

Advances in Nanomedicine for Cancer Therapy: A Comprehensive Review

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ABSTRACT

Cancer remains the most significant cause of death worldwide, and this shows how pathetic the situation is in terms of putting better intervention systems in place. With such an analysis, we can be able to discover the transformative capability of nanotechnology and its application in the process of treating cancer. Imbued with all the peculiarities of nanomaterials, nanomedicine offers new approaches to individual care, imaging, drug delivery, and diagnostics. Pharmaceutical delivery of drugs using nanoparticle materials- metallic nanoparticles, dendrimers and liposomes- increases the bioavailability of drugs to greater extents and reduces the systemic toxicity as well as the issue of multidrug resistance to very great extents. Furthermore, nanotechnology offers imaging with great accuracy, early disease detection and enhanced clinics. The primary treatment methods, including photothermal therapy, magnetic hyperthermia, or RNA-based treatments, are mentioned, with a description of their concept and implementation provided. Challenges such as toxicity, regulation and manufacturing standardization also challenge it. The review points out the fact that nanomedicine holds

promise when it comes to revolutionising the handling of cancer and adds that additional studies ought to be carried out to ensure the full potential of the technology is realised in clinical practice.

Keywords: Nanomedicine, Cancer Therapy, Targeted Drug Delivery, Nanoparticles, Photothermal Therapy

INTRODUCTION

Cancer is a sickness that has several synonyms that depict that cancer is heterogeneous and is due to a lack of control in appending and repelling abnormal cells in the body. These abnormal cells do not act as the standard biological requirements and functions in regards to biochemistry; therefore, they are likely to creep into the local tissues or may metastasize and assault those that are remote in the body. The World Health Organization has estimated that 10 million people will have been killed by cancer in the world by 2020, making it one of the leading causes of death in the world. The statistic is expected to be on the same scale as the economic burden of absenteeism, which amounts to about a sixth of the occurrences of death, on the global level. [1,2]. The problem of cancer in the world is growing; according to the World

Health Organization, in 2020, more than 19.3 million new cases were registered, and it is obvious how crucial it is that there be effective means of prevention of this disease, its early diagnosing, and methods of control. More than half the number of the diseases represent cancer, and the most favored diseases are prostate cancer, colorectal cancer, lung cancer, and breast cancer. All cancers affect a person individually, and every cancer has a different pathophysiology and clinical presentation, and therefore requires a different kind of management. [1,3]

1. Solid Tumor Cancers

Solid tumors develop in solid organs and tissues, i.e., breast, lung, prostate, colon, among others. This type of tumor can be characterized by the development of a scar or lump, which is considered to be either benign (non-cancerous) or malignant (cancerous).

Breast Cancer: This belongs to the categories of cancer that have claimed millions of lives of both men and women, besides being among the most widespread kinds of cancer and a leading cause of death. It starts as ductal or lobular glands of the breast and is usually a result of screening methods such as Mammography or Ultrasound. An estimate of 2,296,840 cases of breast cancer among women is reported in the year 2022; This is 23.8 percent of all the newly diagnosed breast cancer cases in women. Also, the world was experiencing nearly 670,000 deaths because of breast cancer; it contributed to all of the deaths of women with cancer by 15.4 percent; it is the leading cause of death among women.⁴ The causes of breast cancer are various, e.g., genetic predisposition is a cause of breast cancer with genes linked with risks of cancer, such as the BRCA1 gene and the BRCA2 gene. It has other causes like hormonal defects and environmental factors involving lifestyle, radiation and infections. Breast cancer, particularly mammography screening, ought to be carried out frequently, as at this stage,

the five-year relative survival statistics stand at 99 percent. Breast cancer remains the most significant health issue globally despite the many efforts to detect this disease into detection and there has been some advancement in treatment procedures; therefore, additional research programs, awareness-raising activities, as well as formulation of more efficient resultant screening processes have to be initiated worldwide. [5,6]

Lung Cancer: Lung cancer is one of the global concerns as far as health diseases go globally because of its broad impacts as well as its prevalence, as shown in the 2022 data. A total of approximately 2,480,675 new cases of lung cancer were diagnosed in the world that year. It constituted 12.4 percent of the new cancer cases discovered. It is also projected to cause 1,817,469 deaths in 2015, or 18.7 percent of all cancer-related deaths globally, which is rather unfortunate as it became the leading cause of death due to cancer [7]. The two major divisions of non-small-cell lung cancer (NSCLC) are a kind of lung cancer. They include small-cell lung carcinoma, squamous cell carcinoma and adenocarcinoma. The type of cancer is (SCLC), which is quite rare but very aggressive. Tobacco smoking is the most dominant risk factor, accounting for about 70 percent of deaths due to lung cancer. In contrast, environmental exposure to radon gas, asbestos and air pollutants are other major contributors to its onset. These data highlight the drive to have effective prevention interventions, such as smoking cessation campaigns and the limitation of exposure to carcinogenic environmental factors, and improvement of early detection and treatment as a means of reducing its burden in the world population. [8,9]

Prostate Cancer: Among males, prostate cancer poses a significant threat to their health and especially those aged fifty and above. It is a type of cancer that mainly attacks the glandular prostate cells, and its detection is usually done by the use of blood tests known as PSA or a digital rectal

examination (DRE). Among the risk factors, there is an increase in age, family tendency, and hormonal impact. Although prostate cancer at an early stage, that is, Gleason Grade Groups 1 and 2, does not show symptoms most of the time, more advanced stages may include symptoms in the urinary tract, bone pains, and other systemic conditions. The 2024 projections have shown that approximately 299,010 new prostate cancer cases will be diagnosed in the United States, representing an approximate percentage of 14.9 percent of all the brand-new cancer diagnoses. Moreover, it is projected that 35,250 deaths among males will be caused by this disease, which reveals that it is one of the key causes of male death caused by cancer. The data shows that the probability of developing prostate cancer in a male life lifespan is estimated at 12.8 percent, with 116.5 cases per 100,000 males per annum. [10,11] The statistics paint a sorry state of survival of prostate cancer patients. Once it has been identified early, that is, when it is localized in the prostate gland, the five-year relative survival rate is nearly 100 percent. In contrast, this rate considerably reduces to about 36.6 percent of patients whose cancer has spread to other parts of their body. [12] The risk factors for the prevalence of prostate cancer are clearly stated. Many of these factors are permitted, but the likelihood increases very fast depending on the years, beyond fifty years. In addition to the family history of prostate cancer, especially among the first-degree relatives, diabetes, high blood pressure, obesity, excess calories, and fat consumption are some of the most significant determinants of the disease. Hormonal components also play a role of great significance, and in most cases, androgens tend to play a greater role in determining the disease course. Prostate cancer remains the second most commonly occurring cancer among males in the world, hence a significant health threat to people. The screening procedures, such as PSA, are expected to lead to improved detection, mortality, and survival. These figures not

only stress the importance of increasing the level of community education and preliminary screening among the target group, but also the ongoing search for methods of preventing and curing. [11]

Colorectal Cancer: This is a global health issue that can only be distinguished by the diet, as well as the exercise program adopted by an individual and their genetic background. A combination of both Lynch syndrome, also referred to as hereditary non-polyposis colorectal cancer, and FAP, when added to personal and family history, as a characteristic of CRC/Polyps, significantly increases the risks. Unhealthy diets that are rich in red meat and processed meat, low fiber diets and those that contain a high proportion of saturated fats put people at a higher risk of colorectal cancer. Besides, the risk is higher when it comes to other modifiable behavioral risk factors, such as low physical activity, obesity, especially abdominal obesity, hazardous drinking, and smoking tobacco. Chronic inflammation plays a part to play on the inflammation of the body in the digestive tract, Crohn's disease and ulcerative colitis.[13] World data shows that 1,903,192 new cases of colorectal cancer are diagnosed each year, or 9.6 percent of all recently diagnosed malignancies. Moreover, it was also the second most global cause of death by cancer, and it numbered about 935,000 deaths or 9.6 of the total cancer deaths. These statistics raise awareness of the problem of Colorectal cancer in regions where people have transitioned to Western cuisine. [13,14] Screening is a critical intervention in the prevention of colorectal cancer and its fatal outcome. The prevention and screening can be carried out most effectively with the help of colonoscopy, as it will be possible to detect and remove precancerous polyps. It is highly recommended to individuals who are 50 years old or more, or to those with a history of family diseases or illnesses in their side of family. Screening test does the trick for fast diagnosis, and hence remedy is good, and the mortality level is set to be reduced

on a massive scale. There is a sequence of public health issues, such as the rising global colon cancer, which beckons modification of lifestyle as well as changes in diet, together with general screening. There are lesser-known causes to this disease, and the preventive measures that can be followed to reduce the effects of this disease are needed by the public. [14,15]

2. Hematologic (Blood) Cancers

The hematologic malignancies are contrasted with solid tumors because they start in the tissues that form blood, like the lymphatic system and bone marrow. They are systemic diseases involving the involvement of the immune system, in contrast to solid tumors, which do not affect the normal functioning of the immune system.

