

Revolutionizing Cancer Care: The Potential of Transition Metal Nanoparticles (TMNPs) in Diagnosis and Treatment

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Research Question: To what extent can transition metal nanoparticles (TMNPs) revolutionize cancer diagnosis and treatment?

Abstract

Cancer remains a global health crisis, affecting over 20 million people annually and disproportionately burdening low-resource regions. Conventional therapies, such as chemotherapy and radiotherapy, face limitations including severe side effects, drug resistance, and poor accessibility. Transition metal nanoparticles (TMNPs) - notably gold (Au), silver (Ag), platinum (Pt), and copper (Cu) - are emerging as transformative tools in oncology. Their unique physicochemical properties enable precise drug delivery, real-time diagnostics, and targeted therapies such as photothermal and photodynamic treatments. Advances in green synthesis methods and AI integration further enhance their potential. Despite challenges like toxicity management, regulatory hurdles, and scalability, TMNPs promise to revolutionize cancer care by improving treatment precision, reducing side effects, and addressing global disparities in healthcare access. This paper explores the extent to which TMNPs can redefine the landscape of cancer diagnosis and treatment, emphasizing their role in advancing equity and sustainability in oncology.

Key Words: TMNPs, cancer diagnosis, photothermal therapy, targeted drug delivery, precision medicine

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Introduction

In 2022, an estimated 20 million new cancer cases were reported globally, with 9.7 million deaths attributed to the disease. If now is not the time for a revolutionary solution, then when is?

Ahead of World Cancer Day, the World Health Organization (WHO), through its cancer research division, the International Agency for Research on Cancer (IARC), released updated statistics on the global cancer burden. Based on the most reliable data from 2022, these estimates highlight the rising prevalence of cancer, its disproportionate impact on underserved populations, and the urgent need to address global cancer disparities (World Health Organization, 2024). A survey conducted across 115 countries revealed that most nations fail to adequately fund essential cancer treatment and palliative care services under universal health coverage (UHC).

Current cancer treatments, including chemotherapy, radiotherapy, and immunotherapy, face notable limitations that challenge their effectiveness. Chemotherapy, while targeting rapidly dividing cancer cells, often harms healthy cells, leading to debilitating side effects such as fatigue, nausea, and heightened vulnerability to infections (National Cancer Institute, 2022a). Similarly, radiotherapy can damage surrounding healthy tissues, causing complications like skin irritation and persistent fatigue (National Cancer Institute, 2022b). Immunotherapy, designed to enhance the immune system, is not without risks, as it may trigger adverse reactions, including flu-like symptoms, skin issues, and neurological effects like muscle weakness (Gupta & Shukla, 2022). These therapies are not only physically taxing but also financially burdensome, limiting their accessibility, particularly in resource-constrained settings. In response, transition metal nanoparticles (TMNPs) have emerged as a revolutionary alternative, offering precise drug delivery, enhanced imaging capabilities, and potential solutions to treatment resistance.

TMNPs are nanoscale materials composed of transition metals, often possessing unique physical and chemical properties due to their high surface area, quantum effects, and catalytic activity (Xiong et al., 2022). TMNPs encompass diverse materials, including gold, silver, copper, and platinum, each offering unique properties. These characteristics make TMNPs highly versatile in medical science. For instance, their antimicrobial properties enable their use in combating drug-resistant pathogens, while their catalytic activity is

pivotal in biosensing applications for detecting disease biomarkers. Additionally, TMNPs are integral to drug delivery systems, allowing precise targeting and controlled release of therapeutics, thereby minimizing side effects. In cancer therapy, TMNPs play a role in photothermal and photodynamic treatments, where their ability to absorb and convert light into heat or reactive oxygen species is harnessed to destroy tumor cells selectively (Karthik & Geetha, 2019). These applications highlight TMNPs' potential to revolutionize diagnostics and therapeutics, addressing critical challenges in modern medicine through innovative nanotechnology solutions. Considering the aforementioned, this research paper aims to answer the following question: **To what extent can transition metal nanoparticles (TMNPs) revolutionize cancer diagnosis and treatment?**

This research paper argues that, through innovations in drug delivery, theranostics, and targeted therapies like photothermal and photodynamic treatments, TMNPs offer a more precise and sustainable approach to oncology, possessing the potential to revolutionize cancer diagnosis and treatment by addressing critical limitations of conventional therapies, including high toxicity, poor targeting, and drug resistance.

