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Advancements in Therapeutic and Diagnostic Applications of Phytogenic Nanomaterials for Lung Cancer Management

Rupa Devi[1]*, Dushyant[1].

[1] Global Research Institute of Pharmacy, Radaur, Yamuna Nagar-135133, Haryana, India.

* Correspondence: rupakamboj41@gmail.com

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Abstract: Lung cancer is still a serious global health issue, and traditional therapy is hindered by drug resistance, toxicity, and non-selective activity against cancer cells. Phytogenic nanomaterials derived from plants provide a promising alternative since they are biocompatible, environmentally friendly, and show improved therapeutic efficacy. Nanomaterials such as metallic, polymeric, lipid-based, and carbon-based nanomaterials have highly effective anticancer activities by inducing apoptosis, reactive oxygen species (ROS) production, targeted drug delivery, inhibition of angiogenesis, and immune stimulation. Phytogenic nanomaterials have shown efficiency in the treatment of lung cancer, such as targeted drug delivery systems, chemotherapy triggered by phytogenic nanomaterials, photothermal therapy, and gene therapy. Targeted drug delivery occurs by ligand-functionalization of nanoparticles, improving the specificity of therapy along with minimum systemic toxicity. Phytogenic nanoparticles also tackle drug resistance, increase chemotherapy, and allow the release of the drug in a controlled manner. Gold nanoparticles, carbon nanotubes, and graphene oxide also offer photothermal therapy with local ablation of the tumor by heat. Gene therapies like RNA interference and CRISPR-Cas9 also increase therapeutic specificity. Apart from therapy, phytogenic nanomaterials are used in diagnostics and imaging, which improve the early diagnosis of disease by biomarker sensing and improved imaging contrast. Through continued research and development in the clinic, phytogenic nanomaterials have the potential to transform lung cancer therapy into personalized, efficient, and safer treatments.

Keywords: Phytogenic nanomaterials, Lung cancer, Drug targeting, Apoptosis, Reactive oxygen species (ROS), Photothermal therapy.

1. Introduction

Lung cancer is still one of the most debilitating cancers and one of the main causes of cancer-related deaths all over the world. Traditional treatment using chemotherapy, radiation, and surgery has failed to keep pace because of drug resistance, systemic toxicity, and limited selective targeting of cancer cells [1]. This has led scientists to seek alternative directions of treatment, one being nanotechnology and one of choice and viable alternatives. Phytogenic nanomaterials that had been synthesized by plant extracts had shown promise due to their biocompatibility, lowered toxicity, and greater therapeutic activity towards chemotherapy of lung cancer. Phytogenic nanomaterials represent a novel generation of nanoparticles whose synthesis follows green chemistry guidelines in which plant extracts act as reducers and stabilizers [2]. Contrary to traditional chemical and physical synthesis routes using harmful reagents, this green synthesis is both economical and environmentally friendly. Certain medicinal plants like Curcuma longa (turmeric), Azadirachta indica (neem), Ocimum sanctum (holy basil), and Camellia sinensis (green tea) are widely researched in an effort to synthesize nanoparticles due to the fact that they contain bioactive compounds. The bioactive compounds are enhancing the activity and stability of the nanoparticles to a highly significant level, and thus, they are highly efficient for their biomedical applications [3]. The major phytogenic nanomaterial classes used to treat lung cancer are metallic, polymeric, lipid, and carbon nanomaterials. Metallic nanoparticles, including gold (Au), silver (Ag), and iron oxide (Fe_3O_4), exhibited effective anticancer activities via apoptosis induction, production of reactive oxygen species (ROS), and drug targeting [4].

