Review Article
DOI: https://doi.org/10.70749/ijbr.v3i3.810

INDUS JOURNAL OF BIOSCIENCE RESEARCH
https://induspublishers.com/IJBR
ISSN: 2960-2793/ 2960-2807

Nano-Engineering for Precision Oncology Unraveling Molecular Mechanisms and Pioneering Revolutionary Cancer Therapies

Ayesha Liaqat[1], Mohsin Saleem Ghouri[2], Raheela Shehzadi[3], Rida Munir[4], Mehwish Bashir[4], Ali Rehmat[5], Malka Saba Bashir[6], Muhammad Irshad[7], Haseeb Ahmed[8]

[1]Department of Zoology, Government College University Faisalabad, Punjab, Pakistan.
[2]Department of Chemistry, Government Murray Graduate College, Sialkot, Punjab, Pakistan.
[3]Department of Biological Sciences, Superior University Lahore, Punjab, Pakistan.
[4]Department of Bioinformatics and Biotechnology, Government College University, Faisalabad, Punjab, Pakistan.
[5]Department of Medical Physics, NED University of Engineering and Technology, Karachi, Sindh, Pakistan.
[6]Department of Zoology, The Women University Multan, Punjab, Pakistan.
[7]Department of Computer Science, Shah Abdul Latif University, Khairpur, Sindh, Pakistan.
[8]Department of Biochemistry and Biotechnology, University of Gujrat, Punjab, Pakistan.

ARTICLE INFO

Keywords

Nano-engineering, Precision Oncology, Molecular Mechanisms, Targeted Drug Delivery, Nanomedicine, Cancer Therapy, Tumor Microenvironment, Nanoparticles, Nanocarriers, Personalized Medicine, Immunotherapy, Theranostics, Biomarker-Driven Therapy, Nanotechnology in Oncology, Nano Drugs, Cancer Nano Theranostics, Molecular Targeting, Nanostructures, Cancer Diagnostics, Controlled Drug Release.

Corresponding Author: Ayesha Liaqat, Department of Zoology, Government College University Faisalabad, Punjab, Pakistan.
Email: ayeshaliaqat8244@gmail.com

Declaration

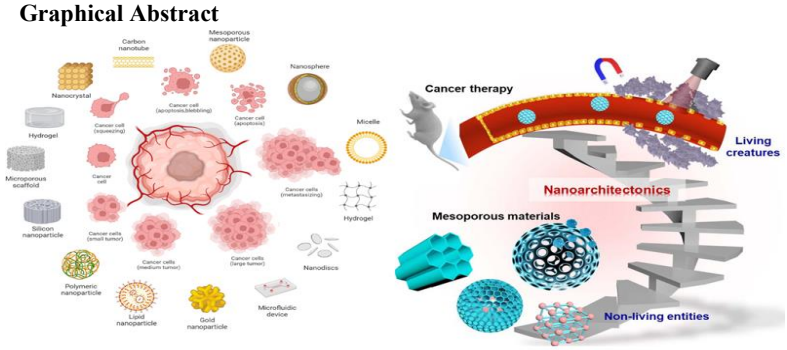
Authors' Contribution: All authors equally contributed to the study and approved the final manuscript.
Conflict of Interest: No conflict of interest.
Funding: No funding received by the authors.

Article History
Received: 06-01-2025
Revised: 21-02-2025
Accepted: 10-03-2025

ABSTRACT

With previously unheard-of improvements in cancer detection, therapy, and monitoring, nano-engineering has become a game-changer in precision oncology. Researchers can create nanoscale drug delivery systems that maximize therapeutic efficacy and reduce systemic toxicity by utilizing nanotechnology. With an emphasis on targeted drug delivery, tumor microenvironment manipulation, and nanocarrier-mediated immunotherapy, this study investigates the molecular processes underlying nano-engineered therapeutics. By increasing specificity and lowering side effects, innovations including photothermal and photodynamic therapy, biomimetic nanostructures, and nanoparticle-based CRISPR gene editing are transforming the treatment of cancer. Furthermore, real-time, non-invasive cancer detection and monitoring are made possible by liquid biopsy technologies and nano-biosensors, allowing for early intervention and individualized treatment plans. A comprehensive approach to cancer management is provided by the interaction of nanotechnology and molecular oncology, which also makes it easier to create multipurpose nanoplatforms that combine diagnosis and treatment (theranostics). Nano-engineering has enormous promise to overcome drug resistance, improve immune system engagement, and enable precision-targeted treatments as precision oncology develops. To enable clinical translation, however, issues including biocompatibility, large-scale production, and regulatory permissions need to be resolved. With a focus on its role in developing ground-breaking cancer treatments and changing the face of precision oncology, this study focuses on recent advances, present difficulties, and potential future paths in nano-engineering for cancer therapy.