Leukemia: Cancer of hematologic malignancy whose source is either the bone marrow or the white blood cells, whose consequences culminate in the production of aberrant WBCs, compromise in the production of typical elements of the blood, and its reflection in anemia, infection susceptibility, and bleeding disorders. It is classified as acute and chronic depending on the aggressiveness of the disease and based on the level of maturity of red blood cells in the body of the patient. There is acute leukemia that develops rapidly, accompanied by immature blood cells, whereas there is chronic leukemia that develops slowly, alongside mature blood cells, which include CLL and CML. Approximately 60,650 individuals in the U.S. develop and 24,000 die of various forms of leukemia, with every one of them resulting in disease differential composition of 34 % AML, 11 %ALL, and 15 percent CML, whereas CLL is the commonest of chronic leukemia.[16, 17] New treatment devices, particularly the tyrosine kinase inhibitors in CML, have increased life expectancy and enabled many victims to have a relatively normal existence. The rest of the treatment modalities are also significant here, which include

chemotherapy as well as stem cell transplantation are not left behind, especially in the acute types of the disease severity. Nonetheless, leukemia remains a significant health issue, and it is evident that further research is to be conducted to streamline the treatment of this disease and improve survival rates of the patients. [18]

Lymphoma: There are two types of lymphoma, including Hodgkin lymphoma (HL) and non-Hodgkin lymphoma (NHL). One of the groups of malignancies is known as lymphomas, which occur due to lymphatic system cells. The uniqueness of Hodgkin lymphoma is that it is a disease that occurs among the youth as age oscillates between 20-30 years, and it happens to present cases of Reed-Sternberg. In many cases, it is cured with more success than the NHL. However, non-Hodgkin lymphoma constitutes 90 percent of the instances of lymphoma. It even has a variety of sub-types, and the most aggressive of all the types is the DLBCL, and a less aggressive type is the FOLL. The typical symptoms of lymphoma have been described as the development of swellings which are generally painless and might be located in the neck, pits, armpits, and groins, night sweats, uncontrolled weight loss and sluggishness. Based on the number crunching, around 81,560 the development of new Hodgkin and non-Hodgkin lymphomas would be estimated in the US in 2022, with more than 20,510 individuals losing their lives to the disease [19,20]. The use of chemotherapy when it comes to lymphoma treatment is every day, although it serves as the first-line treatment in the case of both HL and NHL. There is also immunotherapy, which improves the working of the immune system to attack cancerous cells successfully, and radiation therapy, which targets particular areas that are primarily localized during communication of the cancer, and targeted therapies that further increase the rate of treating the elderly, especially the DLBCL. These are preventable deaths since early detection and better management have

improved the survival rates of lymphoma patients.

Multiple Myeloma: The white blood cells, also known as plasma cells, which produce antibodies, are affected especially by this cancer, referred to as multiple myeloma. The feature of this disease is the uncontrolled proliferation of monoclonal plasma, which suppresses the formation of healthy blood cells that are healthy, in the bone marrow. Serum or urine monoclonal proteins (M-proteins) are typically present in the case of multiple myeloma and are usually found in amounts greater than 3 grams in a 24-hour urinary collection. The general symptoms that accompany this condition are bone pain, anemia, hypercalcemia, and impairment of the kidneys. It is important to note that the bony sites, including the spine and ribs, could be prone to acute pain communicated by patients; this could be one of the early signs of the disease. Anemia is brought about through the low production of red blood cells, and its symptoms are fatigue and weakness. Also, the wearing away of the bone tissues causes an increase in the level of calcium in the bloodstream that could be characterized by the presence of additional thirst, nausea, and confusion [21,22] Owing to the accumulation of the so-called M-

proteins in the kidneys, the dysfunction of the organs is also probable, whereas, since the body is immunosuppressed, one is likely to encounter a frequent infection. The symptoms that come along with the last phase of the disease are referred to as CRAB symptoms. They include hypercalcemia, renal failure, anemia and pain in bones. In the United States alone, some 35,730 new multiple myeloma cases will probably be registered during 2023, with 12,590 multiple myeloma deaths. Its particular prevalence is about 7.4 per normal hundred thousand citizens. The development of some new therapeutic methods took place over the past decade; these are immunomodulators, i.e., thalidomide and lenalidomide, monoclonal antibodies, and chemotherapy. Such therapies enhance the immunity of the affected person to destroy cancer cells and are specific to some proteins found on myeloma cells, such that the cancer is easier to deal with. Though it causes untold complications as a disease in the production of blood within the bone of the body and the defense system, tangible improvements made on its diagnosis and treatment have led to the fact that many patients live longer with an aspect of freshness of life referred to by some patients. [23,24]

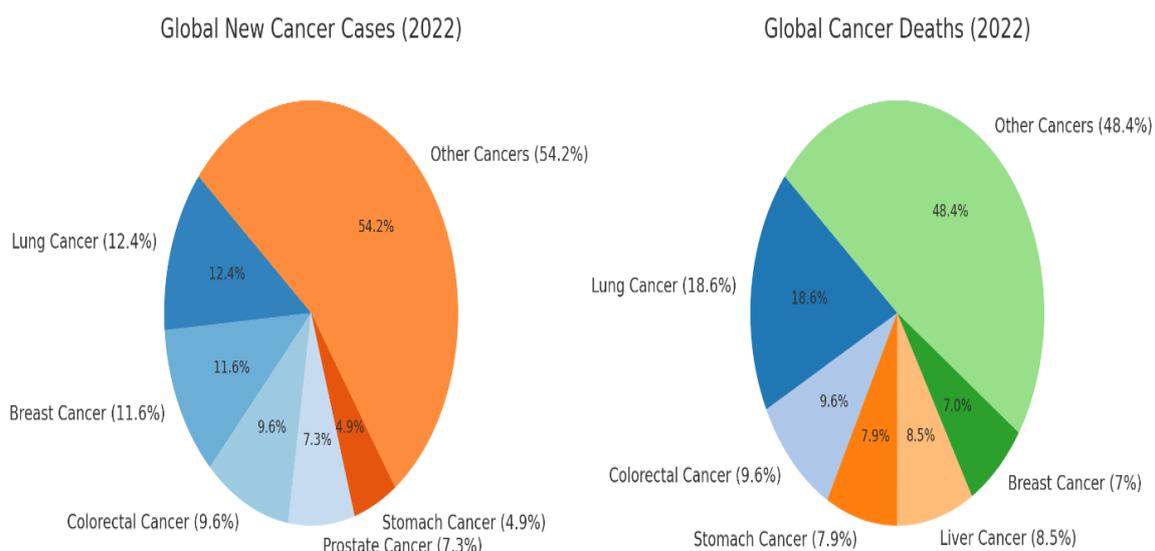


Figure 1: Global Cancer Statistics (Pie Chart)

Table No. 2: Summarizing the global cancer statistics for 2022: [4]

Cancer Type	New Cases (2022)	Percentage of Total Cases	Deaths (2022)	Percentage of Total Deaths
Lung Cancer	2.5 million	12.4%	1.8 million	18.6%
Breast Cancer	2.3 million	11.6%	685,000	7.0%
Colorectal Cancer	1.9 million	9.6%	935,000	9.6%
Prostate Cancer	1.5 million	7.3%	N/A	N/A
Stomach Cancer	970,000	4.9%	769,000	7.9%
Liver Cancer	N/A	N/A	830,000	8.5%
Other Cancers	10.84 million	54.2%	4.7 million	48.4%
Total	20 million	100%	9.7 million	100%

Role of Nanotechnology in Medicine: An area of science that has transformed medicine, especially in the detection of illnesses as well as therapeutic and preventive measures, is nanotechnology science that concerns itself with materials at an atomic or molecular level. Nanoscale items and devices have remarkable properties that are used in the treatment field in a specific branch of science, namely, nanomedicine. Nanoparticles are substances that may be up to one or a hundred nanometers. With these sizes, a group of scientists and clinicians is capable of developing new therapies that are more precise as well as effective compared to older therapies.

1. Targeted delivery: Nanotechnology in medicine promises to offer the opportunity to selectively transport the drugs to cancer cells, blood vessels near the tumor, etc, leaving the healthy tissue intact and increasing the success of the drug. Nanoparticles can be programmed to recognize and stick to some receptors present on the external membrane of pathologic cells and then release their medication. Examples of systems which are designed to entrap their medicines as well as to control the delivery rate of the agents include liposomes, dendrimers and micelles, among others, with the objective being to effectively assure the patient that the medicine will be delivered to the correct dose at the proper time. The nano-liposomes have been prepared as a vehicle to deliver

drugs in cancer management with improved bioavailability and minimal systemic toxicity [25]. One area that is advancing the study is the use of polymer nanoparticles for the development of synthetic platelets whose role would be to form clots at the point of injury to reduce blood loss in cases of trauma patients [26].

2. Medical Imaging: Nanoparticles can also help in the enhancement of medical imaging in terms of contrast and sensitivity. And sensitivity. This can be used as a contrast agent in Magnetic Resonance Imaging, Computed Tomography and ultrasound of where the resolution will be higher and images will be more detailed. As an example, iron oxide nanoparticle finds application in MRI to enhance image contrast, whereas quantum dots deliver sensitive fluorescent imaging, and this has been useful in the detection of diseases at early stages on the molecular level²⁵. Gold nanoparticles are also being researched because of their role in computed tomography (CT) to help increase their capacity and image in making diagnoses of disease and tumors. They can be engineered so that these nanoparticles bind preferentially to certain biomarkers and allow the early detection of a wide range of health problems. [27]. Nanotechnology has enabled the conception of fast and precise diagnostic tools for a variety of diseases by bringing the world of machinery and microorganisms together. Nanoparticles can be applied as a contrast agent in the range of

imaging techniques like magnetic resonance imaging (MRI), CT scans, and ultrasound, to increase the resolution of images and detail. Iron oxide nanoparticles are another example of MRI applicants commonly used to improve the quality of the imaging means, whereas quantum dots deliver a very sensitive level of fluorescence that is useful when diagnosing the onset of any disease, as it can be observed at the molecular level. [25]. There is tremendous research on the potential use of gold nanoparticles to improve resolution images with CT scans, to make the detection of cancer and other diseases in the body through this technique easier. Such particles can be armed to latch on to targeted biomarkers, hence, the detection of the disease at a highly earlier stage [27].