Background: Nanoparticles and an Introduction to TMNPs

Nanoparticles have emerged as a cornerstone of modern nanoscience, attracting the attention of researchers across multiple disciplines - from materials science and chemistry to biomedical engineering and environmental science. At their core, nanoparticles are defined as particles with one or more external dimensions confined to the nanoscale, typically between 1 and 100 nanometers (Joudeh & Linke, 2022). This stringent size regime is not merely a matter of nomenclature; it fundamentally transforms the physical and chemical behavior of the material. As noted in the comprehensive review from the Journal of Nanobiotechnology, when all external dimensions of a particle are within the nanoscale, novel phenomena arise that are not observed in larger, bulk materials (Joudeh & Linke, 2022). Encyclopaedia Britannica reinforces this idea by emphasizing that the measurement of these entities in nanometers (where 1 nm is equivalent to 10^{-9} meters) underscores their remarkably high specific surface area, which in turn critically influences their reactivity and overall functional performance.

The transition from macroscopic to nanoscale dimensions introduces a suite of extraordinary attributes. One of the most profound effects of size reduction is the dramatic increase in the surface area-to-volume ratio. When the dimensions of a material shrink to the nanoscale, a significant fraction of its constituent atoms or molecules are exposed at the surface, thereby enhancing interfacial interactions. This amplification of the surface presence not only provides an abundance of active sites for chemical reactions but also gives rise to altered thermodynamic properties, such as modified melting points and binding energies. Moreover, as nanoparticles become exceedingly small, quantum confinement effects begin to play an influential role. These effects result in discrete energy levels, altered absorption and emission spectra, and even changes in electrical conductivity, properties quintessential for optoelectronics and photonics applications. Articles by both Joudeh & Linke (2022) and Altammar (2023) describe how these quantum mechanical phenomena, in conjunction with enhanced surface energy contributions, contribute to the unique behavior observed in nanoscale materials.

In addition to these intrinsic characteristics, nanoparticles offer an unparalleled degree of tunability. Advances in synthetic methodologies have enabled researchers to exert fine control over particle size, shape, and surface chemistry. This capacity for customization means that nanoparticles can be engineered to meet very specific performance criteria. For example, by modifying the surface with various functional groups or ligands, one can tailor nanoparticles for improved biocompatibility or enhanced catalytic specificity. The versatility afforded by such modifications is particularly crucial in the design of drug delivery systems, where targeted therapeutic action and controlled release are paramount. In their review, the authors discuss how this tunable nature of nanoparticles leads to materials with distinctive mechanical, thermal, magnetic, and electronic properties that are optimized for a vast array of technological applications (Altammar, 2023).

The implications of these size-dependent properties are far-reaching and have catalyzed significant innovations across numerous fields. In the realm of biomedicine, the high surface reactivity and customizable interfaces of nanoparticles have paved the way for revolutionary drug delivery systems. Nanoparticles can encapsulate therapeutic agents, thereby facilitating targeted delivery and controlled release profiles that enhance treatment efficacy while minimizing adverse side effects. Their optical properties, influenced by phenomena such as localized surface plasmon resonance, have also been harnessed to improve diagnostic imaging techniques, offering higher resolution and sensitivity compared to traditional methods. Jarvie and King (2019) highlight that such properties are instrumental not only in diagnostics but also in therapeutic applications, where precision is of utmost importance.

Beyond healthcare, nanoparticles are making substantial contributions to the fields of electronics and energy. Their unique electrical characteristics, derived in part from quantum confinement, enable the fine-tuning of electronic band structures, which is critical for the development of advanced sensors, transistors, and photovoltaic devices. The significant catalytic activity inherent to nanoparticles, driven by their expansive surface areas, is being exploited in energy conversion and storage applications, such as in the fabrication of high-performance batteries and supercapacitors. Furthermore, the environmental sector benefits from the catalytic properties of nanoparticles, where they serve to degrade pollutants or facilitate the conversion of hazardous substances into environmentally benign products. Altammar's (2023) review offers a detailed exposition of these applications, illustrating nanoparticles' multifaceted roles in contemporary technology and environmental management.