Graphical Abstract



INTRODUCTION

Traditional nano-oncology has unquestionably improved cancer therapy by increasing medication bioavailability, decreasing systemic toxicity, and boosting tumor penetration (Li et al., 2021). It mainly uses nanoparticle-

based drug delivery and tumor-targeting techniques. The complexity of cancer, which includes highly adaptable cellular networks, genetic variability, and dynamic tumor microenvironments that constantly change to evade therapy, makes traditional methods insufficient today (Baghban et al., 2020). By actively altering tumor biology at the molecular level and using cutting-edge nanotechnology to disrupt cancer's signaling networks, metabolic requirements, and immune evasion strategies, the developing concept of molecular nano-disruption aims to go beyond simple medication delivery. This approach makes use of multifunctional nanoplatforms that can modify the tumor immune microenvironment, interfere with oncogenic circuits, and change intracellular biochemical responses (Farhana et al., 2023). In contrast to traditional nanoparticle carriers, molecular nano-disruptors operate at the systems biology level, destroying cancer's basic survival pathways by precision-guided processes, including RNA interference (RNAi), CRISPR-based gene editing, or nanomechanical force modulation. They also incorporate real-time biosensing capabilities, which allow for dynamic tumor profiling-based adaptive treatment responses (Sun et al., 2019). Molecular nano-disruption is a revolutionary development that not only improves treatment specificity but also opens the door for intelligent, self-regulating nanotherapeutics that can adapt to the tumor's adaptive mechanisms. This is in contrast to traditional nano-oncology, which faces challenges with drug resistance, off-target effects, and limited penetration in hypoxic or fibrotic tumor regions (Wong et al., 2020). By attempting to not only remove tumors but also radically alter the genetic landscape of disease, this next-generation strategy transforms our understanding of cancer therapy (Morganti et al., 2019).

Using radiation, chemotherapy, and surgery to directly target tumors is the primary objective of conventional cancer treatments (Abbas et al., 2018). However, new developments in cancer treatment are moving toward a more comprehensive approach, which involves designing the body to act as an anti-cancer machine. This idea makes use of the body's natural defenses, including the immune system, metabolic processes, and regeneration processes, to make the environment unsuitable for the growth of cancer (Jakóbisiak et al., 2003). Checkpoint inhibitors and modified T cells (CAR-T cells) are examples of advanced immunotherapies that improve the body's innate capacity to identify and eliminate cancer cells (Innao et al., 2020). Furthermore, metabolic reprogramming techniques optimize the patient's systemic metabolism to impede the growth of cancer while depriving tumors of vital resources. By precisely altering immune cells, gene-editing methods like CRISPR-based interventions make them more effective at destroying cancerous cells while causing the least amount of collateral harm to healthy areas (Chira et al., 2022). Furthermore, microbiome engineering is a new field that uses good gut bacteria to control immune responses and lower systemic inflammation, which makes the environment less conducive to the growth of tumors. Additionally, nanotechnology is essential because it makes it possible to deliver bioengineered chemicals that directly disturb tumor microenvironments and improve immune surveillance (Gao et al., 2021). When taken as a whole, these tactics change the way cancer is treated from a reactive to a proactive, body-wide defensive mechanism, potentially changing the paradigm from treatment to prevention (Rainey et al., 2024).