3. Diagnostics: Nanotechnology has revolutionized the process of diagnostics by assisting in the development of rapid and ultra-sensitive tools for the detection of illness. With the use of innovations like nanosensors, microfluidic systems, and lab-on-a-chip technologies, point-of-care diagnostics is achievable as the tools facilitate rapid and precise infection and biomarker analysis. Such developments give the chance to have a faster diagnosis that would lead to more timely and efficient treatment [25]. Johns Hopkins University scientists are coming up with new sensors that can be used to detect COVID-19 based on the nanoimprint lithography technology. The sensors hold the benefit of quick, precise detecting in diverse environments such as hospitals and faraway premises [26]. **Antimicrobial Treatments:** Some of the nanoparticles, such as silver and nitric oxide, have been demonstrated to have sufficient antibiotic properties that could be used as an antibiotic resistance combating factor. Biotic-resistant infections. These act by several means that encompass: infiltration of the bacterial cell wall and membrane; uptake into the bacterial cell; and spreading of the production of reactive oxygen species, a characteristic that makes

the functional nanoparticles the perfect choice against a wide variety of pathogens. Nanoparticles are a solution to the paradigm of resistance to antibiotics, which could also effectively be addressed with antimicrobial treatments prepared using nanoparticles, especially for gold nanoparticles in conjunction with infrared radiation. [26]. The strategy utilizes specific attributes of the gold nanoparticles in combination with the bactericidal effect of the reaction to the light that may be applied in the treatment of infections in clinics. Nanotechnology has become a central point in the development of tissue engineering, especially in the delivery of better products to support cell organization and tissue regeneration. The problem of antibiotic-resistant infections is becoming even larger. It is seen that nanoparticles have antimicrobial properties that are expressed by a wide variety of mechanisms, which are as follows: destruction of bacterial membranes, the production of reactive oxygen, which makes them valuable against a wide range of pathogens. With its use of nanotechnology as an antimicrobial treatment, the implication of the use of nanotechnology as a solution to curb this conservative issue of antimicrobial resistance provides a promising speculative ground to investigate the functionality of conventional antibiotics. It is also the combination of the gold nanoparticles and the infrared light that is being researched in order to understand how far the two would be effective in the eradication of bacteria. In this newer strategy, the special characteristic of gold nanoparticles is utilized due to the fact that upon the addition of light, the bactericidal effect is greater and thus offers a different method of treating infection under clinical circumstances. [25,26].

Tissue Engineering: Nanotechnology, in the scope of the tissue engineering field, is an important aspect, as it introduces new materials (at least in the context of scaffold production, to aid in the proliferation of the cells, and to repair tissue) The use of nanofibers and nanomaterial during the

construction of the scaffolds can replicate the action of the extracellular matrices and enhance the attachment, proliferation and differentiation processes of the cells. These advanced materials are acting in key roles during the production of complex implants, wound dressing and artificial organs. To be more exact, electrospun nanofibers are increasingly applied to develop tissue scaffolds that could improve the healing process and integration of the tissues. Such scaffoldings have been demonstrated to be successful in several regenerative designs and in particular in skin, cartilage and bone tissues generation. [25,27].

Cancer therapy: Nanotechnology has given it a twist to how cancer is being treated more perfectly by treatment strategies like photothermal treatment and Magnetic Hyperthermia. Treatment of such kind implies the insertion of nanoparticles (which might be excited with light or a magnetic field to kill the malignant cells only). The nanoparticles can transport the anti-cancer drugs without destroying the other tissues and cells present in the body; hence, they can be used to deliver the anti-cancer drugs to the tumour sites.

There is research being done on the opportunities of applying gold nanoparticles in chemotherapy medication use. These nano-particles may just release the drugs on the basis of the stimulus around them, e.g., heat and light and such localized therapy become so precise that it cannot produce any adverse effect on other parts of the body [4]. The new understanding of the mechanism of action of vaccines has helped scientists to come up with new ideas in vaccine delivery via nanotechnology, such as the delivery of antigens and immunization. Hyperthermia. These treatment procedures make use of nanoparticles to target the delivery of the drugs to the cancer cells to kill the cells and not the surrounding healthy cells by making

use of external factors to switch the nanoparticles ON, e.g., light or magnetic fields. In addition to this, the anti-adverse effects of chemotherapeutic agents and general efficacy may also be enhanced by nanoparticles due to the fact that, as shown in the study, nanoparticles may make it possible to deliver chemotherapeutic agents to tumor locations. [25, 28]. Researchers are exploring the prospects of gold nanoparticles in targeted chemotherapy. With the help of these nanoparticles' ability to be activated by the outer world, such as heat or light, therapeutic medicines can be directly released inside the tumor location. This procedure also reduces the systemic toxicity and allows a more precise method of therapy. [27].

Vaccine Development: Nanotechnology has also helped to create superior vaccines by helping to deliver novel antigens and improve immune responses. The antigens are then integrated with nanoparticles, thereby facilitating their better delivery, besides making them more stable. It can also be used to reinforce the human immune system of the human to vaccines, and this implies that it will have a longer as well as a stronger immunity against diseases. Applications are of biodegradable vaccine stability and efficacy carriers through nanoparticle-based systems that can be used to provide global usage of vaccines. [25,28].

Neurosurgery: Neurosurgery Nanotechnology is increasingly being applied in the field of neurosurgery to overcome the blood-brain barrier, commonly referred to as the BBB, a primary obstacle to the therapy of neurological diseases. To ensure that the medicinal drugs reach all the way to the brain, scientists are designing Blood-brain barrier-crossing nanoparticles. This has been a discovery that can alter the treatment of many disorders like brain tumors, Parkinson's, and Alzheimer's diseases. [25,26]

Table No. 2: Comparison of Conventional vs. Nano-Based Therapies

Aspect	Conventional Therapies	Nano-Based Therapies	References
Targeting	Non-specific affects healthy and cancerous tissues alike.	Delivery targeting tumor cells with precision, reducing harm to healthy tissues.	[29–31]
Toxicity	High toxicity with significant side effects.	Reduced toxicity due to targeted action and controlled release.	[29,30,32]
Bioavailability	Limited bioavailability and inconsistent drug distribution.	Enhanced bioavailability and improved distribution in tumor tissues.	[31,32]
Drug Resistance	Often ineffective against drug-resistant cancer cells.	Potential to overcome multidrug resistance through combination therapies.	[32]
Formulation Complexity	Simpler formulations are often less effective for complex diseases.	More complex formulations can encapsulate multiple drugs and modulate release profiles.	[30,31]
Clinical Applications	Primarily used in chemotherapy, radiation, and surgery.	Utilized in many fields, including the development of vaccines, infections, and cancer.	[30,31]
Market Availability	Established but limited options for targeted therapies.	A growing market with over 100 nanomedicines approved or in clinical trials.	[30,31,33]

Fundamentals of Nanomedicine:

Nanomedicine can be defined as the application of nanotechnology to the healthcare sector with an emphasis on disease management, prediction, cure, and prevention by use of nanoscale devices and materials. Almost generically, the term nanoscale describes a length range of 1 nanometer to 100 nanometers, a range at which Materials possess discrete biological, chemical, and mechanical properties that are very different from the same Materials at larger scales. Nanomedicine can solve all those long-standing problems of the healthcare sector thanks to its unique qualities, such as high surface area, quantum effects, and high reactivity. This discipline marks a revolution in the unification of nanotechnology and medicine, giving rise to novel methods in almost all fields of medicine. With such nano control of materials, scientists will be able to design biological structures to solve complicated problems with a precision never heard of before. With ongoing research, the commercial application of nanomedicine is increasingly expanding, signifying the imminence of significant developments in the fields of diagnostics, therapeutics and personalized medicine. As an example, it is now under investigation how nanoscale

devices can be used to observe biological processes in real time and modulate these processes. Moreover, it is expected that, as the related fields of artificial intelligence and robotics are emerging, their synergy will boost the impact of nanomedicine on healthcare. Current research into nanoscale phenomena in biological systems is likely to increase our understanding of how illnesses occur and allow the creation of more effective medicines in the future. [34,35].

Drug Delivery Systems: Drug delivery systems are one of the applications of nanomedicine that is potentially the most valuable. Polymeric, dendrimer and liposome nanoparticles, as well as metallic nanoparticles, can be specially produced to capture a medicinal compound and directly deliver it into specific cells, like cancerous cells. This mode of delivery assures that the large amounts are delivered to the desired location with minimal interaction with healthy tissue, reducing any systemic side effects that an intervention may exhibit, as well as enhancing the efficacy of the drug. As an example, the liposomal preparations of doxorubicin, i.e., Doxil, have had a low cardiotoxicity compared to the traditional form of doxorubicin. Also, the design of stimuli-sensitive nanoparticles, which can deliver therapeutic cargo upon stimulation

by a particular signal like enzyme interaction, temperature or pH changes, is improving the accuracy of the targeted delivery of a drug [35].

Diagnostics: Nanotechnology enables the development of highly sensitive diagnosis tools that would detect diseases at the early stages of their development. Correction and improvement of the level of diagnosis are provided by the use of nanosensors and imaging substances, such as quantum dots and gold nanoparticles. These innovative devices are able to support a steady check-up of health conditions and deliver accurate results of biomarkers related to various diseases such as infections, cancer, and cardiovascular diseases. One of them is the incorporation of gold nanoparticle-conjugated antibodies in a lateral flow assay that can detect pathogens quickly. [35,36].

Therapeutics: Nanomedicine is also about the use of novel therapeutic strategies, including gene therapy and regenerative medicine. By manipulating nanomaterials, scientists can develop systems that facilitate cellular repair or the present ability to deliver genetic material to specific cells directly. A good application of this technology is the use of lipid nanoparticles (LNPs) in COVID-19 vaccines based on mRNA. LNPs are highly effective with mRNA protection and cell uptake, resulting in an immune response. Also, research is underway to enhance the process of gene editing by the adoption of nanocarriers to carry the CRISPR-Cas9 components. [34,35].

Imaging Techniques: Nanoparticles aim at improving advanced imaging tools, including magnetic resonance imaging (MRI), computed tomography (CT), and positron emission tomography (PET), which take a significant boost from the use of nanoparticles. The contrast agents that enhance the capability of differentiating between healthy and sick tissues in the magnetic resonance imaging (MRI) are the superparamagnetic iron oxide nanoparticles (SPIONs). Likewise, gold nanoparticles also increase the contrast of CT scan images,

hence providing higher resolution, more explicit photos. These technical advances would help improve the accuracy of the staging of a disease and the successful monitoring of treatment progress [35]. Regenerative Medicine Nanotechnology plays a vital role in tissue engineering since it can be applied towards building scaffolds to mimic the properties of native extracellular matrices, which will support tissue remodeling and cell regeneration. Scientists are working on nanofibers and hydrogels that are made using biocompatible materials that help in repairing different damaged tissues, such as cartilage, bone and skin. An example is those scaffolds made using electrospinning that contain growth factors or stem cells, which have shown sufficient promise in the improvement of wound healing as well as bone regeneration. Moreover, the use of nanoparticles is also examined to use in their ability to deliver bioactive compounds that promote tissue repair and regeneration [36].