Polymeric nanoparticles based on biocompatible biopolymers like chitosan and alginate provide drug stability and controlled delivery of the drug in a slow process. Phytogenic liposomes and SLNs deliver solubilization and bioavailability of hydrophobic anticancer drugs with better absorption in the body [5]. Carbon nanomaterials like graphene oxide and carbon nanotubes are promising nanotools with high surface area and potential for being functionalized for photothermal therapy and drug delivery applications [6]. Aside from structural complexity, phytogenic nanomaterials have anticancer mechanisms which include induction of apoptosis, ROS formation, targeted delivery of anticancer drugs to the tumor tissue, antiangiogenesis, and immunomodulation. Such phytogenic nanomaterials' potential to target tumor areas selectively without causing extensive harm to normal tissues has made them the new focus towards replacing conventional lung cancer treatment [7]. This review depicts the synthesis, action mechanism, and future scope of applications of phytogenic nanomaterials as a chemotherapeutic drug against lung cancer based on their pioneering character for the achievement of a cure rate maximization along with their promotion of new development in nanomedicine [8]

2. Phytogenic Nanomaterials

Lung cancer is one of the most dangerous, life-threatening cancers in the world. Traditional treatments, such as chemotherapy, radiation, and surgery, face the problem of drug resistance, toxic side effects, and a lack of specificity to cancer cells. The development of nanotechnology, especially phytogenic nanomaterials, has been identified as a new alternative treatment for lung cancer [9]. The nanomaterials, which are derived from plant extracts, are biocompatible, have improved therapeutic activity, and are low in toxicity. This book discusses the application of phytogenic nanomaterials in cancer treatment, especially lung cancer, their preparation, mode of action, and future use [10].

2.1 Phytogenic Nanomaterials: Preparation and Properties

Phytogenic nanomaterials are plant extract-based nanocrystals prepared as reducing and stabilizing agents naturally. The green synthesis process used is a green and affordable process compared to the traditional physical and chemical synthesis processes that do not incorporate the use of harmful chemicals [11]. Several phytochemical medications such as Curcuma longa (turmeric), Azadirachta indica (neem), Ocimum sanctum (holy basil), and Camellia sinensis (green tea) are highly employed in nanoparticle formation based on their bioactive molecules that are responsible for the stability and functionalization of nanoparticles [12]. Phytogenic nanomaterials exhibit vast prospects in lung cancer studies with the advantages of targeted treatment, minimal side effects, and improved drug efficacy. The large categories include:

2.1.1 Metallic Nanoparticles

Gold (Au), silver (Ag), and iron oxide (Fe_3O_4) nanoparticles have high anticancer activity. They cause apoptosis (cell death), release ROS, and allow drug targeting. Silver nanoparticles, among others, have been found to cause cytotoxicity in lung cancer cells [13].

2.1.2 Polymeric Nanoparticles

These nanocarriers, which are made from biopolymers like chitosan and alginate, stabilize the drugs, prevent the degradation of therapeutic substances, and deliver drugs under programmed conditions. They are non-toxic and biocompatible and hence suitable carriers in lung cancer treatment [14].

2.1.3 Lipid-Based Nanocarriers

Phytogenic liposomes and SLNs enhance the hydrophobic anticancer agents' solubility and bioavailability for enhanced drug absorption and targeted action. Lipid carrier systems further reduce systemic toxicity by ensuring maximum site-specific drug concentration [15].

2.1.4 Carbon-Based Nanomaterials

Graphene oxide and plant extract-derived carbon nanotubes have been identified as promising therapeutic tools for the treatment of lung cancer. They can be employed to facilitate photothermal therapy, where the heat generated at the target site causes the cell-killing effect, and as efficient drug delivery agents for anticancer drugs. They possess high surface area and functionalization capability, which makes them suitable for efficient drug loading and targeted delivery [16].

3. Action Mechanisms of Phytogenic Nanomaterials against Lung Cancer

Phytogenic nanomaterials, being of plant compound origin, exhibit strong anticancer activities against lung cancer through numerous different mechanisms. Some of these include the induction of apoptosis, induction of oxidative stress, drug-targeted delivery, anti-angiogenic activity, and immunomodulation [17].