By bridging the gap between static, laboratory-designed treatments and dynamically responsive therapies that adapt inside live systems, self-evolving nanotherapeutics offer a fundamental leap in the field of medicine (Grinin et al., 2024). These cutting-edge nanoscale platforms use adaptive evolution, biomimicry, and artificial intelligence to adjust their therapeutic responses in real-time. Self-evolving nanotherapeutics use feedback-responsive materials, machine learning algorithms, and bio-interactive components to optimize drug delivery, immune modulation, and regenerative processes as they interact with the body's microenvironment (Pollock et al., 2008). This is in contrast to conventional nanomedicines, which are pre-programmed with fixed pharmacokinetics and targeting mechanisms. Through the integration of genetically encoded biosensors, self-assembled nanostructures, and stimuli-responsive polymers, these intelligent therapeutics can independently modify their surface chemistry, shape, and drug release profiles in response to biochemical cues like pH, enzyme activity, or inflammatory markers (Kashani et al., 2024) in complicated and diverse diseases like cancer, neurodegenerative diseases, and infectious diseases, where treatment resistance and unexpected disease development present major obstacles, this flexibility is especially encouraging. Additionally, developments in synthetic biology and CRISPR-based gene editing are making it possible to create nanocarriers that selectively alter gene expression or cellular interactions in addition to delivering medications (Chen et al., 2023). Although regulatory, safety, and scalability issues will need to be resolved as research advances to move from lab-based proof-of-concept studies to clinical applications, self-evolving nanotherapeutics have the potential to revolutionize personalized medicine and Long-term illness control is still very important (Wang et al., 2023). By identifying molecular pathways and creating next-generation cancer treatments that improve therapy specificity, effectiveness, and patient outcomes, this research seeks to investigate the role of nano-engineering in precision oncology. Examine the molecular interactions between malignant cells and nano-engineered platforms to improve targeted medicine

delivery. Examine how tumor penetration and cellular uptake are affected by the size, shape, and surface changes of nanoparticles. To combat medication resistance, create intelligent nanomaterials that can adjust to changes in the tumor microenvironment. Examine immunotherapies enabled by nanotechnology that improve the immune system's ability to identify and eliminate cancer cells.

Quantum Topological Nanostructures: The Uncharted Territory in Cancer Therapy

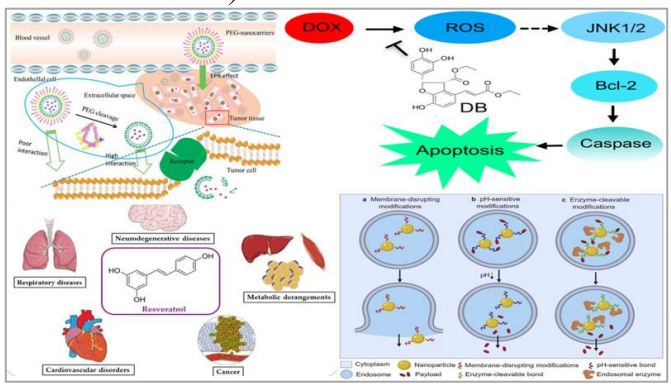
Utilizing the special qualities of topological insulators, electron-spin dynamics, and quantum-engineered nano scaffolds, quantum topological nanostructures provide a novel approach to cancer treatment that enables previously unheard-of levels of accuracy (Ramezani et al., 2023). Topological insulators provide a novel method for quantum-controlled medication administration because of their capacity to conduct surface states while retaining insulating bulk characteristics. To ensure highly targeted therapeutic action with little collateral damage, these materials can be designed to encapsulate and transport anticancer agents while using quantum confinement to modulate drug release based on external stimuli like magnetic fields or particular tumor microenvironments (Thorat et al., 2019). Furthermore, because spin-polarized electrons may be controlled to interfere with malignant cell signaling pathways and cause selective cytotoxicity without harming healthy tissues, using electron-spin dynamics offers a paradigm change in tumor eradication techniques. These quantum devices' spin-momentum locking feature adds another degree of control and opens the door to extremely effective, non-invasive medicinal treatments. Quantum nanoflowers, a new class of hierarchical nano-scaffolds, are being developed for controlled therapy, adding to this innovative landscape. They combine tunable electronic properties, high surface area, and biocompatibility to improve drug loading, cellular interactions, and precision targeting. These nanoflowers, which draw inspiration from biomimetic designs, provide a platform where quantum effects and structural flexibility work together to maximize therapeutic efficacy, creating new opportunities for cancer therapy that will improve patient outcomes and decrease resistance. Researchers are prepared to change the future of oncological therapies as they continue to investigate the unrealized potential of these quantum topological nanostructures, pushing the frontiers of precision medicine into the world of quantum-driven discoveries (Jung et al., 2020).