Personalized Medicine: Nanotechnology integrated with proteomics and genomics simplifies the production of individualistic treatment options, which are customized to the specific patient-based genotype. Nanoparticles can transport drugs or genetic materials that fit most precisely with the individual molecular markers of a patient, thus enhancing the effectiveness of therapy with a reduction in the adverse effects. In the case of cancer, to counter multidrug resistance, new nanoscale drug delivery mechanisms are also being worked upon, which employ siRNA or other resistant-gene blocking agents. [35,36].

Preventive medicine: Indeed, nanomedicine is the hope of revolutionizing preventive care using enabling early detection and treatment of the disease. The sensitivity of nanoscale biosensors to even trace amounts of variations in the concentration of the biomarkers presents enormous potential in the early detection of diseases such as diabetes, cancer, and neurodegenerative diseases. Also, the

nanoparticle-based vaccinations (like the COVID-19 ones) demonstrate the efficiency of nanotechnology in preventing infectious diseases. [34,35]

Nanocarriers: A modern family of synthetics called nanocarriers was explicitly designed to assist medications in their delivery by the body to specific sites, significantly increasing their medicinal powers and reducing the risk of causing unintended side effects. All these carriers have individual benefits in drug delivery as they are used and categorized depending on their structure and composition characteristics. The variety of nanocarriers becomes central to the modern delivery systems of medications, since it allows offering a customized solution to the patient, which enhances the clinical outcomes, and limits the side effects. To improve the benefit of therapy for many medical diseases, emerging research is actively attempting to find new uses and enhance older nanocarrier designs. Moreover, the advances in nanocarrier technology are quickly being unified with such cross-compatible technologies as bioinformatics and artificial intelligence to develop even cleverer and more capable medication delivery systems. The interdisciplinary approach has great potential to provide solutions to some of the most critical health challenges today, such as cancer, neurodegenerative diseases and infectious diseases.

1. Polymeric Nanocarriers

Polymeric Micelles: Nanocarriers, a special type of artificial device, are manufactured to enhance how medications are transported around the body, improving their control and lowering any unwanted side effects. These carriers are divided based on their makeup as well as composition, and each type has unique advantages when it comes to the delivery of drugs. The abundance of nanocarriers is critical to modern drug delivery systems since it offers tailored applications, improving the treatment outcomes and reducing the side effects. To

enhance therapeutic success against various health conditions, continued drug development research teams are paying attention to exploring new uses and improving the design of current nanocarriers. Advanced and effective drug delivery systems are being created due to the increasing integration of nanocarrier technology with such areas as bioinformatics and artificial intelligence. This method of multidisciplinary science has a lot of potential in solving some of the current and most eminent health adversities in our times, such as cancer and neurodegenerative diseases, as well as infectious diseases [35].

Polymeric Nanoparticles: Solid colloid particles can be made using natural and synthetic polymers. They enhance stability and ease of discharge of medicines under control. As per the studies, poly (lactic-co-glycolic acid) (PLGA) nanoparticles with doxorubicin can deliver it efficiently and minimize toxicity and enhance anti-tumor activity. Also, PLGA nanoparticles have been investigated during vaccine application, and results have indicated better antigen stability and enhanced immune response [37].

Dendrimers: Highly branched macromolecules can be delicately developed and could be used to transport medication. Investigations have also discussed the administration of dendrimers to transport antisense oligonucleotides, which bind the genes of the cancerous ovarian cells, and thus hold a significant therapeutic implication. Moreover, the multifunctionalization is also possible with the help of dendrimers, which means that medicinal medicine and imaging probes can be used at the same time and with the same vector to deliver [35].

2. Lipid-Based Nanocarriers

Liposomes: Spherical vesicles can contain various hydrophilic and hydrophobic drugs. Because of their composition of lipid bilayers. One of the admirable applications of this technology is regarding the use of

liposomal preparations in the administration of doxorubicin in the treatment of breast cancer. This procedure causes less systematic toxicity and, at the same time, enables greater medication levels at tumor sites. Also, in order to strengthen specific distribution to specific cell types, liposomes can be modified with special ligands, including peptides or antibodies [37,38].

Solid Lipid Nanoparticles (SLNs): Curcumin and other poorly soluble drugs can be carried with Solid Lipids that are stabilized with the help of a surfactant, forming the foundation of the Solid Lipid Nanoparticles (SLNs). This would increase the bioavailability and the effectiveness of the medications. Also, antiviral drugs have been studied in the delivery of SLNs with improved properties of drug stability in increased efficiency and prolonged release.

Niosomes: Niosomes are structurally similar to liposomes, with the importance being noted as being more stable and cheaper to manufacture due to non-ionic surfactants being used. They have been demonstrated to be quite efficient in the use of antiretroviral drugs to treat HIV. The niosomes are also examined in their application in terms of delivering the drug through the skin, thus providing a non-invasive route of medication delivery while enhancing the penetration of drugs [35,39].

3. Inorganic Nanocarriers

Carbon Nanotubes (CNTs): A Cylindrical structure is investigated in the case of delivering various anticancer drugs, including cisplatin and methotrexate. Their unique properties, like wide surface area and ability to infiltrate the cell membrane, facilitate improved cellular absorption and accurate administration of medications. Moreover, the possibility of carbon nanotubes (CNTs) in one photothermal therapy (a type of treatment where they can absorb the light of the near-infrared wavelength to produce heat, leading to the death of cancerous cells) is under assessment [40].

Gold Nanoparticles: Nanoparticles composed of gold are identified to have unusual optical properties and have been used in delivering therapeutic agents and serving as facilitators of imaging activities as well. It has been studied for potentially using them in targeted therapy of cancer, whereby the surfaces may be functionalized with pharmaceuticals, targeting ligands, and imaging agents. Moreover, gold nanoparticles have photothermal as well as radiosensitizer properties, which can enhance cancer therapy plans [35,40].

Iron Oxide Nanoparticles: Iron oxide nanoparticles are applied in most targeted medication delivery systems and magnetic resonance imaging (MRI). The superparamagnetic characteristics of chemotherapeutic agents have helped to achieve an effective range, delivering them to the particular tumor region efficiently. Additionally, hyperthermia treatment by applying an alternating magnetic field to induce localized heat to cause the death of cells found in the malignant areas is causing investigation of the iron oxide nanoparticles as a potential application [35,41].

4. The hybrid nanocarriers: The hybrid nanocarriers are a mixture of organic and inorganic materials to enhance the stability and targeting of these nanocarriers. To illustrate, studies have proved the development of a hybrid system in which a polymeric outer wall as well as an inorganic core are used that improve the loading capacity and release properties of the drug to treat cancer. Such hybrid systems often possess synergetic properties such as the improvement of biocompatibility and versatility, and this makes them suitable in complex therapeutic applications [35].

5. Nano Suspensions and Nanoemulsions

Nanoemulsions: Fine oil-in-water or water-in-oil emulsions enhance the bioavailability and the solubility of lipophilic drugs. It has been revealed that they can be effectively used in the treatment of anti-inflammatory medications, resulting in improved therapy

outcomes. Nanoemulsions were also studied as a system to deliver vaccines, where they offer antigen stability and greater immune response [39,41].

Nanosuspensions: to enhance the solubility of poorly soluble drugs, these occur in the form of a colloidal suspension of nanoparticles, where the particle size is

minimized. These systems came into practical use in the distribution of antifungal drugs. Also, the use of nanosuspensions has been proposed to be investigated in the delivery of drugs to the eye, which offers a more extended stay, as well as increased absorption of the drug in the ocular system [34].

Table No. 3: Properties of Different Nanocarriers

Property	Polymeric Nanocarriers	Lipid-Based Nanocarriers	Inorganic Nanocarriers	References
Particle Size	Typically range from 10 nm to 1000 nm; they affect biodistribution and cellular uptake.	Usually between 50 nm and 200 nm; optimal for cellular uptake.	Varies widely; often in the range of 1 nm to 100 nm, affecting magnetic properties and drug loading.	[40]
Surface Charge (Zeta Potential)	It can be modified to enhance stability and targeting; it typically varies from -30 mV to +30 mV.	Zeta potential can be tuned for stability, generally neutral to slightly negative.	Highly variable; affects aggregation and interaction with biological systems.	[40]
Hydrophobicity	Can be engineered for hydrophilic or hydrophobic drug loading; affects drug release profiles.	Generally hydrophobic core with a hydrophilic shell enhances the solubility of hydrophobic drugs.	Often hydrophilic or amphiphilic, depending on surface modifications.	[40]
Loading Capacity	High loading capacity for both hydrophobic and hydrophilic drugs; can encapsulate large amounts of therapeutic agents.	Moderate loading capacity; adequate for lipophilic drugs but limited for hydrophilic ones.	High loading capacity for small molecules, but limited for larger biomolecules.	[42]
Stability	Generally stable in physiological conditions; stability can be enhanced through cross-linking.	Stability is influenced by formulation and storage conditions; prone to aggregation if not properly formulated.	Highly stable under various conditions, but may require surface modification for biocompatibility.	[43,44]
Biocompatibility	Generally biocompatible, especially when using natural polymers like chitosan or gelatin.	High biocompatibility due to lipid composition; widely used in clinical applications.	Biocompatibility varies; metal nanoparticles may elicit immune responses unless coated appropriately.	[42]
Targeting Capability	Can be functionalized with targeting ligands (e.g., antibodies) for specific delivery to diseased cells.	Can be modified by targeting moieties like antibodies or peptides for enhanced specificity.	Functionalization is possible, but targeting is often less precise compared to polymeric carriers.	[40]

Types of Nanoparticles Used in Cancer Therapy

Metal-Based Nanoparticles (Gold, Silver, etc.): The metallic NPs gold, silver,

palladium, and iron oxide have undergone a revolutionary transformation regarding the treatment of cancer. Several special physical and chemical properties of these

nanoparticles will make them helpful in treatment and diagnostic approaches, and hence enhance the targeting and treatment of cancer. Their application in other therapeutic applications has been beneficial since they give improved results of treatment without many side effects. Their usage is still in development, and further research is conducted in order to enhance their use, and that is why the list of possibilities is open in the treatment of cancer by means of modern, highly individual approaches. [45,46]

Gold Nanoparticle (AuNPs)