3.1 Induction of Apoptosis

One of the mechanisms utilized by phytogenic nanoparticles to treat lung cancer is the induction of programmed cell death (apoptosis). They induce pro-apoptotic proteins like Bax and caspases, which are the main inducers of apoptosis. Simultaneously, they suppress anti-apoptotic proteins like Bcl-2, thereby inducing cell death. Cancer cell-specific killing bars them from proliferation and improves therapy [18].

3.2 Induction of Reactive Oxygen Species (ROS)

Most plant-based metal nanoparticles, including silver and gold nanoparticles, cause oxidative stress in lung cancer cells by generating ROS. Elevated ROS disrupts mitochondrial function, resulting in damage to DNA, oxidation of proteins, and peroxidation of lipids. The generated oxidative stress produces a hostile environment for the survival of cancer cells, eventually triggering apoptosis or necrosis. Interestingly, cancer cells are also more susceptible to ROS-induced damage compared to normal cells, and hence, this offers a promising therapeutic option [19].

3.3 Targeted Drug Delivery

Phytogenic nanomaterials can be tagged with targeting ligands, such as transferrin and folic acid, to enhance the specificity of targeting lung cancer cells. The ligands are recognized and attached to the receptors overexpressed on the cell membrane of the cancer cells, thus enabling selective entrapment of the drug in the tumor with low toxicity in normal tissues. This delivery system enhances the efficacy of the drugs while limiting the toxicity of conventional chemotherapy [20].

3.4 Angiogenesis Inhibition

Angiogenesis or vessel formation supports tumor growth and metastasis. Phytogenic nanoparticles created from bioactive phytochemical compounds such as curcumin and resveratrol strongly inhibit VEGF expression and hence inhibit angiogenesis. Inhibiting blood supply to the tumor, the nanoparticles inhibit the supply of oxygen and nutrients for the cancer cell survival and growth [21].

3.5 Immune System Modulation

There are phytogenic nanoparticles that possess an immune-modulation capacity with the identification of and eradication of cancerous lung cells. They release cytokines, initiating entry into the tumor environment for immune cells. They are causing prolonged repletion of the cancers through enhancement of the immunity levels and risk decrement in tumor regrowth [22].

4. Therapeutic Applications of Phytogenic Nanomaterials in Lung Cancer

4.1 Drug Delivery Systems

Lung cancer is still one of the main causes of death from cancer across the globe, owing to the delay in diagnosis and inefficient delivery of medication. Conventional chemotherapy is not a specific process and leads to harmful side effects as well as weakening the treatment efficiency [23]. Figure 1 illustrates the targeted drug delivery via nanoparticles, as indicated by the picture, which is an innovative solution for eliminating these issues. The process starts with functionalization, where nanoparticles are functionalized with proteins, antibodies, or targeting ligands targeting specific markers of lung cancer cells. This facilitates selective deposition within tumor tissue without harming healthy tissues [24]. Drug loading is the second process, in which anticancer drugs are loaded into the nanocarrier, improving drug stability and bioavailability. These nanoparticles, once administered, cross the blood and get deposited at the tumor location via the EPR effect. At the cancer cells of the lung, internal triggers like pH, enzymes, or external triggers like heat or light induce drug release [25]. Controlled drug delivery minimizes systemic toxicity and maximizes therapeutic effects. Nanoparticle-based targeted drug delivery maximizes chemotherapy efficacy, minimizes drug resistance, and maximizes patient benefits [26]. Additionally, biodegradable and phytogenic nanoparticles maximize safety and sustainability. Advances in nanomedicine hold enormous potential for more targeted and less toxic individualized lung cancer treatment. The novel therapy is revolutionizing the management of lung cancer, improving the survival and quality of life of patients. Combinational drug therapy and nanocarrier modification can be optimized even further in future studies for targeted therapies [27].