Synthetic Morphogenic Nanoparticles (Hijacking Cancer's Evolution)

With the ability to take over the evolutionary processes of tumors, synthetic morphogenic nanoparticles are becoming a game-changer in the treatment of cancer (Khafaga et al., 2024). These nanoparticles are made to adjust to the changing conditions of malignant tissues by utilizing shape-shifting nanostructures, which allows for accurate tumor behavior reprogramming and targeting. By causing changes in cell destiny that favor tumor suppression and even the differentiation of malignant cells back into benign states, these morphogenic nanoparticles can modify the tumor's microenvironment. The utilization of bioelectricity-guided therapies is one novel feature of this strategy. These nanoparticles can influence the remodeling of tumor structures by modulating the bioelectrical signals that govern cellular processes through the manipulation of electric fields. By improving the capacity to affect tissue architecture and cellular communication, this bioelectric guidance creates an environment that inhibits the growth of tumors (Chernet et al., 2013). Additionally, by targeting certain oncogenes, synthetic morphogenic nanoparticles function as epigenetic rewriters, allowing for real-time molecular interventions. As molecular "erasers," these nanoparticles can effectively silence or alter the epigenetic markers that cause malignant mutations. Precision medicine, which addresses the underlying molecular causes of cancer by dynamically changing the tumor's genetic expression in addition to genetic targeting, is made possible by this epigenetic regulation. By actively rewiring tumor development and eliminating resistance mechanisms frequently observed in conventional treatments, this synergistic approach, a state-of-the-art combination of nanotechnology, bioelectricity, and epigenetics, offers the potential to completely transform cancer therapeutics (Costa et al., 2024).

Figure 1

Synthetic Morphogenic Nanoparticles (Hijacking Cancer's Evolution)



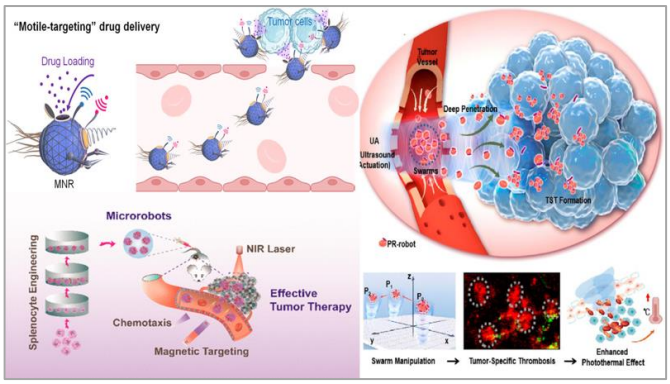
Decentralized Nano-Swarms: Self-Organizing Cancer Assassins

By using bioinspired nanobot collectives that imitate the self-organizing characteristics of natural swarms, including ant colonies or bacterial clusters, decentralized nano-swarms provide a breakthrough approach to cancer therapy by penetrating deep into tumor tissues (Debela et al., 2021). These autonomous nano-swarms, in contrast to traditional nanomedicine approaches, use

decentralized control systems to maneuver across intricate tumor microenvironments, get past biological barriers, and improve the accuracy of drug administration. These nanorobots can coordinate, interact, and modify dynamically in response to the biochemical signals of the tumor by integrating swarm intelligence algorithms. This enables the discharge of a multi-drug payload at specific places in unison. By guaranteeing that various therapeutic drugs are administered in exact ratios and at ideal intervals, this self-organizing activity greatly increases the effectiveness of combination treatments by reducing resistance and optimizing cytotoxic effects (Ma et al., 2024). Furthermore, by responding to real-time changes within tumors, such as hypoxia, acidity, or immune evasion strategies, cancer-aware nanorobots with adaptive learning capacities can continually improve their treatment approach. Molecular computer components may be included in these programmable nano-swarms to allow them to sense and understand tumor markers on their own, change their collective behaviors, and optimize their treatment plans without outside guidance (An et al., 2023).

Figure 2

Decentralized Nano-Swarms: Self-Organizing Cancer Assassins



Entangled Nanoparticles (The Next Wave of Remote-Controlled Cancer Therapy)

By utilizing quantum entanglement to provide non-invasive, highly focused therapeutic activation, entangled nanoparticles represent a revolutionary advancement in remote-controlled cancer therapy (Cheng et al., 2024). The accuracy and depth penetration of traditional nanoparticle-based therapies, such as drug-loaded carriers or hyperthermic agents, may be limited since they frequently call on localized triggers like heat, pH shifts, or external fields. To minimize harm to healthy cells, scientists can use correlated photon interactions to remotely trigger nanoparticles located deep within the body by taking advantage of quantum entanglement. Entangled photon pairs interact with specially made nanoparticles at the tumor location in photon-guided nano-therapeutics, an inventive method that precisely induces localized medication release or hyperthermic reactions. This technique is an appealing method for removing deep-seated or metastatic cancers since it enables real-time, external control of therapeutic effects without intrusive procedures (Sun et al., 2022). Furthermore, spintronic nanoparticles provide an additional degree of control in the therapy of cancer by precisely manipulating magnetic fields using electron spin characteristics. Ultra-precise, low-intensity magnetic fields may be used to remotely direct these nanoparticles, greatly increasing tumor targeting and lowering systemic toxicity. The next generation of remote-controlled oncology therapies is being propelled by the confluence of quantum physics, nanomedicine, and spintronics. This will allow for safer, more individualized, and more successful interventions by fine-tuning cancer therapy at the quantum level (Mazumdar et al., 2025).