In cancer therapy, gold nanoparticles (AuNPs) have been recently used because they offer certain benefits to serve as anticancer agents. These nanoparticles possess several advantages, such as their size and shape factor can be tuned by the user, which then determines the entire profiling of the biological activity and cell absorption, so that they can be profitable for a vast number of therapeutic options. 47 They also possess the optical property of the so-called surface plasmon resonance, which enables them to absorb near-infrared (NIR) light; hence, they can be used to engage in photothermal therapy (PTT) by converting the absorbed light energy into heat, thereby killing the cancer cells.[50]

In photothermal therapy, AuNPs COC has been determined to be highly effective in destroying cancer cells selectively without posing a threat to the surrounding healthy cells. As an example, other studies demonstrate that AuNP usage to supplement the administration of NIR irradiation can be equally effective at halting tumor growth, and none of the procedures involved are invasive, and only a minimal amount of systemic toxicity is present. [48,51] In addition to PTT, AuNPs-based drug delivery involves pre-organizing the surface with targeting moieties. Such a strategy has specifically been used efficiently when doxorubicin (DOX) and miR-122 chemotherapeutic agents have been administered together with conjugated NPs,

displaying super-additive effects. 47 Also, AuNPs are assessed in drug combination therapy and radiotherapy as the high atomic number augments the radiation dose delivered to a tumor. This amplification, as a result of the photoelectric effect, boosts damage in the DNA of cancerous cells. This greater effect has been evidenced in the lab tests where mice exposed to AuNPs before radiation had much smaller tumors compared to a control group. 51 Other than therapeutic application, AuNPs have theranostics, that is, a projection of both therapeutic and diagnostic capabilities. They can capture real-time reactions of tumors to treatment, and so cannot be substituted in the course of prescription of personalized therapy because of their use as contrast agents in procedures like X-ray Computed Tomography (CT). Nevertheless, the Nanobio crew has a few issues at hand, such as the problem of biocompatibility, targeting, and translational issues. Certain necessary future studies that need to be made on AuNPs are that they should never elicit a special immune response, and that their specificity should be enhanced towards different types of cancer. [49,50] Additional studies to overcome existing challenges will significantly contribute to the use of their full potential in clinical practices and will be a breakthrough in the concept of personalized treatment. [52,53]

Ag Nano Particles (AgNPs)

The silver nanoparticles (AgNPs) have been recognized as potential anticancer agents due to their enhanced physicochemical properties in cancer oncotherapy. Having a size that is less than 100 nm, and Reactivity that is superior due to a large surface-to-volume ratio, which makes them suitable to interact with cellular features.54 AgNPs are also ideal in the dual transformation of treating microbes and cancer cells because of their inherent activity towards microbial and cytotoxicity. These nanoparticles cause cytotoxicity through various ways, such as the formation of reactive oxygen species (ROS), destabilization of DNA and RNA,

and cell stagnation, among other mechanisms, in addition to death by apoptosis, which is responsible for destroying cancer cells. [54,55]

It is also indicated in some studies that modification of the cells' apoptotic machinery, such that cancer cells are subjected to predetermined cell death, even as healthy cells remain normal, is one of the basic ways that AgNPs can be used in cancer treatment. Production of silver ions (Ag⁺) enhances the generation of reactive oxygen species and causes oxidative stress that incurs damage to the components of the cellular organelles, such as lipids, proteins, and DNA, which is a significant parameter of their toxicity. [54, 55] The AgNPs can also influence the control of the cell cycle in cancer cells by blocking their multiplication in addition to the reinforcement of the action of performing the chemotherapy drugs. [55, 56] Conjugating targeting ligands to the AgNPs provides an opportunity to deliver the drug. This preferential process increases the solubility and performance of anticancer agents when nano-complexed with AgNPs substantially. [55,57]

By recent research findings, AgNPs in varying diameters have demonstrated potential therapeutic proficiency against various cancers, which include prostate, lung, colon, and breast cancer, including in vitro and animal cancer therapy. As an example, the preferential cytotoxicity of glutamine-functionalized AgNPs has been shown on colon cancer cells without affecting normal fibroblasts, demonstrating the potential of targeted cancer therapy [57]. They are still researching combination therapies with orthodox modalities such as chemotherapy and radiotherapy, and early observations indicated that the modalities can be enhanced by the efficacy of AgNPs in synergistic processes. AgNPs are also being put into use in the diagnosing of cancer due to their modern imaging features, besides their medical treatment applications. However, the issues of suspending AgNPs to translate such benefits

to practice do exist. Toxicity concern is a significant issue because the safety of AgNPs applied in humans is yet to be determined, and the risks that can be associated with systemic exposure are severe. The debate towards the advancement of nanomedicine is even thwarted by the regulatory climate governing such technologies. In addition to it, the synthesis of AgNPs needs to be streamlined, especially in terms of reproducibility and stability of the end product in diverse applications. Because of the multiple specified effects and the capability of targeted action, silver nanoparticles can be described as promising not only in the future development of theories of cancer treatment, but also in the actual performance of cancer treatment methods. Issues of toxicity limit, government approval, and challenges of the standard base of the synthesis of such molecules will play a critical role in the management of clinical oncology. [55, 58]

Palladium Nanoparticles (PdNPs)

Palladium nanoparticles (PdNPs) are already being recognized as a helpful resource in the treatment of cancer, and this is attributable to their diverse use in the area of cancer research and their physicochemical characteristics. The high surface area to volume ratio of these nanoparticles enhances catalytic competency and interacts with biological systems. Moreover, the strong absorption across the near-infrared (NIR) region makes them active photothermal therapy (PTT) agents. It is worth noting that PdNPs, synthesized by the use of green-based techniques, e.g., plant extracts, have higher biocompatibility and reduced toxicity compared to the same ones prepared with typical harsh chemical conditions, which provides a safer alternative in terms of biomedical applications. [59,60]

Levels of PdNPs are multiple in terms of their meeting anticancer objectives. They induce apoptosis by producing reactive oxygen species (ROS) and disturbing

cellular homeostasis, as well as activating apoptotic pathways. As an example, ginseng and rosemary-based PdNPs have been demonstrated to induce autophagy and cell death of colon cancer cells effectively. They can also work selectively to kill the cancerous cells, yet sparing the healthy tissue that surrounds the cancerous cells, since they can absorb the near-infrared (NIR) light and convert it into thermal energy. This behavior has been affirmed in studies done in vivo, where there was a considerable reduction of the tumor upon using PdNPs in conjunction with NIR irradiation. They also lead to an enhancement of mixed therapy, e.g., chemotherapy and radiation, by serving as photosensitizers, which PdNPs characterize. They generate local heat and ROS when light is irradiated, thus destroying tumors [61]

When functionalized with specific target ligands, Palladium nanoparticles (PdNPs) have much more success in eradicating cancer. The chitosan oligosaccharides and RGD peptides modified PdNPs present outstanding tumor targeting capabilities and biocompatibility features. These tailored nanoparticles enhance the effectiveness of treatment and limit systemic toxicity and side effects by making the direct delivery of medications to the sites of tumors possible. PdNPs are promising imaging tools, as well as contrast reagents in computed tomography (CT) and photoacoustic imaging. It helps to observe tumor responses in real time, which allows for the effectively integrating of both therapeutic and diagnostic approaches to cancer treatment [61,62]

Although the clinical use of palladium nanoparticles (PdNPs) can be promising, there are a number of drawbacks that are faced. Toxicity fear is one of the chief impediments, which requires precise evaluations of their safety data among human subjects to prevent the occurrence of adverse effects. Secondly, the regulatory complexities of the field of nanomedicine also hamper the incorporation of such

nanoparticles in a clinical setup. Lack of consistent synthesis procedures is another challenge that makes it hard to attain comparable efficacy and security in different research studies. However, PdNPs are a versatile platform for improved cancer therapy as they demonstrate a variety of mechanisms of action and the ability to perform targeted therapy. The problem of toxicity, compliance with regulations and standardization of synthesis needs to be approached to utilize their potential in clinical oncology fully. Further study of PdNPs may create significant breakthroughs in cancer treatment and diagnostic procedures [59,62]

Nanoparticles of iron oxide, Iron Oxide Nanoparticles

With their multi-faceted application in diagnosis and therapy, Iron oxide nanoparticles (IONPs), mainly Superparamagnetic iron oxide nanoparticles, or SPIONs, have attracted a lot of interest in cancer treatment. The provided nanoparticles behave as superparamagnetic ones, which can be manipulated by external magnetic fields with great precision in terms of distribution and treatment of specific areas. Their low immunogenicity and ability to be transformed conveniently into functionalized entities devoted to controlled delivery of targeting ligands, drugs, or imaging agents contribute to their added value in the oncology field. The magnetic hyperthermia is one of the most significant therapeutic uses of IONPs because, as the alternating fields are applied to magnetic material, the local heating effect destroys cancer cells but not normal ones. This method has demonstrated success in pre-clinical trials, enhancing patient survival in cancers.[63] More so, IONPs can carry chemotherapeutic agents, making it precise to target the malignancy with drugs. Tumor-specific ligands used in functionalization have shown effectiveness in targeting HER2-positive breast cancer cells, reduced systemic toxicity, and improved treatment outcomes, which made targets such as

Herceptin seem promising in cancer treatment.[64]

The dental aspects. The use of IONPs in photothermal therapy (PTT) is another area where near-infrared (NIR) light exposure triggers a thermal reaction that causes the apoptosis of cancer cells and improves the effect of other related therapies.[65] New studies report that IONPs could be used to influence immune outcomes, which presents a new opportunity to integrate them with immunotherapy processes.[63] IONPs have demonstrated efficiency in treating numerous types of cancer, such as breast cancer and leukemia, and these nanoparticles are also used as contrasting agents in Although they are mostly biocompatible, the safety of their accumulation in the body should be reviewed with long-term effects in mind. Also, the regulatory environment of nanomedicine is overwhelmed, and involves sound clinical evidence in order to streamline the approval procedures. Unification of synthesis procedures is essential too, so that the effectiveness and safety are unified regardless of the area of application. To sum up, IONPs are also a promising, versatile platform that can advance cancer therapy with desirable mechanisms of action and uses. Further studies are required to address existing problems. And actualize their therapy in clinical oncology to the fullest extent.[69]

Polymer-Based Nanoparticles

Polymer-based nanoparticles (NPs) have been proven to be an efficient and biphasic drug delivery mechanism in the treatment of cancer due to physio-chemical properties of their nature, such as biocompatibility, biodegradability and their ability to enclose different types of therapeutic agents. These nanoparticles can elevate drug solubility, stability and bioavailability, reduce the toxicity in the systems, and enhance therapeutic effect. The nanoparticle constructed using polymers can be termed as a potential emerging frontier in the field of cancer treatment, trying to cope with the

existing limitations of the actual therapies, as well as enhance the living standards of the patients. Micelles, nanospheres, nanogels, dendrimers, polymer-drug conjugates, vesicles and smart nanoparticles are among the actively-researched chemical systems that are future players in the targeting of anti-cancer drugstuffs. The further research and enhancement of these nanocarriers will hence provide an opportunity for well-developed and customized cancer remedies.

