver malignant development cell line exhibits more movement as the fixation of the particles increases.[48] The standard use to calculate the anticancer effect of gold nanoparticles is cyclophosphamide. In comparison to regular cyclophosphamide, gold nanoparticles exhibit excellent performance.[52] Licorice root-mediated AuNPs demonstrated superior antiproliferative efficacy against HepG-2. Significant morphological alterations and a decrease in cell density were observed in the HepG-2 cells, which exhibited this as a sign of apoptosis [Table 1].[7]

3.6. Blood cancer

A considerable portion of the population, particularly youngsters, are afflicted by leukaemia, a serious form of cancer.[29] The cannonball tree, or *Couroupit guianensis*, is a plant with a broad range of therapeutic uses. Gold nanoparticles led to an investigation into their anti-leukemic cancer activity.[53] HL-60 cells were exposed to different quantities of gold nanoparticles, which altered the nucleus morphology of dying HL-60 cells, and these effects varied with dose, indicating that gold nanoparticles caused HL-60 cells to undergo apoptosis and DNA fragmentation.[4] The extract of the fruit of *Couroupit guianensis* is effective in the treatment of blood cancer. To check the IC50 value, the MTT assay was used, which found 37 μg/mL.[54] AuNPs are produced by *Hibiscus sabdariffa in vitro* using its aqueous extract.[55] In a leukemic rodent model, the anti-acute myeloid leukaemia activity of AuNPs was assessed. TEM and FE-SEM showed that nanoparticles have a consistent sphere shape ranging from 15 to 45 nm.[17] AuNPs derived from *Camellia sinensis* leaf aqueous extract have dietary therapeutic potential in comparison to *daunorubicin.* The cytotoxicity effects of HAuCl4*, C. sinensis,* AuNPs, and *daunorubicin* were examined using the MTT test on the cell lines HUVEC, Human HL-60/vcr, 32D-FLT3-ITD, and Murine C1498. These nanoparticles, which resembled *daunorubicin,* showed no cytotoxicity against the HUVEC cell line but low cell viability dose-dependently against the human HL-60/vcr, 32D-FLT3-ITD, and murine C1498 cell lines.[30] The IC50 of HAuCl4, H. sabdariffa, AuNPs, and daunorubicin against the murine C1498 cell line, human HL-60/vcr cell line, and 32D-FLT3-ITD cell line were found to be 761, 803, 587, 189, and 178 mg/ml, respectively.[56] Daunorubicin and gold nanoparticles significantly reduced the weight and volume of the liver and spleen, pro-inflammatory cytokines, while increasing the anti-inflammatory cytokines and the lymphocyte, platelet, and RBC parameters.[30] The Clone E6-1 cell line showed the best outcomes from anti-acute leukaemia effects of gold nanoparticles, suggesting gold nanoparticles as novel chemotherapeutic medications in the treatment of acute leukaemia of different kinds [Table 1].[50]

3.7. Breast cancer

With a high frequency of around 25% in developed nations, this is the most common type of cancer in women and the second leading cause of cancer-related deaths. Green-synthesised AuNPs have primarily been tested against the MCF-7 cancer cell line.[57] AuNPs interact with MCF-7 cells *via* changing the integrity of cell membranes, causing oxidative stress, disrupting physiological and metabolic processes, cutting off ATP synthesis, stopping the transfer of electrons, and ultimately causing cell shrinkage and apoptosis.[58] AuNPs were examined for anticancer efficacy on the MCF7 (cancer) and MCF 10A (normal) cell lines, employed as an anticancer drug since they specifically destroyed cancer cells without harming the normal cell line.[59] The vitality of zinc oxide (ZnO), gold (Au), and Au/ZnO NPs was assessed in MCF-7 cells, and oxidative stress was assessed by measuring calcium ion levels, lipid peroxidation, and antioxidant enzyme activity. ZnO, Au/ZnO, and Au NPs had average sizes of 50.7, 51.6, and 8.45 nm, respectively, and the produced NPs were found to have spherical or semi-spherical irregular forms.[60] Licorice root-mediated AuNPs demonstrated superior antiproliferative efficacy against MCF-7, with decreased cell density observed in the MCF-7 cells, which is indicative of apoptosis. The generated AuNPs mediated by the licorice root extract compared to the anticancer cell line of MCF-7 at a dosage of 50 µg/ml. This observation proved that AuNPs displayed a great cytotoxic effect at the lowest dose [Table 1].[7]

3.8. Colon cancer

Among the most common types of cancer in the world, colon cancer ranks significantly.[61] The synthesis of gold nanoparticles using phytoconstituents for treating colon cancer (HCT-116) was attempted.[51] The green technique was used to employ the aqueous leaf and seed extract of *Albizia lebbeck* (AL) and flower extract of *Hibiscus rosa-sinensis* in the production of AuNPs showing anti-cancer properties to prevent colon cancer cells. MTT assay used to observe the cytotoxic effect of *Albizia lebbeck* AuNPs and the IC_{50} level of HCT-116 cells recognised as 48 µg/ml [Table 1].[62,63]

4. CONCLUSION & TECHNOLOGY PERSPECTIVE

This review highlights the technological potential of green-synthesised AuNPs as sustainable and biocompatible platforms for cancer diagnosis and therapy. By replacing toxic chemical reductants with plant-derived biomolecules, this approach enables an eco-friendly and scalable route for producing functional nanomaterials with controlled morphology and optical properties. The ideal conditions for fabricating effective NPs are the binding behaviour, solubility, and surface modification. Such bio-capped AuNPs demonstrate strong promise in targeted drug delivery, bioimaging, and photothermal applications, offering safer and more cost-effective alternatives for cancer theranostics. However, translating these laboratory findings into clinical technologies faces key challenges. Variations in plant composition often led to inconsistent nanoparticle characteristics, affecting reproducibility and therapeutic reliability. Moreover, standardised protocols for large-scale biosynthesis, *in vivo* safety evaluation, and regulatory compliance are still underdeveloped. Integration of green nanofabrication with automated systems and real-time monitoring technologies remains limited, restricting scalability and commercialisation. Future advancements should focus on combining green nanotechnology with data-driven optimisation, artificial intelligence, and advanced materials engineering to achieve precise control over synthesis and performance. Developing hybrid AuNPs-based composites with biopolymers or peptides may extend applications beyond oncology into biosensing, regenerative medicine, and environmental diagnostics. Collaborative efforts linking biochemistry, nanotechnology, and clinical sciences will be critical for transforming green AuNPs into clinically approved, multifunctional therapeutic tools.

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