Necroptotic Nanodevices Engineered to Force Cancer Cell Death beyond Apoptosis

By using alternate cell death pathways like necroptosis and ferroptosis to target drug-resistant malignancies, necroptotic nanodevices represent a breakthrough in the treatment of cancer (Zang et al., 2022). Many aggressive malignancies avoid apoptosis, a tightly controlled and scheduled type of cell death, by upregulating survival pathways and causing genetic abnormalities. This is why traditional cancer therapies frequently rely on it. To get over this resistance, tailored nanodevices are made to activate receptor-interacting RIPK1 and RIPK3 and mixed lineage kinase domain-like MLKL to forcefully cause necroptosis, an inflammatory, caspase-independent kind of cell death. To guarantee complete tumor eradication, ferroptosis, an additional alternate form of cell death marked by lipid peroxidation and iron-dependent oxidative stress, is also being used in conjunction with necroptotic techniques. Iron-oxide-based necroptotic activators are a potential strategy because they can penetrate deep-tissue cancers and produce reactive oxygen species (ROS) in response to external stimulation (Fei et al., 2020). This increases oxidative damage and upsets the homeostasis of cancer cells. Furthermore, by combining biochemical and biophysical stress-inducing mechanisms, hybrid nano-biotics are becoming a next-generation therapeutic approach. By using organelle-specific targeting and stress amplification, these hybrid nanoparticles alter intracellular conditions and set off an auto-destructive cascade in cancer cells. When traditional therapies are ineffective for malignancies found in hypoxic, chemo-resistant tumor microenvironments, these precision-driven methods are very helpful. Necroptotic nanodevices are enabling a paradigm change in oncology by employing regulated activation mechanisms and intelligent drug delivery systems, providing hope to

patients with aggressive and treatment-refractory malignancies (Capuozzo et al., 2024).

Nano-Black Holes

Using Artificial Gravity Fields to Collapse Tumor Cells

By using artificial gravity fields at the nanoscale to cause controlled tumor collapse, the idea of nano-black holes in oncology offers a novel approach to cancer treatment. This technique, which is often referred to as nano-collapse treatment, combines cutting-edge nanomaterials designed to apply tremendous stress to cancer cells, therefore exploding them from the inside out, with concepts from mechanobiology. The tactic entails the production of superdense nanomaterials that provide localized gravity effects that disturb tumor architecture when activated by external stimuli like electromagnetic fields or ultrasonic vibrations (Wrześniewski et al., 2019). Because of their unique biomechanical characteristics, these artificial gravity fields cause mechanical stress, which leads to structural breakdown in malignant tissues while largely ignoring the surrounding healthy cells. The intrinsic vulnerability of tumor cells, which frequently display aberrant cytoskeletal integrity and modified mechano-transduction pathways, rendering them very vulnerable to mechanical collapse, is exploited by such force-induced demise. Furthermore, real-time imaging systems and computer models might be combined with nano-black hole technology to precisely target cancerous growths, guaranteeing maximum effectiveness with little side effects. In addition to directly destroying tumors, this method may also boost immune responses because the quick mechanical disintegration of tumor cells may generate damage-associated molecular patterns (DAMPs), which would strengthen anti-tumor immunity (Wu et al., 2024). To further improve the accuracy and safety of nano-collapse treatment, future developments in this field may include hybrid nanostructures that combine quantum materials, piezoelectric characteristics, and intelligent biomolecular coatings. Therefore, by presenting mechano-physical forces as a unique therapeutic axis, this developing discipline has the potential to alter oncological therapy paradigms and pave the way for non-invasive, highly effective, and focused cancer eradication treatments (Adeola et al., 2018).