1. Polymeric Micelles

Hence, the polymeric micelles consist of a nano-sized organization that comprises amphiphilic block copolymers in water. These are especially valuable in the dissolution and stabilisation of poorly soluble substances (in particular hydrophobic medicines). Solid and steady polymeric Paclitaxel was also observed to be encapsulated and transported to breast cancer cells through polylactic acid-polyethylene glycol (PEG-PLA) micelles. When compared to the free paclitaxel, the micelles exhibited more therapy and enhanced bioavailability. The other study revealed that the PEG-PLA micelles were able to load paclitaxel and extend its circulation time in the blood and augment the amount of paclitaxel that amassed in the ovarian cancer cells, in addition to boosting the effectiveness of cancer treatment [70]

2. Nanospheres

The nanospheres are defined as solid polymer materials that have a cross-linked, spherical appearance and are able to encompass drugs in their polymeric body. These nano-particles enable prolonged therapeutic drug release patterns, and their cycles can be modified to liberate therapeutic drugs at the tumor sites. A study conducted has shown that doxorubicin, when packed into the PLGA nanospheres, has a prolonged drug release, equally increasing the cytotoxicity of a variety of cancer cell lines that include those of ovarian as well as breast cancer. This

strategy reduces the exposure of the drug to healthy organs and tissues and also makes sure that high doses are delivered directly to the tumor. In another study, the authors discovered that doxorubicin-loaded PLGA nanoparticles resulted in sustained drug release rates and a significant reduction in tumor volume [71]

3. Nanogels

Three-dimensional polymeric nanogels can swell in response to external stimuli such as temperature or pH changes. These characteristics make them the most suitable for activities that entail controlled drug release. They are well-defined pH-sensitive nanogels prepared by the introduction of chitosan and polyacrylic acid to deliver anticancer drugs, doxorubicin. These nanogels could vastly increase the therapeutic effect, especially on cancer cells and show the optimal discharge of the drug at the acidic values of the pH of the milieu that surrounds the tumor. Production of chitosan and poly (N-isopropyl acrylamide) nanogels that augment the cytotoxicity of cancer cells and the high level of drug release into an acidic environment was also described in another study [72]

4. Dendrimers

Dendrimers are special tree-like structures of three dimensions, which can be intricately prepared as drugs. They can carry large quantities of medicines and their versatility in their usage. We used the PAMAM (polyamidoamine) dendrimers in the resistance breast cancer cells, which were conjugated with the siRNA against the Bcl-2 gene. This course enhanced apoptosis as well as the chemosensitivity [73]

5. Polymer-Drug Conjugates

The name of polymer-drug conjugates speaks for itself: the conjugation of drugs to the backbones of polymers through a covalent bond. The method enhances the drug dissolution rate, stability and release profiles that subsequently reduce the whole-body toxicity. They improved

pharmacokinetics and decreased the systemic toxicity of PEG-doxorubicin conjugates compared to free doxorubicin in animal xenografts of breast cancer and had an improved therapeutic effect on the disease. One of the works talked about PEG-doxorubicin conjugates, whose adverse effects are less, and their antitumor activity is higher compared to the free drug derivatives.[74]

6. Vesicles

Vesicles that contain liposomes and polymeric vesicles are versatile systems that have the possibility of containing a hydrophobic drug or a hydrophilic drug. They offer possibilities to release controlled drugs and to apply multiprofessional therapies. In fabricating a combined drug delivery, polymeric vesicles of PEG-PLA were utilized in encapsulating doxorubicin along with an antiangiogenic agent. This combination showed synergetic effects, which intensify the therapeutic effect in tumor models and cure morbidity due to the tumor. [75]

Lipid-Based Nanoparticle: Lipid-based nanoparticle (LNP) has received much attention in cancer therapy due to its desirable biocompatibility, ability to package hydrophobic drugs, and its capability to achieve targeted drug delivery.

1. Liposomes

The ability of the liposomes to entrap diverse therapeutic chemicals and redistribute through specific targeting and enhance the therapeutic efficiency has promoted them into an essential platform in the context of cancer treatment. Namely, these natural phospholipid-based lipid-based nanoparticles are extremely biocompatible and can carry both hydrophilic and hydrophobic drugs, hence being highly flexible regarding carrying various small molecules, proteins, peptides and even nucleic acids. One of the advantages of liposomes is the ability to have controlled release; liposomes can be designed in such a way that they can be made to deliver their

payload upon contact with some stimulus, such as temperature or PH changes. Moreover, liposomes can be modified with different ligands, such as antibodies and peptides, to get more affinity to some cancer cells; tailored delivery is therefore a key aspect. Indicatively, HER2 targeting liposomes have shown promising results in breast cancer cells HER2-positive, where therapeutic agents become highly prevalent as chemotherapeutic agents are delivered into the tumour cells effectively. There is minimal toxic effect on other body parts since it is a passive targeting mechanism. It enhances the therapeutic index of the drugs entrapped in the liposomes considerably, and this has found sufficient validation in numerous pre-clinical as well as clinical studies. Liposomes also play an essential role in combination therapy since they can be used to deliver multiple agents, such as chemotherapies and immunomodulators, simultaneously to achieve synergistic responses to produce a strong therapeutic effect. An example is the combination of chemotherapeutic agents with immunotherapeutic agents, which has yielded promising results in preclinical studies. Within the setting of immunotherapy, liposomes play a key role in antigen-presenting cells (APCs) as adjuvants that transport antigens and thus boost immune responses against the tumors. Intimately, stealth liposomes carrying IL-12 and anti-CD137 have shown massive immune activation in the mice, even though they convey minimal systemic poisoning. On the clinical side, various liposomal products have been approved by the FDA, including Doxil(r) (liposomal doxorubicin) and Onivyde(r) (liposomal irinotecan), to display improved pharmacokinetics and reduced toxicity compared to their non-liposomal counterparts. In addition, new strategies making use of fusogenic liposomes, which can be used in a direct way to enter the cytoplasm of a cell by fusing across the membrane, also enhance the curative potential of liposomal formats. However, some challenges do exist, such as

specificity issues, immune response possibilities and regulatory challenges. Some formulations are yet to have target delivery, and some might trigger an unwanted immune response. Nanomedicine is complex, making the regulatory approvals a challenge. In the future, it is necessary to develop liposomes that are more specific and safer and to test their suitability in theranostics, where therapy and diagnostics are incorporated in a single platform. Liposomes offer a multifunctional and robust system in cancer treatment, which can be very beneficial as compared to conventional methods of drug delivery systems. Innovation and exploration are likely to continue to come up with more targeted and effective therapies for patients who are affected by cancer. [76,77]

2. Solid Lipid Nanoparticle (SLN)

Solid lipid nanoparticles (SLNs) have drawn a lot of attention to cancer therapy because of their unique advantages that support the delivery of medications and treatment performance. These nanoparticles, consisting of solid lipids that remain in a solid state at ambient and physiological temperatures, have many advantages over conventional drug delivery systems. This solid lipid core has the effect of producing more stability, which will protect the drug's integrity during the delivery as well as in storage. Also, SLNs are biocompatible; this reduces the chances of some adverse reactions and hence makes a patient safe. The ability to entrap drugs that are hydrophilic and hydrophobic makes them versatile drug carriers that can have a wide variety of therapeutic agents [78,80].

One of the significant mechanisms of action of SLNs is their ability to deliver drugs selectively. The targeting of the specific cancer cells by functionalization using specific ligands enhances the localization of the medication in the target areas and lowers the dose in the systemic regions. As an example, antibody-coated SLNs have demonstrated the capacity of targeting breast cancer cells, thereby enhancing

therapeutic outcomes [81,82]. Also, tumors exhibit leaky vessels, which means that SLNs exploit such effect as the EPR, or enhanced permeability and retention, that allows them to accumulate in tumor tissues. This passive targeting process enhances drug delivery into the tumor microenvironment since the healthy tissues are also not exposed to much [79,83]. Moreover, SLNs offer sustained drug release and keep the effective drug concentrations over time because they exhibit biphasic profiles, i.e., early burst and followed by sustained release [84].

SLNs hold tremendous potential, especially in the case of cancer treatment, where they overcome the multidrug resistance (MDR). By enhancing the bioavailability of anticancer drugs and enabling their rate of mass absorption in drug-resistant cancer cells, SLNs take care of one of the most significant problems in the oncological environment. [80]. Their effectiveness has been known to be effective both in vivo and in vitro according to numerous studies. As an example, the cell viability of HT-29 colorectal cancer cells was significantly lower when papain-loaded SLNs were used as compared to free papain, which indicates that cytotoxicity has been elevated by using nanoparticle delivery systems. SLNs are equally being researched in terms of clinical use, especially in the management of cancer, such as in breast cancer, where their capacity to deliver drugs efficiently at low doses and lower side effects makes them a strong candidate in the future clinical setting [82]. Also, they have been used in combination therapy applications that allow several medicinal compounds to be combined in their delivery, which has potential in attacking various pathways implicated in tumor growth and survival. There are still Challenges in the clinical translation of SLNs. Despite the functionalization development, achieving precise targeting remains a challenge. The safety of SLNs longitudinally needs to be well investigated so as to guarantee the least adverse effects. In addition, regulatory

routes of nanomedicine are complicated, requiring high-quality and consistent clinical data and production procedures. SLNs are an accessible and supportive framework upon which cancer treatment can be developed. They contribute to improvement in the outcomes of the therapy in terms of enhanced microdosing, reduced adverse side effects, and provide reliable, biocompatible, and potentially effective medication delivery strategies. Further research and development on the design and utilization of SLNs will probably see the emergence of better and specific procedures for reducing the disease in cancer patients. [80,82]

3. Nanostructured Lipid Carriers (NLCs)

In comparison to the conventional Nanostructured lipid carriers, or NLCs, present compositions can be used in several ways and offer numerous benefits compared to the former, being a new way The delivery of delivering drugs in the scenario of cancer treatment. The solid and liquid lipid mixture used to constitute these suspension carriers endows them with special characteristics such as improved stability, large drug loading capacity, as well as reasonable biocompatibility. The mix of liquid and solid ability leads to a more stable composition than liquid lipid nanoparticles (SLNs), making it less probable that medicine will be released during storage and prolonging the shelf life of the product [85,86]. This is because of their amorphous arrangement, which can accommodate drug molecules better, making them have increased drug-loading capacity, especially for hydrophobic drugs. [87]. Furthermore, biocompatibility and biodegradability of the lipids utilized in the production of the NLCs reduce the chances of toxicity and adverse reactions. [88].