TMNPs are a distinctive subclass of nanomaterials derived from d-block elements such as silver, gold, platinum, and copper. Owing to their dimensions - typically between 1 and 100 nanometers - these particles exhibit an extremely high surface area relative to their volume, a property that confers enhanced reactivity, tunable optical responses, and superior catalytic activity compared to their bulk counterparts (Joudeh & Linke, 2022). As discussed in the Springer article, this unique nanoscale confinement not only increases the fraction of atoms exposed at the surface but also gives rise to quantum effects that are critical for a range of applications in energy conversion and catalysis (Xiong et al., 2022).

The synthesis of TMNPs can be broadly categorized into three methods: chemical reduction, green synthesis, and physical techniques. In chemical reduction, metal salts are converted to nanoparticles using reducing agents such as sodium borohydride or citrate. This approach allows for precise control over nucleation and growth, resulting in nanoparticles with relatively uniform sizes. However, as Roszczenko et al. (2022) highlighted, these methods often rely on toxic chemicals and generate hazardous by-products, posing significant environmental concerns. Green synthesis methods have gained prominence in addressing these issues. These methods utilize biological reducing agents - derived from plant extracts, fungi, or bacteria - to both reduce metal ions and stabilize the formed nanoparticles. Drummer et al. (2021) emphasize that the biomolecules present in plant extracts serve as effective capping agents, enabling the production of TMNPs with controlled size and morphology while minimizing toxicity. Additionally, physical methods such as laser ablation and evaporation-condensation offer solvent-free synthesis routes. However, these techniques tend to be more energy-intensive, as discussed in a study by Orabi et al. (2020) and further supported by insights from an article published by AZoNano (2013).

The physicochemical properties of TMNPs are intricately linked to their synthesis route. For instance, the small size and high surface area of these particles contribute to their enhanced catalytic efficiency and reactivity. This is particularly evident in applications where surface-mediated processes are paramount. According to Drummer et al. (2021), controlling synthesis parameters such as precursor concentration, temperature, and pH is essential for tailoring the size and shape of the nanoparticles, which in turn dictate their performance in catalytic and biomedical applications. Such control over morphological features is a critical aspect when considering the functionality of TMNPs in practical applications.

Below is an in-depth analysis of the different types of TMNPs:

Silver nanoparticles (AgNPs) are especially noted for their broad antimicrobial and anticancer activities. AgNPs are typically synthesized by both chemical reduction and green synthesis methods. Zhang et al. (2016) explain that while chemical methods can yield high quantities of AgNPs, green synthesis using plant extracts offers the dual advantage of reduced environmental impact and enhanced stability due to the natural capping provided by biomolecules. These AgNPs, because of their high reactivity and the ability to generate reactive oxygen species, have proven effective in inhibiting microbial growth and inducing cancer cell apoptosis.

Gold nanoparticles (AuNPs) have garnered significant attention because of their remarkable optical properties, particularly localized surface plasmon resonance (LSPR). LSPR arises from the coherent oscillation of conduction electrons at the nanoparticle surface when excited by light, resulting in strong and tunable absorption bands. As detailed by Toma et al. (2010), the surface atoms of AuNPs interact with donor-acceptor species in a manner similar to metal complexes. This interaction not only stabilizes the particles but also allows for sophisticated surface functionalization, making AuNPs valuable in biosensing and diagnostic applications. Both chemical and green synthesis methods are employed to produce AuNPs, with the latter offering improved control over particle uniformity and reduced chemical contamination.

Platinum nanoparticles (PtNPs) are prized for their exceptional catalytic properties, which are crucial in applications such as fuel cells and chemical synthesis. While conventional chemical reduction methods are often used to synthesize PtNPs, green synthesis routes have been developed to mitigate the environmental drawbacks of toxic reagents. Roszczenko et al. (2022) note that biosynthesized PtNPs tend to display high catalytic activity due to the increased exposure of active sites, a direct consequence of their nanoscale dimensions. This makes PtNPs highly effective in promoting rapid electron transfer and enhancing overall catalytic performance.

