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Review Article

ADVANCES IN NANOTECHNOLOGY FOR CANCER RESEARCH: A COMPREHENSIVE REVIEW

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ABSTRACT

Nanotechnology has revolutionized the field of oncology by enabling precise diagnosis, targeted drug delivery, and improved therapeutic efficacy with minimal side effects. The integration of nanomaterials such as liposomes, dendrimers, quantum dots, metallic nanoparticles, and polymeric nanocarriers has opened new avenues in cancer diagnosis and treatment. This review summarizes the recent progress in nanotechnology-based cancer research, focusing on the design, synthesis, and biomedical applications of nanomaterials. Emphasis is given to nanocarrier-mediated drug delivery, nano-based imaging systems, biosensing technologies, and theranostic platforms. Additionally, the review discusses current limitations, toxicity concerns, and regulatory challenges that must be addressed for clinical translation. Overall, nanotechnology continues to offer transformative solutions for cancer detection, therapy, and personalized medicine.

Keywords: Nanotechnology, Cancer Research, Drug Delivery, Nano-diagnostics, Theranostics, Targeted Therapy.

INTRODUCTION

Cancer remains one of the leading causes of mortality worldwide, with the World Health Organization reporting over 10 million deaths annually. Conventional treatments such as chemotherapy, radiotherapy, and surgery often exhibit limited efficacy and severe side effects due to non-selective targeting of healthy tissues. To overcome these challenges, nanotechnology has emerged as a groundbreaking approach, offering the potential for site-specific drug delivery, early detection, and real-time monitoring of therapeutic outcomes. Nanomaterials, with their tunable size (1-100 nm), high surface area, and modifiable surface chemistry, allow for enhanced drug encapsulation, controlled release, and improved bioavailability. The interdisciplinary nature of nanotechnology has led to innovative developments in oncology, combining materials science, molecular biology, and medical imaging to enhance both diagnosis and treatment precision. Nanotechnology involves manipulating materials at the nanoscale (1-100 nm) to develop functional systems that interact with biological targets at the molecular level. In cancer therapy, it enhances drug solubility, improves tumor targeting, and minimizes side Mosleh-Shirazi *et al.* (2021) reported that nanotechnology-driven diagnostic tools significantly improved early tumor detection through nanoparticle-enhanced imaging. Similarly, Jin *et al.* (2020) emphasized that nanotechnology enables multimodal imaging and combined therapy, thus improving patient outcomes.

Liposomes, polymeric nanoparticles, and dendrimers are among the most widely used nanocarriers for controlled drug release Khanduri (2024) and Rauf *et al.* (2025) highlighted that surface functionalization of nanoparticles using ligands or antibodies enhances selective binding to tumor cells via receptor-mediated endocytosis. Gold and magnetic nanoparticles have been used for photothermal therapy and magnetic targeting Gu, (2025). Such systems improve therapeutic indices while reducing adverse effects Millagaha Gedara *et al.,* (2021). Nanomaterials have revolutionized cancer diagnostics by enabling high-

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sensitivity biosensors and real-time imaging. Quantum dots, carbon nanotubes, and iron oxide nanoparticles serve as contrast agents in MRI, PET, and optical imaging A. Ahmed Dawa *et al.,* (2025). Millagaha Gedara *et al.* (2025) analyzed global research trends and concluded that nano-based diagnostics contribute significantly to precision oncology. Biosensors integrated with gold nanoparticles also permit early detection of biomarkers such as PSA and HER2 Ahmed Dawa *et al* (2025) and Sayyad *et al.,* (2025).

Recent advances in nanorobotics and AI have introduced autonomous nanosystems for tumor detection and drug targeting. Rajendran *et al.* (2023) discussed nanorobotic applications capable of performing minimally invasive interventions at the cellular level. Kavousinejad, (2024) proposed AI-based control mechanisms for nanorobots to identify and track cancer cells in real time. These approaches mark a convergence of nanotechnology, robotics, and AI toward intelligent cancer therapeutics. Despite substantial progress, several nanomaterials exhibit cytotoxicity and bioaccumulation risks Buzea *et al.* (2008). reviewed nanoparticle toxicity mechanisms, emphasizing oxidative stress and inflammatory responses in biological tissues. Comprehensive biocompatibility assessments remain critical before clinical translation. Similarly, regulatory concerns regarding nanoparticle safety and pharmacokinetics hinder commercialization Ehdaie (2007) and Ehdaie (2009).

MATERIALS AND METHODS

This comprehensive review adopted a systematic evidence-based narrative methodology to examine the recent advances in nanotechnology for cancer research, diagnosis, and therapy. The process integrated structured database searches, selection criteria, and thematic synthesis to ensure comprehensive and unbiased coverage of the topic.