The coexistence of several mechanisms of action of the NLCs boosts its medicinal performance. The anticancer drugs can be given to the tumor cells selectively and expose the healthy tissues to a limited extent by engineering them with a change on the

surface, which enhances the targeted drug delivery. NLCs Functionalized NLCs, e.g., have demonstrated promise in effectively targeting breast cancer cells [87,88]. In addition, NLCs also exploit what is called the Enhanced Permeability and Retention (EPR) effect because of the leaky vasculature that tumors possess, allowing them to be readily delivered within the tumor tissues when it comes to arriving in the tumor tissues. This technique of passive targeting enhances the therapeutic index of encapsulated drugs [85,86]. NLCs are also able to deliver sustained release of encapsulated drugs, keeping the concentration of the drug efficient throughout extended periods of time and experiencing the biphasic release process. [85,87]. Moreover, NLCs have also demonstrated potential to overcome the multidrug resistance (MDR) aspect of cancer treatment by improving the bioavailability of the anticancer agents and their incorporation into resistant cancer cells, thus overcoming the multidrug resistance. [86,88].

Nanostructured lipid carriers (NLCs) have numerous possible advantages in the treatment of cancer. The effectiveness of multiple studies has been affirmed by several studies on various types of cancers, including breast, colorectal, and lung cancer, for example, NLCs containing doxorubicin. Owing to the significant cytotoxicities against cancer cell lines in vitro and little cytotoxicity to regular cell lines, selected NLC-based formulations have been demonstrated to show promising potential in therapy against cancer. NLCs in clinical research are in search of their ability to enhance drug efficacy or reduce any adverse effects, particularly in breast cancer treatment [85]. Also, NLCs are well-suited for combination treatment, and this enables multiple therapeutic compounds to be administered en bloc to target various tumor growth and survival pathways. [86]. Even though there are benefits attached to NLCs, challenges exist. A low degree of target specificity is a primary challenge, no

matter how the surface is modified. Perfect targeting of tumor cells needs additional studies. Also, despite their overall biocompatibility, the long-term safety of NLCs should be investigated in detail to achieve a minimum level of side effects. Regulatory barriers are also a problem because the complexity of nanomedicine requires well-developed clinical evidence and repeatable logistics. Nanostructured lipid carriers are an adaptive and emerging technology in the development of cancer treatment. NLCs can promise new therapeutic efficacy and reduced side effects by offering stable, non-toxic and efficient carrier systems of the drug. Further study and development on the design and use of NLCs is likely to lead to greater selective and effective treatment. Options for patients having cancer. [86,87]

4. Lipid-Core Nanoparticles

The lipid-core nanoparticles (LNPs) are a prospective platform in cancer treatments with improved delivery, improved therapeutic effect, and fewer side effects as compared to conventional formulations. These nanoparticles have a lipid core capable of holding both hydrophilic and hydrophobic drugs, thus having excellent flexibility. They are mainly biocompatible and biodegradable since they are comprised of naturally occurring or biologically analogous lipids and therefore do not produce much toxicity and undesirable effects in biological systems. [89,90]. Moreover, LNPs have a high drug-loading capacity, and they can have greater values of lipophilic drugs to enhance solubility and stability in the biological milieu. [90,91]. They also offer controlled drug-release characteristics, keep effective drug concentrations intact over time and increase therapeutic efficiency. [90,92]. LNPs activate multiple mechanisms of action to enhance cancer treatment benefits. Targeted drug delivery is one of the most pronounced mechanisms, and in these, the Targeting capacities are enhanced by ligands that exist on the surface of the nanoparticle.

Investigations on oral squamous cell carcinoma proved that this kind of active targeting lowers the long-term exposure of healthy tissue, permitting selective delivery of anticancer drugs to tumor cells (OSCC). [90]. The other mechanism is the enhanced permeability and retention (EPR) effect, whereby the leaky vasculature allows the LNPs to accumulate in the tissues of the tumors. This does not target specifically, but increases the amount of drug that reaches the tumor microenvironment and decreases systemic toxicity. [89,91]. Moreover, LNPs enable combination kits (i.e., co-delivering) of more than two therapeutic modalities, e.g., combining chemotherapy and RNA-based therapy (e.g., siRNA) to address drug resistance mechanisms in cancer cells. With such a multifaceted approach aimed at attacking the different pathways by which tumors manifest, the rate at which treatment is successful is elevated. [90,92].

The use of LNPs in the treatment of cancer has received a lot of research. Both in vivo and in vitro evidence on their efficacy has been proven on various types of cancer, notably breast cancer and OSCC. As an example, both doxorubicin-loaded LNP formulas have demonstrated high cytotoxicity in cancer cell lines, accompanied by low toxicity in normal cells. [89,92]. Some LNP compositions are being studied in clinical practice that potentially can maximize the effect of the medication and minimize the adverse impact, and thus they have a good prospect to be a candidate for future cancer treatment. [93,94]. Moreover, LNPs have potential applications in theranostics involving the combination of therapy and diagnostics. Imaging agents can also be incorporated into the LNP formulations that permit monitoring of the treatment efficacy along with therapy delivery in real-time [89,93]. Irrespective of their benefits, LNPs have a number of problems. Accurate targeting is another major challenge since to achieve specific targeting; the functionalization strategies need to be improved to enhance targeting specificities.

[92]. The long-term safety of LNPs still should be thoroughly examined, despite their being mainly biocompatible. In addition, regulatory barriers such as insufficient and high-quality evidence on clinical studies and standardization of production have to be overcome to translate LNPs to clinical practice. [91,93]. The possible application of LNP in the future ought to be centered on the maximization of LNP formulations with the view of maximizing targeting capabilities and therapeutic efficacy and ensuring safety through innovative pathway design. Lipid-core nanoparticle is a versatile platform that is used in facilitating cancer therapy by offering viable modes of Drug administration that maximize therapeutic outcomes by limiting unwanted side effects. Further study of their capabilities will probably mean the development of better treatment methods for those with cancer.[94]

5. Nanoparticle-based Delivery of Nanocarriers on RNA

Nanocarriers made of lipids have become one of the life-changing cancer therapies in the delivery of RNA medicines. Examples of such nanocarriers are lipid nanoparticles (LNPs), the solid lipid nanoparticles (SLNs) and nanostructured lipid carriers (NLCs), which have several advantageous properties. The fact that they used natural or biologically similar lipids that introduce minimal toxicity and adverse effects into biological systems makes them very biocompatible. They are also characterized by high drug loading ability with the potential of capturing both hydrophilic and hydrophobic RNA molecules, which is good for increasing stability and solubility. Also, due to the controlled release of lipid-based nanocarriers, the therapeutic effect is sustainable with time. [95,96].

The mode of action of lipid-based nanocarriers in delivering RNA is complicated. Targeted delivery is a fundamental mechanism in which the functionalization of the targeting ligands

increases specificity towards cancer cells. This enabled targeting leads to the concentration of RNA therapeutics in tumor areas and sparse introduction to healthy tissues. As an example, the tumor-specific ligand functionalized LNPs have shown effective delivery of small interfering RNA (siRNA) to target cells. [96]. One of the additional mechanisms concerns transcending biological barriers. These disadvantages encountered in RNA therapeutics include low molecular weight, negative charge, enzyme susceptibility, and so on. Lipid-based vectors shield RNA against degrading agents, improve cell uptake (undergo endocytosis) and endosomal release, to allow RNA traffic to the cytosol, where they will execute therapeutic effects. [95,97]. Besides, these carriers allow so-called combination treatments, co-delivering their RNA-based counterpart and other drugs, including chemotherapeutics. As an example, drug-conjugated lipids containing paclitaxel, incorporated with mRNA producing tumor suppressor proteins, have been used to treat triple-negative breast cancer and are a compound example of chemotherapy and gene therapy. [98].

The uses of the lipid-based nanocarrier in cancer treatment are broad-spectrum. Preclinical researchers have shown they can be used to administer RNA therapeutics against numerous types of cancers. As an example, LNPs that are used to deliver anti-oncogene-directed siRNA have shown a considerable decrease in tumor growth in animal models. [96,98]. Lipid-based formulation is being explored as a potential RNA delivery material in clinical practice in the oncology setting because of the success in the COVID-19 vaccine area using mRNA. Among this latter group are the means of mRNA encoding tumor antigens or therapeutic proteins. [97]. In addition, therapeutic and diagnostic functions are investigated that are combined in theranostics. The use of lipid-based formulations of imaging agents and RNA therapeutics allows real-time monitoring of

the therapeutic ability of the therapeutic agent delivered. [95]. There are various challenges, though, despite the promise of lipid-based nanocarriers. Off-target remains an issue because there is a risk of non-specific trafficking that could result in undesirable immune effects or diminished efficacy.[96]. The storage and shelf lives of lipid-based formulations are the most critical factors to consider in clinical use, given that they are required to be maintained in their integrity over time. They also face the challenge of regulatory impediments, such as the requirement of a solid clinical evidence base and uniformity in the manufacturing process should be used to limit their adoption. Future studies are recommended so as to optimize the lipid-based formulation with the aim of increasing the targeting efficiency, therapy efficiency, and stability, addressing the safety issue using clever design tactics. Lipid-based nanocarriers are a broad and potent platform that can further develop cancer treatment; the ability to define efficient RNA delivery strategies with fewer adverse effects and better therapeutic outcomes. This is likely to extend their potential, and subsequent cancer patients will be treated with solutions that are more efficient and innovative.