Copper nanoparticles (CuNPs) offer an appealing combination of cost efficiency and substantial catalytic and antimicrobial activities. However, CuNPs are more susceptible to oxidation compared to other TMNPs. Recent studies indicate that employing green synthesis methods can significantly improve the stability of CuNPs by using plant extracts that act as both reducing and capping agents. As explained by Roszczenko et al. (2022) and further corroborated by the AZonano (2013) report, such biologically synthesized CuNPs exhibit controlled size distribution and enhanced resistance to oxidation, making them promising for large-scale applications in catalysis and biosensing.

Problem Statement

Cancer treatment involves several approaches, including chemotherapy, radiotherapy, immunotherapy, and surgery, each with distinct mechanisms and challenges. Chemotherapy employs cytotoxic drugs to destroy rapidly dividing cancer cells, but also affects healthy cells, leading to side effects such as hair loss and nausea. Despite its effectiveness, some cancers develop resistance, reducing its long-term efficacy. Radiotherapy uses high-energy radiation to damage cancer cells' DNA, preventing their proliferation. It is effective for localized tumors and can be combined with other treatments. However, radiation exposure can harm nearby healthy tissues, causing side effects like skin irritation, fatigue, and, in some cases, secondary malignancies. Immunotherapy enhances the immune system's ability to recognize and eliminate cancer cells. Techniques like checkpoint inhibitors and CAR T-cell therapy offer long-term remission. However, immunotherapy responses vary, and it may trigger immune-related side effects, including neurological complications. Surgical intervention remains a primary treatment for localized cancers, offering immediate tumor removal. While often curative, surgery carries risks like infection and does not address microscopic metastases, requiring additional treatments.

Conventional cancer treatments have significant limitations, necessitating the development of more precise and cost-effective alternatives. Additionally, their high cost often limits accessibility. These challenges highlight the need for more advanced treatment strategies. TMNPs offer a promising alternative by integrating targeted therapy, real-time imaging, and controlled drug delivery. Their unique physicochemical properties allow enhanced tumor penetration while reducing toxicity to normal cells. TMNPs not only improve treatment efficacy but also enable early diagnosis and personalized therapy, reducing systemic side effects. With their potential to revolutionize oncology, TMNPs provide a more effective, selective, and accessible approach to cancer treatment, addressing the major shortcomings of conventional therapies.

Application of TMNPs in Oncology

TMNPs are gaining attention in cancer research for their potential in both diagnosis and treatment. Their high reactivity allows them to generate reactive oxygen species, which can selectively induce cancer cell death while minimizing harm to healthy tissues. By modifying their surfaces with biomolecules, TMNPs become more biocompatible and capable of precise drug delivery, reducing side effects. Their small size enables them to accumulate in tumors through the enhanced permeability and retention (EPR) effect, ensuring better drug concentration at the target site. In addition to treatment, TMNPs improve imaging techniques such as MRI and photoacoustic imaging, helping with early detection and more accurate tumor monitoring. They also play a role in photothermal therapy, where they convert light energy into heat to destroy cancer cells, and in drug delivery systems that enhance the effectiveness of chemotherapy. With ongoing research, TMNPs continue to be refined for safer and more effective clinical applications, offering a promising approach to improving cancer diagnosis and treatment with greater precision and fewer side effects.

Silver nanoparticles (AgNPs)

Cytotoxic Effects of AgNPs In Cancer Therapy

AgNPs have gained significant attention in cancer treatment due to their strong cytotoxic effects, primarily driven by their ability to generate reactive oxygen species (ROS) and disrupt cellular membranes.

Their unique physicochemical properties make them highly effective in inducing oxidative stress, triggering cellular responses that ultimately lead to cancer cell death.

Generation of Reactive Oxygen Species (ROS) and Oxidative Stress

One key mechanism behind AgNPs' cytotoxicity is their capacity to generate ROS, including superoxide anions, hydroxyl radicals, and hydrogen peroxide. When produced in excess, ROS leads to oxidative stress, which damages essential cellular components such as proteins, lipids, and DNA. According to Yesilot and Aydin (2019), AgNPs significantly elevate intracellular ROS levels, leading to mitochondrial dysfunction and a loss of membrane potential. This oxidative imbalance activates apoptotic pathways, ultimately driving programmed cell death.