Table 1

Nano-Black Holes and Artificial Gravity Fields in Tumor Collapse Therapy

Aspect	Description
Cencept	Nano-black hole therapy involves the use of artificially generated gravitational fields at the nanoscale to collapse tumor cells, disrupting their structural integrity.
Mechanism of Action	Superdense nanomaterials create intense force fields that selectively target cancer cells, leading to their mechanical destruction via implosion.
Superdense Nanomaterials	Engineered nanoparticles with extreme density that generate localized gravitational forces are designed to collapse tumor cells under high mechanical stress. Composed of materials such as ultra-dense metallic alloys, carbon nanotubes, or engineered quantum dots.
Artificial Gravity Fields	Nanoscale gravitational forces are induced through controlled interactions of dense nanostructures with external stimuli like electromagnetic waves or ultrasound, creating a force gradient that disrupts tumor cell organization.
Targeting Specificity	Tumor cells are more susceptible due to their altered mechanical properties and weak cytoskeletal structures, making them collapse under gravitational stress. It can be enhanced with ligand-functionalized nanomaterials that specifically bind to cancer biomarkers.
Activation Methods	External electromagnetic fields, ultrasonic waves, and laser excitation can be used to activate gravitational collapse effects. Some approaches use infrared laser pulses to generate localized thermal expansion, triggering mechanical compression.
Biophysical Effects	Disrupts tumor integrity, induces cytoskeletal failure, collapses intracellular components, and triggers apoptosis or necrosis. It may also affect mitochondrial function, leading to metabolic stress and energy depletion in tumor cells.
Immunogenic Response	Releases damage-associated molecular patterns (DAMPs) that may enhance anti-tumor immune activity and stimulate an immune response. It can synergize with checkpoint inhibitors to boost the immune system by targeting residual cancer cells.
Advantages Over Conventional Therapies	Minimally invasive, highly targeted, and capable of eliminating tumors mechanically without chemical toxicity or radiation damage. Potential to be used in deep-seated tumors where conventional therapies are less effective.
Potential Side Effects	Requires precise control to avoid damaging surrounding healthy tissues; excessive gravitational forces could disrupt normal cellular functions. Nanoparticle accumulation in non-target tissues may require advanced clearance mechanisms.
Integration with Other Therapies	It can be combined with immunotherapy, chemotherapy, or photodynamic therapy for enhanced anti-cancer effects. Experimental models suggest improved efficacy when paired with targeted drug delivery systems.
Current Research and Development	Experimental studies are exploring superdense nanomaterials, their biocompatibility, and safe delivery mechanisms to tumor sites. Research efforts also focus on optimizing nanoparticle size, charge, and coating for improved circulation and tumor penetration.
Computational Modeling	Advanced simulations help optimize gravitational field strengths and nanoparticle interactions within tumor microenvironments. Machine learning models are being developed to predict patient-specific responses and optimize treatment protocols.
Challenges	Requires precise engineering of superdense nanomaterials, targeted delivery, and regulatory approval for clinical applications. The potential toxicity and long-term effects of artificially induced gravitational forces remain unknown.
Future Directions	Development of hybrid nanostructures combining quantum materials, piezoelectric properties, and smart biomolecular coatings to refine therapy. Research is also exploring self-assembling nanomaterials that can form localized high-density zones dynamically.
Clinical Prospects	Ongoing preclinical research is evaluating the feasibility of nano-collapse therapy in animal models, with potential for human trials in the future. Early-stage trials may focus on glioblastoma, pancreatic cancer, and metastatic lesions due to their aggressive nature.
Regulatory Considerations	Requires rigorous safety assessments, FDA/EMA approvals, and long-term studies to determine effectiveness and risks. Regulatory agencies may

	need to establish new guidelines for mechanobiology-based therapies.
Commercial Viability	Startups and biotech firms are exploring funding and partnerships to bring nano-black hole therapy from lab research to clinical application. Investment trends indicate a growing interest in physics-based medical interventions.
Ethical Implications	Raises ethical questions about artificial gravity manipulation in human tissues and potential unforeseen long-term biological effects. Ensuring equitable access to such cutting-edge therapies may also pose socioeconomic challenges.
Conclusion	Nano-black hole therapy represents a novel frontier in cancer treatment, offering a mechanobiology-based approach that could revolutionize oncological care. Ongoing interdisciplinary collaboration between physicists, oncologists, and nanotechnologists is crucial for advancing this field.