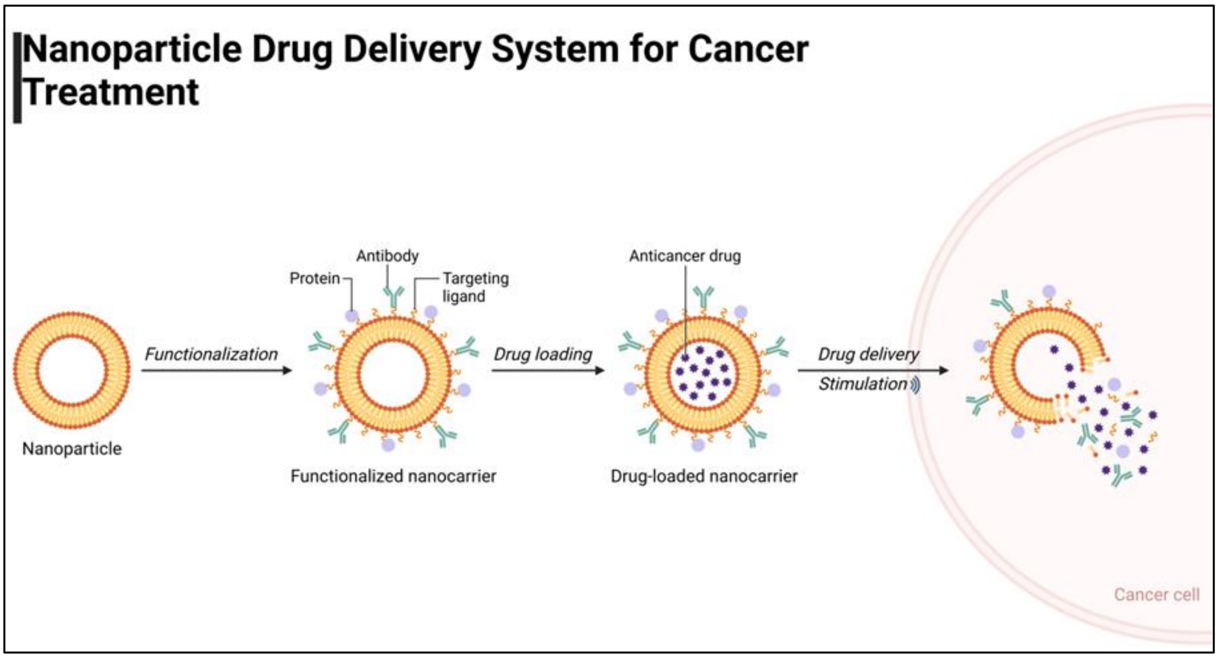

Figure 1: Targeted Drug Delivery via Nanoparticles for Lung Cancer Treatment.

4.2 Chemotherapy

Lung cancer is among the most common reasons for cancer-related death globally, against which chemotherapy is a part of the treatment regimen. Though restricted by drug resistance and systemic toxicity, recent advancements in nanotechnology in the field of phytogenic nanoparticles introduce a new door to overcoming the limitations [28]. The phytogenic nanoparticles, synthesized by plant-biomolecule-derived synthesis, offer a number of benefits such as biocompatibility, low toxicity, and targeted drug delivery. The nanoparticles can encapsulate chemotherapeutic drugs, which are released in a controlled and sustained way and with enhanced drug accumulation at tumor sites. The natural antioxidant and anti-inflammatory nature of the particles also helps to minimize side effects and enhance cancer cell apoptosis [29]. The prime hindrance of lung cancer chemotherapy is drug resistance, most of which is the result of gene mutations, overexpression of efflux pumps, and alterations in apoptotic signaling. Phytogenic nanoparticles cross-resistance barriers by administering combinations of therapeutic compounds, inhibiting resistance-related gene expression, and evading efflux mechanisms for drugs [30]. Their ability to target tumor microenvironments also increases the penetration and persistence of drugs. The use of phytogenic nanoparticles in lung cancer chemotherapy has the potential to enhance therapeutic outcomes, reduce side effects, and reduce drug resistance, opening the doors to more potent and targeted approaches to cancer therapy [31].