Similarly, research from Kovács et al. (2022) highlights that ROS-induced oxidative damage not only compromises DNA integrity but also weakens cellular repair mechanisms, making cancer cells more susceptible to apoptosis. Furthermore, excessive ROS accumulation results in endoplasmic reticulum stress, which intensifies cellular damage and promotes autophagy-related cell death.

Disruption of Cellular Membranes and Induction of Cell Death

In addition to generating ROS, AgNPs directly interact with cellular membranes, altering their structure and function. Due to their nanoscale size, these particles can penetrate cell membranes, increasing permeability and causing ion leakage. Takáč et al. (2023) describe how AgNPs disrupt lipid bilayers and interfere with membrane proteins, leading to cell swelling, rupture, and ultimately, necrosis or apoptosis, depending on the extent of the damage.

Moreover, findings from Kah et al. (2023) indicate that AgNPs promote apoptosis through caspase-dependent pathways. The mitochondrial-mediated apoptosis pathway is initiated by cytochrome c release, which activates caspase-3 and caspase-9, leading to controlled cell death. Additionally, silver ions released from AgNPs interact with thiol groups in proteins, disrupting cellular metabolism and signaling pathways, further amplifying their cytotoxic effects.

Successful Applications in Cancer Cell Elimination

Numerous studies have demonstrated that AgNPs selectively target cancer cells while sparing normal cells. Research by Taati et al. (2024) provides experimental evidence showing that AgNPs effectively induce cytotoxicity in various cancer cell lines, including breast and lung cancer models, with minimal impact on healthy cells.

Additionally, recent advancements discussed explore the use of AgNPs in combination with traditional cancer treatments such as chemotherapy and radiotherapy. The synergistic effect of AgNPs alongside conventional therapies enhances treatment efficacy, reduces drug resistance, and minimizes systemic toxicity (Tunç, 2024). These promising findings highlight AgNPs as a next-generation nanomedicine with significant potential for targeted cancer therapy.

Gold Nanoparticles (AuNPs)

AuNPs are tiny yet powerful particles that are transforming cancer treatment. Their ability to interact with light and their nanoscale size make them highly effective in targeted therapies. Researchers have discovered that these nanoparticles can selectively destroy cancer cells while minimizing harm to healthy tissues. AuNPs are particularly valuable in photothermal therapy (PTT) - a treatment that uses heat to eliminate tumors - and in advanced drug delivery systems, ensuring that cancer medications reach tumors more precisely.

Photothermal Therapy to Destroy Tumors

One of the most promising applications of AuNPs is photothermal therapy (PTT). These nanoparticles possess a unique property called surface plasmon resonance, which enables them to absorb light and convert it into heat (Jain et al., 2012). Scientists utilize this feature by injecting AuNPs into a tumor and then exposing the area to near-infrared light. The nanoparticles absorb this light, heat up, and effectively kill cancer cells while leaving surrounding healthy tissue largely unaffected.

Why is this significant? Traditional cancer treatments, such as chemotherapy and radiation, often damage both cancerous and healthy cells, leading to severe side effects. In contrast, photothermal therapy using AuNPs provides a more targeted, less toxic approach by selectively destroying cancer cells. Studies have demonstrated the effectiveness of this method in treating cancers such as breast, lung, and colorectal cancer (Cai et al., 2008).

Enhanced Drug Delivery

Another groundbreaking application of AuNPs is their ability to improve drug delivery systems. Conventional chemotherapy distributes drugs throughout the body, attacking both healthy and cancerous cells, often leading to serious side effects. However, gold nanoparticles can be engineered to carry chemotherapy drugs directly to tumors, significantly reducing damage to healthy tissues.

AuNPs can be coated with tumor-targeting molecules, allowing them to attach specifically to cancer cells. This precision drug delivery increases the concentration of chemotherapy drugs at the tumor site, enhancing treatment effectiveness while minimizing side effects. Recent research has demonstrated the potential of AuNPs in treating breast and colorectal cancers by delivering chemotherapy drugs like oxaliplatin directly to tumors (Yang et al., 2022).