Supramolecular Nano-Architectures Building Artificial Cellular Organelles in Tumors

A novel approach to cancer treatment is represented by supramolecular nano-architectures, which make it possible to create artificial cellular organelles that can enter tumors specifically and change their metabolic processes (Wang et al., 2022). These self-assembling nanomachines are designed to act similarly to natural organelles and carry out preprogrammed biological tasks, including interfering with the synthesis of ATP, creating localized medicines, and modifying intracellular signaling pathways. The creation of synthetic mitochondrial organelles that interfere with oxidative phosphorylation and ATP synthesis to target cancer cell metabolism is one of the most promising uses. These artificial mitochondria can either overproduce reactive oxygen species (ROS) to cause apoptosis or take over metabolic pathways to reduce ATP levels, so starving tumor cells, by using bioresponsive nanomaterials (Pei et al., 2023). Another innovation is the design of reactors based on intracellular nanoparticles that serve as factories for site-specific drug production. These nano-reactors avoid systemic toxicity while retaining excellent therapeutic efficacy because they are made of catalytic nanomaterials that initiate in situ drug synthesis within the tumor microenvironment. Because supramolecular assemblages are dynamic and adaptable, precise control over biological events is possible, allowing for real-time therapeutic modification in response to tumor growth. Additionally, by utilizing cutting-edge nanotechnology, scientists can create multipurpose organelle-mimetic systems that combine therapeutic and diagnostic capabilities, opening the door for intelligent theranostic platforms. To guarantee these artificial organelles' clinical translation into next-generation cancer treatments, further research attempts to improve their biocompatibility, stability, and targeting accuracy (Saminathan et al., 2022).

Table 2

Supramolecular Nano-Architectures for Artificial Cellular Organelles in Tumors

Feature	Self-Assembling Nano-Machinery	Artificial Mitochondrial Organelles	Intracellular Nanoparticle-Based Reactors	References
Primary Function	Infiltrates tumor cells and rewires metabolism	Disrupts ATP production and oxidative phosphorylation	Enables localized synthesis of therapeutic agents within cancer cells	Leone et al., 2020
Mechanism of Action	Self-assembly into functional nanostructures that mimic organelles	Generates oxidative stress or interferes with mitochondrial function	Uses catalytic nanomaterials to activate prodrugs or synthesize drugs on-site	Richard et al., 2015
Targeted Cellular Location	Cytoplasm, mitochondria, lysosomes	Mitochondria of cancer cells	Cytoplasm, perinuclear region	Wang et al., 2011
Key Nanomaterials Used	DNA-based nanostructures, peptide amphiphiles, polymeric nanoparticles	Mitochondria-targeting liposomes, iron-sulfur clusters, cerium oxide nanoparticles	Metal-organic frameworks, mesoporous silica nanoparticles, gold nanoclusters	Nguyet et al., 2018
Metabolic Disruptions Induced	Alters glycolysis, increases ROS, and modulates hypoxic adaptation	Inhibits ATP production, triggers apoptosis, and disrupts mitochondrial membrane potential	Triggers local drug synthesis, bypasses systemic toxicity, and enhances therapeutic precision	Solaini et al., 2010
Tumor Targeting Strategies	Passive and active targeting via enhanced permeability and retention (EPR) effect and receptor-mediated endocytosis	Selective uptake by tumor cells through mitochondrial membrane potential-dependent targeting	Enzyme-responsive and pH-sensitive activation for tumor microenvironment selectivity	Ge et al., 2013
Advantages Over Conventional Therapy	Programmable and modular, capable of executing multiple intracellular functions	Highly specific disruption of tumor energy metabolism with minimal off-target effects	Site-specific drug activation minimizes systemic toxicity and enhances drug efficacy.	Liu et al., 2024
Challenges and Limitations	Stability, precise control of assembly, and immune clearance concerns	Potential off-target effects on normal mitochondria and energy metabolism	Need for improved catalytic efficiency and biocompatibility	Li et al., 2024

Future Directions	Development of stimuli-responsive and biohybrid nano-machinery	Integration with nanorobotics for targeted intracellular interventions	Optimization of catalytic efficiency and real-time monitoring of drug synthesis	Kasegn et al., 2025
Clinical Translation Potential	High potential but requires further safety validation and long-term efficacy studies.	Promising strategy for drug-resistant tumors but needs precise targeting mechanisms.	Could revolutionize localized chemotherapy with minimal systemic side effects	Jin et al., 2023