4.3 Photothermal Therapy

Photothermal therapy (PTT) is an emerging nanotechnology-based technique in which light-excited nanomaterials create localized heat to kill cancer cells effectively. In lung cancer therapy, this method provides a potential replacement for traditional therapies as targeted tumor ablation with less tissue injury [32]. Gold nanoparticles, carbon nanotubes, and graphene oxide are efficient photothermal converters of light with high absorbance of light and high thermal conversion capabilities. Under irradiation by an NIR laser, these nanomaterials convert the photons to heat, increasing the tumor tissue temperature to higher than 42°C [33]. This thermal effect causes irreversible cell damage, protein denaturation, and apoptosis of tumor cells. Selectivity of PTT is promoted by the modification of nanomaterials with tumor-targeting ligands, e.g., antibodies or peptides, to ensure selective accumulation in cancer locations [34]. Besides, PTT can be combined with chemotherapy or immunotherapy to gain a synergistic therapeutic effect, hence enhancing curative efficacy. Relative to conventional lung cancer therapies, PTT is superior in low systemic toxicity, minimally invasive procedures, and real-time control over treatment efficacy [35]. New research is directed toward maximizing nanoparticle compositions and delivery to achieve improved clinical transfer and patient performance in the treatment of lung cancer [36].

4.4 Gene Therapy

Lung cancer is still one of the most common causes of death among cancer patients globally, and traditional treatments like chemotherapy, radiation, and targeted therapy are often found to have limited long-term effectiveness [37]. Gene therapy is becoming more of a viable method of treating lung cancer by introducing genetic material into cancer cells to trigger apoptosis, inhibit tumor growth, or activate the immune system against cancer [38]. Figure 2 shows a gene therapy mechanism where a therapeutic gene vector enters selectively into a cancer cell and induces apoptosis. Gene therapy employs viral and non-viral vector systems to deliver therapeutic genes [39].