Platinum nanoparticles (PtNPs)

Due to their unique physicochemical properties, PtNPs have gained significant attention in cancer treatment. They exhibit anti-cancer effects similar to traditional platinum-based chemotherapy drugs, such as cisplatin, primarily by inducing DNA damage and inhibiting cell proliferation (Zeng et al., 2020).

DNA Damage Induction

PtNPs interact directly with cellular DNA, forming cross-links and adducts that disrupt essential processes like replication and transcription (Gurunathan et al., 2020). These disruptions trigger cell cycle arrest and ultimately lead to apoptosis, effectively eliminating cancer cells. This mechanism is similar to that of cisplatin, which binds to DNA and forms intrastrand cross-links, thereby inhibiting DNA synthesis and function.

Inhibition of Tumor Cell Proliferation

Apart from DNA damage, PtNPs play a crucial role in halting tumor cell proliferation. By interfering with key signaling pathways involved in cell cycle regulation, PtNPs can suppress uncontrolled cell division. Research suggests that they modulate protein activities responsible for tumor growth, reducing the survival of malignant cells (Alyami et al., 2022).

Improved Cellular Uptake and Targeted Drug Delivery

One of the most promising aspects of PtNPs is their ability to enhance drug delivery efficiency while minimizing systemic toxicity. Due to their nanoscale size, PtNPs accumulate preferentially in tumor tissues through the enhanced permeability and retention (EPR) effect (Abed et al., 2022). This property allows for more precise drug delivery, reducing harmful side effects often associated with conventional platinum-based chemotherapy.

Synergistic Potential in Combination Therapies

PtNPs can also be engineered to serve as carriers for other therapeutic agents, enabling combination therapies that target multiple cancer pathways simultaneously (Alven et al., 2024). This multifunctional approach has shown potential in enhancing treatment efficacy, improving drug stability, and reducing drug resistance.

Copper Nanoparticles (CuNPs)

CuNPs have emerged as promising agents in cancer therapy, owing to their unique properties that enable them to target tumor-initiating cells and induce oxidative stress within cancerous tissues.

Cytotoxic Effects on Tumor-Initiating Cells

CuNPs exhibit significant cytotoxicity against tumor-initiating cells, which are pivotal in cancer development and recurrence. This cytotoxicity is primarily attributed to the generation of reactive oxygen species (ROS), leading to oxidative stress and subsequent apoptosis in these cells. This targeted approach holds promise for effective cancer therapies.

Induction of Oxidative Stress via Fenton and Haber–Weiss Reactions

CuNPs can participate in Fenton-type and Haber–Weiss-type reactions, catalyzing the conversion of hydrogen peroxide into highly reactive hydroxyl radicals. These radicals inflict substantial oxidative damage on cellular components, including lipids, proteins, and DNA, culminating in cancer cell death. This pro-oxidant activity is a cornerstone of their anticancer efficacy.

Exploring the Future of TMNP Applications in Oncology

The future application of TMNPs in oncology depends on overcoming key challenges, leveraging advanced technologies, and addressing regulatory hurdles.

Enhancing Specificity and Minimizing Toxicity

Recent research efforts focus on improving the specificity of TMNPs while reducing their potential toxicity. Modifications in surface coating and chemistry have been instrumental in enhancing biocompatibility and stability while mitigating cytotoxic effects (Zhang et al., 2022). Functionalizing TMNPs with targeting ligands helps in directing them precisely to tumor tissues, thereby minimizing off-target interactions and reducing systemic toxicity (Adepu & Ramakrishna, 2021). Furthermore, advancements in synthesis techniques allow for better control over particle size, shape, and charge, which is crucial for optimizing their biological interactions.

Emerging Technologies: Theranostic Nanoparticles

A significant breakthrough in TMNP research is the development of theranostic nanoparticles - multifunctional systems that combine both diagnostic and therapeutic applications. These nanoparticles offer the advantage of real-time imaging while simultaneously delivering therapeutic agents, significantly improving treatment precision (Ren et al., 2025). Theranostic TMNPs have shown potential in optimizing drug delivery efficiency and monitoring treatment responses, paving the way for more personalized cancer therapies. Additionally, techniques such as photothermal therapy and magnetic hyperthermia, when integrated with targeted drug release, have demonstrated enhanced therapeutic outcomes (Adepu & Ramakrishna, 2021).