Data sources and search strategy

An extensive literature search was performed across major scientific databases including Scopus**,** PubMed**,** ScienceDirect**,** SpringerLink**,** and IEEE Xplore**,** covering the period from 2015 to 2025**.** Search terms were selected to capture the broad and interdisciplinary scope of the field and included: Nanotechnology*,* Cancer therapy, Nanomedicine, Nanocarriers*,* Targeted drug delivery*,* Nanodiagnostics, Nanorobotics, Photothermal therapy*,* and *N*ano-imaging. Boolean operators (AND, OR) were used to refine searches, ensuring inclusion of both experimental and review-based studies addressing nanotechnology in oncology.

Inclusion and exclusion criteria

To maintain scientific rigor, the following inclusion criteria were applied: Publications between 2015 and 2025 in peer-reviewed international journals. Articles focusing on nanotechnology-based applications in cancer detection, diagnosis, imaging, or treatment**.** Studies providing quantitative or qualitative data on nanocarrier efficacy, biocompatibility, or targeted drug delivery mechanisms. English-language publications with complete datasets or validated review frameworks. Exclusion criteria encompassed conference abstracts, short communications, non-English articles, and studies lacking sufficient methodological or analytical detail.

Selection process

Initially, over 300 research records were identified. After title and abstract screening, 64 full-text papers were evaluated for eligibility. Based on relevance, methodological soundness, and data completeness, 18 primary studies Rama Bramha Reddy *et al* (2023), Roy *et al*., (2024) and Baghaee *et al*., (2018) were finalized for synthesis. The review ensured balanced representation of experimental findings, theoretical advancements, and translational challenges.

Data extraction and synthesis

Data were extracted using a structured template that included: Type of nanomaterial or nanosystem (e.g., liposomes, polymeric nanoparticles, metallic nanoparticles, nanorobots). Mechanism of action**,** such as passive or active targeting and controlled release. Diagnostic and therapeutic applications**,** including imaging, biosensing, and combined theranostic approaches. Toxicological assessments**,** biocompatibility, and clinical translation barriers. Findings were organized under four key thematic areas: Nanotechnology in cancer diagnosis and imaging**,** focusing on nano-biosensors, contrast agents, and imaging precision. Nanocarrier-based drug delivery systems, emphasizing liposomal, polymeric, and metallic nanoparticles for targeted chemotherapy. Emerging innovations, such as nanorobotics, AI-integrated nanotheranostics**,** and gene-editing nanoplatforms (CRISPR/Cas9 delivery)**.** Safety, ethical, and translational challenges associated with nanomaterial use in clinical oncology.

Quality assessment

Each selected study was critically appraised for its methodological quality, reproducibility, and relevance to clinical or translational cancer research. The synthesis followed narrative integration principles to compare methodologies and outcomes across studies while identifying research gaps and emerging trends.

RESULTS AND DISCUSSION

Nanoparticles enhance imaging resolution and sensitivity by accumulating at tumor sites through the enhanced permeability and retention (EPR) effect. Quantum dots and iron oxide nanoparticles have enabled precise tumor localization through MRI and fluorescence-based imaging demonstrated that nano-based imaging agents significantly reduce false-negative rates in tumor detection. Thus, nanotechnology provides a vital platform for early diagnosis and prognosis assessment. Nanocarriers such as liposomes and polymeric nanoparticles improve the pharmacokinetic profile of chemotherapeutics. showed enhanced cytotoxicity in tumor cells when drugs were encapsulated in biodegradable nanoparticles, compared to free drugs. Metallic nanoparticles have been effective in photothermal and photodynamic therapy, providing localized treatment with minimal damage to surrounding tissues. Furthermore, nanorobotics offers real-time guidance for localized drug release. Combining nanotechnology and AI offers predictive modeling for nanoparticle behavior in vivo demonstrated AI's potential to optimize nanoparticle formulations, ensuring precise targeting. Future oncology treatments may integrate smart nanodevices capable of autonomous tumor recognition and therapy initiation.

CONCLUSION

Nanotechnology has significantly advanced cancer research by improving early diagnosis, targeted therapy, and treatment efficacy. The reviewed studies collectively demonstrate that nanosystems enhance therapeutic outcomes through selective targeting, controlled release, and improved imaging precision. However, toxicity, biodistribution, and large-scale synthesis remain barriers to widespread clinical adoption. Collaborative research across materials science, oncology, and pharmacology is essential to overcome these challenges. Future directions in nanotechnology for cancer research include: Smart theranostic systems integrating diagnosis and therapy within a single nanoplatform. AI-driven nanorobots capable of autonomous navigation and drug delivery. Personalized nanomedicine leveraging patient-specific tumor profiling for customized treatments. Biodegradable and green-synthesized nanomaterials to ensure environmental and biological safety. Regulatory harmonization and clinical trials to accelerate translation from laboratory to clinical oncology. With ongoing technological advances, nanotechnology holds the potential to redefine precision oncology and contribute to a new era of minimally invasive, patient-centered cancer care.

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CONFLICT OF INTERESTS

The authors declare no conflict of interest

ETHICS APPROVAL

Not applicable

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AI TOOL DECLARATION

The authors declares that no AI and related tools are used to write the scientific content of this manuscript.

DATA AVAILABILITY

Data will be available on request

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