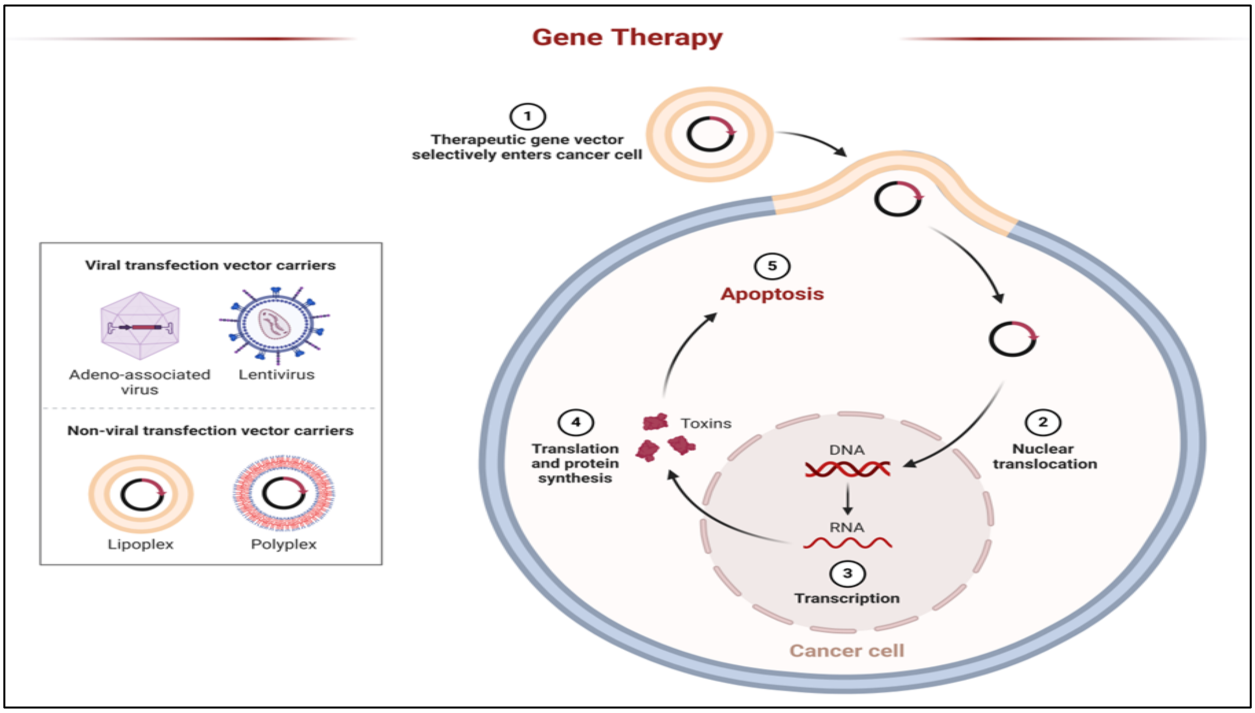

Figure 2: Gene Therapy Mechanism in Lung Cancer – Therapeutic Gene Vector Delivery and Induction of Apoptosis.

Viral vectors like adenovirus-associated viruses and lentiviruses deliver genes efficiently into cells, whereas non-viral vectors like lipoplexes and polyplexes provide safer alternatives with less immunogenicity. In cancer of the lung, gene therapy includes replacement of tumor suppressor genes, RNA interference (RNAi) for silencing oncogenes, and immunomodulation [40]. For instance, the p53 tumor suppressor gene, which is often mutated in lung cancer, may be reintroduced into cancer cells to restore normal regulation of the cell cycle and to cause apoptosis. Likewise, RNAi-based therapies target oncogenic drivers such as KRAS and EGFR mutations to block tumor growth. Recent developments also investigate CRISPR-Cas9 for editing genes in lung cancer, with accurate alterations to rectify mutations [41]. In spite of hurdles like effective delivery of genes and off-target effects, clinical trials continue to examine the potential of gene therapy. Gene therapy has immense potential as a targeted and individualized modality of treatment against lung cancer with continuous development [42]. Table 1 provides a summary of various drug therapies, mechanisms, delivery systems, target diseases, and advantages. It includes chemotherapy drugs, gene therapies, drug delivery systems, and photothermal therapy approaches.

Table 1: Comparison of Drug Therapies and Delivery Systems for Cancer and Genetic Diseases.

S/n	Drug	Therapy	Mechanism of Action	Delivery System	Targeted Disease	Advantages	Ref. (s)
1	Doxorubicin	Chemotherapy	Inhibits topoisomerase II, intercalates DNA	Intravenous (IV)	Breast cancer, leukemia, lymphoma	Broad-spectrum, effective against solid tumors	[43]
2	Paclitaxel	Chemotherapy	Stabilizes microtubules, prevents mitosis	IV, Nanoparticles (albumin-bound)	Ovarian, breast, and lung cancer	Nanoparticles enhance solubility and efficacy	[44]
3	Cisplatin	Chemotherapy	Crosslinks DNA, disrupting replication	IV	Testicular, ovarian, and bladder cancer	Highly effective, used in combination therapy	[45]
4	Methotrexate	Chemotherapy	Inhibits dihydrofolate reductase, blocking DNA synthesis	Oral, IV, Intramuscular (IM)	Leukemia, lymphoma, rheumatoid arthritis	Lower toxicity at controlled doses	[46]
5	Temozolomide	Chemotherapy	Alkylates/methylates DNA, leading to apoptosis	Oral	Brain tumors, glioblastoma	Good blood-brain barrier penetration	[47]
6	5-Fluorouracil (5-FU)	Chemotherapy	Inhibits thymidylate synthase, blocking DNA synthesis	IV, Topical (for skin cancers)	Colorectal, breast, and pancreatic cancer	Effective in combination therapy	[48]
7	Liposomal Doxorubicin	Drug Delivery System	Liposomal encapsulation improves tumor targeting	Liposomal nanocarrier	Breast cancer, Kaposi's sarcoma	Reduces cardiotoxicity, prolongs circulation	[49]
8	Liposomal Paclitaxel	Drug Delivery System	Enhances solubility and bioavailability	Liposomal nanocarrier	Ovarian, lung, and breast cancer	Improved drug stability, reduced side effects	[50]
9	Pegylated Liposomal Irinotecan	Drug Delivery System	Delayed clearance, prolonged circulation time	PEGylated liposomal formulation	Pancreatic cancer	Increased bioavailability, better efficacy	[51]
10	Onasemnogene Abeparvovec (Zolgensma)	Gene Therapy	Delivers SMN1 gene via AAV9 vector	Adeno-Associated Virus (AAV9)	Spinal muscular atrophy	One-time treatment, long-lasting effects	[52]
11	Luxturna (Voretigene neparvovec)	Gene Therapy	Delivers the RPE65 gene to restore vision	AAV2 vector	Inherited retinal disease	Permanent vision restoration in eligible patients	[53]
12	Gendicine	Gene Therapy	Adenoviral vector carrying the p53 gene	Adenoviral vector	Head and neck cancer	Restores tumor suppression function	[54]
13	Kymriah (Tisagenlecleucel)	Gene Therapy	CAR-T therapy targeting CD19	Autologous T-cell modification	B-cell acute lymphoblastic leukemia	Personalized therapy, high remission rate	[55]
14	Yescarta (Axicabtagene ciloleucel)	Gene Therapy	CAR-T therapy targeting CD19	Autologous T-cell modification	Large B-cell lymphoma	Highly targeted therapy, durable response	[56]