Addressing Regulatory Challenges and Clinical Trials

Despite the promising developments, translating TMNPs from the laboratory to clinical applications presents considerable regulatory challenges. Comprehensive preclinical and clinical studies are necessary to evaluate their long-term safety, biodistribution, and toxicity profiles. The complexity of nanoparticle synthesis and functionalization poses difficulties in achieving standardization, necessitating stringent regulatory frameworks to ensure reproducibility and efficacy (Olawade et al., 2024). Moreover, addressing challenges related to large-scale production is critical to maintaining consistency in nanoparticle formulations and meeting clinical demand.

Integration with Emerging Technologies

The convergence of TMNPs with advanced technologies such as artificial intelligence (AI) and nanorobotics holds immense potential in the field of precision oncology. AI-driven computational models can assist in designing optimized nanoparticles, predicting their biodistribution, and refining drug release kinetics to enhance personalized treatments (Das & J, 2023). Additionally, nanorobotics offers promising prospects for targeted drug delivery, enabling nanoparticles to navigate biological barriers with exceptional precision (Naik & Jagtap, 2024). These technological advancements could significantly improve treatment efficacy while minimizing adverse effects, leading to the next generation of cancer therapies.

Conclusion

In 2022, cancer affected over 20 million people globally, with 9.7 million deaths, highlighting an urgent call for innovative solutions. WHO and IARC data reveal not only the escalating cancer burden but also the stark disparities in care, especially in low-resource regions where essential services remain underfunded. Conventional treatments - chemotherapy, radiotherapy, and immunotherapy - pose challenges due to severe side effects and limited accessibility. In response, TMNPs, such as gold, silver, copper, and platinum-based nanosystems, have shown promise in enhancing drug delivery, diagnostics, and targeted cancer therapies like photothermal and photodynamic treatments, addressing key limitations of current modalities while advancing equity and precision in global oncology.

Nanoparticles, defined as particles with dimensions between 1–100 nm, exhibit unique physicochemical behaviors due to their high surface area and quantum effects, distinguishing them from bulk materials. These properties enable enhanced reactivity, tunable optical and electronic functions, and size-dependent catalytic efficiency, which are pivotal in drug delivery, diagnostics, electronics, and energy systems. TMNPs, particularly Ag, Au, Pt, and Cu-based systems, are notable for their superior catalytic and biomedical capabilities. Their synthesis - via chemical, green, or physical methods - directly affects morphology, surface chemistry, and performance. While AgNPs are widely studied for antimicrobial and anticancer actions, AuNPs are for LSPR-based biosensing, PtNPs for catalysis and fuel cells, and CuNPs for cost-effective catalysis despite oxidation challenges. Across studies, the synthesis–property relationship remains central, supporting a growing emphasis on sustainable nanotechnology development.

TMNPs are showing great promise in cancer research for both diagnosis and treatment. These tiny particles can enter tumors easily due to their small size and can be engineered to deliver drugs directly to cancer

cells, reducing side effects on healthy tissues. Silver nanoparticles are especially good at generating harmful reactive oxygen species (ROS) that damage cancer cells' DNA and membranes, leading to cell death, while sparing normal cells. Gold nanoparticles are used in photothermal therapy, where they convert light into heat to kill tumor cells and help deliver chemotherapy drugs more accurately. Platinum nanoparticles work like traditional platinum-based drugs by damaging cancer cell DNA, stopping them from growing, and can be used in combination treatments for better results. Copper nanoparticles target tumor-forming cells and increase oxidative stress through specific chemical reactions, making them effective in killing cancer cells.

In conclusion, TMNPs represent a groundbreaking frontier in oncology, addressing critical limitations of conventional cancer therapies with innovative solutions like targeted delivery, reduced toxicity, and theranostics. From their diverse applications - spanning photothermal therapy to real-time imaging - to advancements in green synthesis and AI integration, TMNPs embody the future of precision medicine. While challenges such as toxicity management and regulatory barriers persist, continued research and technological development will be pivotal in unlocking their full potential. By bridging the gap between cutting-edge science and clinical application, TMNPs hold the promise to revolutionize cancer diagnosis and treatment, bringing us closer to equitable, effective, and sustainable cancer care.

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