Clinical Applications

Nanomedicine Products Approved by FDA to Treat Cancer: Nanotechnology has enabled the creation of numerous FDA-approved nanomedicine products to treat cancer and combat side effects by taking advantage of the characteristics of nanoparticles to deliver medication primarily. Nanotechnology has contributed immensely to the treatment of cancer, with several FDA-approved nanomedicine products being developed to help treat cancer and minimize side effects based on the unique nature of the nanoparticle to deliver medication primarily. [99,100] Case studies and real-world examples of FDA-approved nanomedicines and their impact on clinical practice, as well as the efficiency

of treating patients with different types of cancer, are described below.

Table 4: List of FDA-Approved Nanomedicines

Approval Year	Product	Company	Nanoparticle Material	Drug/Mechanism	Indication
1995	Doxil (Caelyx)	Janssen Pharmaceuticals	Liposomal Doxorubicin (PEGylated)	Doxorubicin	AIDS-related Kaposi's sarcoma, breast cancer, and ovarian cancer
1996	DaunoXome	Gilead Sciences	Liposomal Daunorubicin	Daunorubicin	HIV-associated Kaposi's sarcoma
2005	Abraxane	Abraxis/Celgene	Nanoparticle-bound albumin	Paclitaxel	pancreatic cancer Breast cancer, non-small-cell lung cancer
2012	Marqibo	Talon Therapeutics/Spectrum Pharma	Liposomal Vincristine	Vincristine	lymphoblastic Acute leukemia
2015	Onivyde	Merrimack Pharmaceuticals	Liposomal Irinotecan	Irinotecan	Pancreatic cancer, colorectal cancer
2017	Vyxeos	Celator Pharmaceuticals/Jazz Pharma	Liposome	Cytarabine/Daunorubicin	Acute myeloid leukemia
2019	Hensify (NBTXR3)	Nanobiotix	Hafnium oxide nanoparticle	Radiotherapy	Locally advanced soft tissue sarcoma
1994, 2006	Oncaspar	Enzon-Sigma-tau	Polymer protein conjugate	Pegaspargase/L-asparaginase	Acute lymphoblastic leukemia
2000	Myocet	Teva UK	Liposomal Doxorubicin	Doxorubicin	Metastatic breast cancer
2009	Impact	Takeda Pharmaceuticals	Liposome	Mifamurtide MTP-PE	Osteosarcoma
1999	DepoCyt	Pacira Pharmaceuticals	Liposome	Cytarabine	Neoplastic meningitis
2017	Vyxeos	Celator Pharmaceuticals/Jazz Pharma	Liposome	Cytarabine/Daunorubicin	Acute myeloid leukemia

Doxil (PDL) Pegylated Liposomal Doxorubicin: Doxil was the very first nanomedicine to be approved by the FDA in 1995, compared to normal doxorubicin; the pegylated liposomal form has better solubility and reduces the cardiotoxic effects. The primary conditions under which the use of this formulation is recommended include breast and ovarian malignancies and the AIDS related Kaposi sarcoma. With the help of Enhanced Permeability and Retention (EPR) effect, the liposomal form enhances longer circulation in the body, as well as increased product buildup within the

tumor sites. Clinical trials also suggest that those with recurrent ovarian cancer treated with a dose of 50 mg/m², once in a period of 28days, had an overall response rate of 25 %. They also exhibit significantly fewer side effects compared to patients who receive routine doxorubicin.

Abraxane (Nanoparticle Albumin-Bound Paclitaxel): A preparation known as Abraxane that has been approved by the FDA since 2005 combines paclitaxel with albumin nanoparticles in an effort to increase the solubility of the drug, and to

allow higher doses of the drug and a reduction in the toxicity exposure. It can be applied in treating cancer of the pancreas, non-small cell lung cancer, and breast cancer. This preparation reduces exposure to the system but allows expedited delivery of the medication to the site of the tumors. Abraxane received higher scores in safety with less neuropathy and overall survival of about 23 percent improvement in a significant Phase III study covering patients with metastatic breast cancer.

Onivyde 1(Liposome-Encapsulated Irinotecan):

Onivyde, a liposomal composition of irinotecan approved by the FDA in 2015, can treat metastatic pancreatic cancer after gemcitabine-based therapy with fluorouracil and leucovorin. This liposomal preparation causes decreased systemic toxicity and enhanced treatment of malignancies with the medication. A similar clinical study found that overall survival was significantly improved among patients with metastatic pancreatic adenocarcinoma. Median survival of patients who were given Onivyde was 6.1 months, as compared to 4.2 months for patients who had been given conventional therapy.

Vyxeos A (Liposomal cytarabine/Daunorubicin):

In 2017, Liposomal formulation, Vyxeos, a combination of daunorubicin and cytarabine, was approved by the FDA as a treatment of acute myeloid leukemia (AML). The drug is particularly prescribed among older adults who have been newly diagnosed with therapy-related AML or AML associated with the changes induced by myelodysplasia. Comparing Vyxeos to conventional chemotherapy, clinical studies have determined that it does increase overall survival and complete remission. The liposomal preparation minimizes the toxicity as well as enhances the synergistic effect of the drugs.

Marqibo Liposomal Vincristine: Marqibo is a brand name approved in the year 2012 by the FDA as a form of vincristine that is in liposomal form, used in treating acute lymphoblastic leukemia (ALL). This formulation might allow higher doses of vincristine to be used, and at the same time lessen the neurotoxic effects of the commonly used formulations. Researchers have indicated that the liposomal delivery method enhances both treatment outcomes by lowering the concentrate of a drug within healthy cells as well as in leukemic cells in patients with relapsed or refractory ALLs [99,100]

Future Prospects of Cancer

Nanomedicine:

The future of cancer therapy may see a revolution due to the emerging trends, personalized medicine, machine learning and artificial intelligence (AI), nanomedicine—the Horizon of nanomedicine in cancer therapy. The future outlook of nanomedicine in cancer treatment is sunny due to new developments of hierarchical targeting, stimuli-responsive systems, biomimetic drug carriers, and combination therapies. Biomarker-based treatment strategies and patient-directed designs will also make treatment more precise by being integrated with personalized medicine. AI and ML can transform nanomedicine by better nanocraft design and imaging, as well as faster drug discovery. Nanomedicine is set to change healthcare by providing safer, more effective, and personalized treatments of cancer in the future as research develops.

Nanomedicine: The field of nanomedicine is developing fast, and it is bringing new technologies that presumably will make cancer therapies more effective. The hierarchical targeting approaches involve combining multiple targeting mechanisms, including tumor vasculature, specific cancer cell receptors and subcellular organelles within a single nanocarrier system to optimize the therapeutic effect. [101]. Nanocarriers that are then stimuli-

responsive are being developed to enable the release of medication in a regulated way by exploiting tumor-specific stimuli (i.e., pH changes, temperature, or enzyme activity). And minimize systemic effects. [102]. The increased targeting and therapeutic index of the biomimetic nanoparticles (which reproduce the natural biological system by using the plasma membrane of a cancer or immune cell) is attracting attention. [103]. There is also a potential for a synergetic effect using combination therapy, such as combining nanomedicines with immunotherapy or photodynamic treatment and increase the overall efficacy of treating the tumor.[104].

Combination with Personalized Medicine: Nanomedicine plays a crucial role in the transformation towards personalization and precision in cancer therapy, where medicine is individualized depending on the profile of the patients. Nanomedicine based on biomarkers, the use of tumor-specific biomarkers to design specific nanotherapeutics to enhance treatment outcomes by matching patients with the best nanotherapeutics.[103]. 3D printing and nanotechnology allow the developing of patient-specific nanocarriers, which are ideal for the specific properties of a patient's tumor and, therefore, maximize the efficiency of the delivery of particular drugs and reduce side effects. Moreover, imaging agents embedded into nanoparticles can support real-time monitoring of the impact of the treatment so that clinicians can adjust their treatment to the progress of an individual. [102].

Contribution of Artificial Intelligence and Machine Learning: Artificial intelligence (AI) and machine learning (ML) are dismantling the market of nanomedicine by simplifying the drug development and the delivery phases. The use of AI in predictive modeling undertakes the assessment of clinical and preclinical data to decide therapy selection based on the characteristics of the patient. ML algorithms are used to maximize the design of nanoparticles by forecasting how their

physicochemical characteristics, size, surface charge, etc., influence their interaction with biological systems to make safer and more efficient nanomedicines. The applications of AI in automating drug discovery accelerate the time to discovery of promising candidates in nanomedicine. Besides, AI-improved imaging processes make nanoparticle monitoring and therapeutic activity testing more precise, which allows for estimating the efficacy of treatment in a more accurate way. [105,106].

CONCLUSION

Nanotechnology has become a breakthrough in cancer treatment, so this field has offered approaches to eliminate the deficiencies of conventional therapy. Nanomedicine can improve the treatment efficacy of cancer by increasing the effectiveness of visual tools, the delivery of specific drugs, and targeted approaches to individuals. The flexibility of different nanoparticles, which include liposomes, dendrimers, metallic nanoparticles and polymer carriers, has opened new avenues of treatment of cancer, addressing such problems as multidrug resistance and insufficient bioavailability of some drugs. Further, the advance in the field of diagnostics and theranostics reflects the potential of nanotechnology in early cancer detection and real-time evaluation of therapeutic responses. However, there remain a number of unresolved issues, such as those connected with toxicity, regulatory matters, and the need to develop standardized methods of manufacturing. These challenges must be solved to achieve effective integration of nanomedicine into regular medical practice. Optimization of nanoparticle design and targeting specificity, and long-term safety optimization should be a priority in future studies. Nanomedicine may transform cancer treatment with the continued innovation of interdisciplinary research, promising more patients under treatment and a significant reduction in the world cancer burden.

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