15	Gold Nanoparticles (AuNPs)	Photothermal Therapy	Converts near-infrared (NIR) light into heat	Gold-based nanocarrier	Solid tumors	Localized treatment, minimal invasiveness	[57]
16	Indocyanine Green (ICG)	Photothermal Therapy	Absorbs NIR light, generates heat	Biodegradabl e dye	Tumor ablation, imaging agent	Dual use for therapy and diagnostics	[58]
17	Copper Sulfide Nanoparticles	Photothermal Therapy	Converts light to heat, inducing apoptosis	CuS nanostructure s	Breast and liver cancer	Small size allows deep tissue penetration	[59]
18	Polypyrrole Nanoparticles	Photothermal Therapy	Light-responsive polymer for hyperthermia therapy	Conductive polymer nanoparticles	Skin and breast cancer treatment	Biocompatible , enhanced thermal response	[60]

This table concludes that the development of drug therapies and drug delivery systems has greatly enhanced the treatment of cancer and genetic diseases. Chemotherapy drugs are still utilized, but new technologies like gene therapy and nanotechnology-based drug delivery systems are providing more targeted and effective treatments. Liposomal and PEGylated drugs prolong circulation time for most drugs and minimize systemic toxicity, whereas CAR-T cell therapy offers personalized therapy with high remission rates. Photothermal therapy with nanoparticles offers a novel, non-invasive method that is targeted against tumors. Continued research and clinical advancements will continue to enhance these treatment modalities, optimizing patient results further and adding to the treatment armamentarium against fatal disease. Combining the old with the new, the future promises increasingly efficient, effective, and patient-friendly solutions for the cure.

5. Diagnostic and Imaging Applications of Phytogenic Nanomaterials

Being plant-based materials, phytogenic nanomaterials have been discovered to be an appropriate agent in biomedical applications, especially in diagnostics and imaging. Phytogenic nanomaterials are plant extracts with bioactive compounds and are biocompatible, green, and economical. By virtue of their physicochemical characteristics, they are appropriate for early disease detection, sensing of biomarkers, and sophisticated imaging methods [61].

5.1 Early Detection and Biomarker Sensing

Early disease diagnosis is vital in disease treatment and management. Phytogenic nanomaterial has a crucial function of early disease detection since they bind to certain biomarkers. Biomarkers are bio molecules that symbolize the existence of conditions like cancer, cardiovascular disease, and infection. Molecules can be proteins, nucleic acids, or metabolites in the compound form present in body fluids like blood, saliva, or urine [62]. Nanoparticles synthesized from plant extracts are highly specific and sensitive in the identification of biomarkers because of their intrinsic surface chemistry. Metal nanoparticles like gold (AuNPs) and silver (AgNPs), upon phytochemical synthesis, demonstrate impressive optical, electrical, and catalytic properties. These properties provide a foundation for creating biosensors that can detect extremely trace amounts of disease-specific biomarkers [63]. As an example, gold nanoparticles prepared from green tea extract were utilized for detecting cancer biomarkers colorimetric assay. Contact of the nanoparticle with the biomarker is identified by naked eye visible color change without the use of a microscope. Likewise, silver nanoparticles extracted from neem extract have been found to identify bacterial infection using surface-enhanced Raman spectroscopy (SERS) [64]. These plant-based nanomaterials enhance the sensor's diagnostic sensitivity to offer real-time and credible detection. Phytogenic electrochemical and fluorescent biosensors are another promising direction. Plant extract-based fluorescent nano-particles, termed as quantum dots, can be aptamable using antibodies or aptamers to address specific biomolecules. Phytogenic metal nano-particles to be used in electrochemical biosensors amplify the sense of the signal to offer highly accurate diagnosis of diseases [65].

5.2 Advanced Imaging Techniques

Clinical imaging is a crucial part of the diagnosis and monitoring of disease. The conventional imaging techniques using X-rays, magnetic resonance imaging (MRI), and computed tomography (CT) scans conventionally use contrast media to provide more detailed images. Phytogenic nanomaterials are now being touted as non-toxic and bio-compatible substitutes for the conventional contrast agents for enhancing the precision of imaging and, by proxy, safety for the patient [66]. Gold and silver nanoparticles prepared from plant extracts increase contrast in imaging modalities like optical coherence tomography (OCT) and photoacoustic imaging (PAI). Nanoparticles scatter and absorb a significant amount of light and can be employed in cancer and vascular disorder detection. Iron oxide nanoparticles prepared with phytochemicals like polyphenols and flavonoids are good contrast agents for MRI. The nanoparticles enhance the resolution of imaging and minimise toxicity over traditional gadolinium-based contrast agents. Phytogenic carbon nanomaterials like graphene and carbon dots also have the ability to outdo fluorescence imaging for live cell activity monitoring [67].

6. Challenges and Future Prospects

Phytogenic nanomaterials are very promising in the treatment of lung cancer, but there are many challenges that must be overcome before they can be applied clinically. One of the primary issues is scalability—green synthesis routes are not reproducible, hence, large-scale production becomes a challenge. Batch-to-batch reproducibility in plant extracts impinges on the stability of the nanoparticles and pharmacological efficacy [68]. Toxicity and biodistribution pose the greatest risk. Phytogenic nanoparticles are biocompatible, but no long-term consequences on human health are known. Further research would be required to determine possible immune response and depotentiation within critical organs. Future aspects include the construction of synthesis protocols using novel bioprocessing strategies and nanotechnology coupled with artificial intelligence for the delivery of drugs at the optimum rate [69]. Very functionalized nanoparticles for targeted therapy, plant-based nanomaterials coupled with immunotherapy, and the design of gene-editing tools such as CRISPR can change cancer therapy. Increasing these challenges will deliver more efficient and safer therapies against lung cancer [70].

7. Conclusion

Phytogenic nanomaterials offer a new platform for lung cancer therapy using the bioactive compounds of the natural plant to deliver effective, targeted, and minimally toxic therapy. Their apoptotic activity, ability to produce reactive oxygen species, ability to suppress angiogenesis, and immune stimulant ability show that they break the classical therapy constraints. By their incorporation into drug delivery systems, chemotherapy, photothermal therapy, and gene therapy, the specificity of the treatments may be enhanced with reduced systemic toxicity and drug resistance. Their uses in diagnostics and imaging also enhance their worth for lung cancer therapy. These advancements, however, come with a price in the form of mass production, clinical translation, and approval. Future studies must concentrate on optimizing synthesis pathways, increasing nanoparticle stability, and investigating combinational therapy in an attempt to provide better patient care. More innovation, phytogenic nanomaterials can turn lung cancer treatment into a more effective, targeted, and environmentally friendly treatment strategy

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