Bioelectronic Nano-Pacemakers

Resetting Cancer Cells at the Molecular Level

A revolutionary development in cancer therapy, bioelectronic nano-pacemakers provide a new method of precisely electrically stimulating cancer cells to reprogram them at the molecular level. These nanodevices use nanowire biointerfaces to provide regulated microcurrents, which efficiently disrupt malignant cell signaling and restore normal cellular functioning, in contrast to conventional therapies that use chemical agents to target tumor cells (Huang et al., 2024). Researchers hope to overcome oncogenic pathways that cause unchecked growth and treatment resistance by incorporating bio-nanocircuitry into malignant tissues. This novel approach efficiently resets abnormal gene expression and metabolic activities typical of cancer cells by modulating intracellular communication through the use of nano-electronic microcurrents. To enable localized, real-time intervention without endangering nearby healthy tissues, the fundamental idea is to design nanoscale electrodes that can blend in perfectly with the tumor microenvironment. In addition to acting as electrical signal conduits, these nanowire-based interfaces allow for bidirectional communication, which makes it easier to monitor tumor responses and make adaptive therapy modifications (Shi et al., 2022). Utilizing the intrinsic electrical characteristics of biological systems, bioelectronic nano-pacemakers provide a precision-medicine method of cancer treatment that targets the disease's core without the negative side effects of conventional therapies like radiation and chemotherapy. Furthermore, by opening the door for intelligent, self-regulating treatment systems that can react dynamically to biological changes, the combination of nanotechnology and bioelectronics has the potential to revolutionize oncology. The development of sophisticated bio-nanocircuitry may allow for smooth integration with current medical technology as research advances, significantly improving the effectiveness and customization of cancer treatment. In the end, this new paradigm in nano-oncology aims to restore normal cellular homeostasis in addition to stopping tumor development, providing fresh hope for less intrusive and more successful cancer treatments (Wang et al., 2024).

CONCLUSION

The nexus of nanotechnology, synthetic biology, and sophisticated computer systems holds the key to a constructed cancer-free future, one in which cancer could not be a significant danger to humankind. Although the quick development of nanotechnology has already shown promise in targeted therapy, medication transport, and diagnostics, the ultimate question is still whether or not cancer can be eradicated from the planet. Through the use of synthetic nanosystems, extreme nano-innovation seeks to overcome biological limitations by creating DNA nanostructures, programmable nanoparticles, and biohybrid devices that can identify and eradicate cancer at the molecular level before it has a chance to spread. In contrast to conventional therapies, which frequently find it difficult to keep up with the flexibility of cancer, designed nanosystems can react dynamically to mutations and change more quickly than the illness itself. Outpacing cancer by combining AI-driven molecular design, precision medicine, and autonomous nanotherapeutics that not only target tumors but also proactively address cellular abnormalities is the next big challenge. The combination of engineering, nanoscience, and bioinformatics is gradually removing the obstacles that have long made cancer an unbeatable enemy, even if there are still many obstacles to overcome, such as guaranteeing biocompatibility and overcoming possible resistance mechanisms. With increased research speed, a cancer-free future might not be just a pipe dream but could come to pass thanks to technical advancements and human inventiveness.

REFERENCE

Abbas, Z., & Rehman, S. (2018). An overview of cancer treatment modalities. *Neoplasm*, *1*, 139-157. https://doi.org/10.5772/intechopen.76558

Adeola, H. A., Van Wyk, J. C., Arowolo, A. T., & Khumalo, N. P. (2018). Human hair as a testing substrate in the era of precision medicine: Potential role of 'omics-based approaches. *Keratin*. https://doi.org/10.5772/intechopen.77215

An, M., Feng, Y., Liu, Y., & Yang, H. (2023). External power-driven micro/nanorobots: Design, fabrication, and functionalization for tumor diagnosis and therapy. *Progress in Materials Science*, *140*,

101204. https://doi.org/10.1016/j.pmatsci.2023.101204

Baghban, R., Roshangar, L., Jahanban-Esfahlan, R., Seidi, K., Ebrahimi-Kalan, A., Jaymand, M., Kolahian, S., Javaheri, T., & Zare, P. (2020). Tumor microenvironment complexity and therapeutic implications at a glance. *Cell Communication and Signaling*, *18*(1). https://doi.org/10.1186/s12964-020-0530-4

Brook Chernet, M. L. (2014). Endogenous voltage potentials and the microenvironment: Bioelectric signals that reveal, induce and normalize cancer. *Journal of Clinical & Experimental Oncology*, *s1*(01). https://doi.org/10.4172/2324-9110.s1-002

Capuozzo, M., Santorsola, M., Ianniello, M., Ferrara, F., Zovi, A., Petrillo, N., Castiello, R., Fantuz, M., Ottaiano, A., & Savarese, G. (2024). Innovative drug modalities for the treatment of advanced prostate cancer. *Diseases*, *12*(5), 87. https://doi.org/10.3390/diseases12050087

Chen, Y., & Ping, Y. (2023). Development of CRISPR/Cas delivery systems for in vivo precision genome editing. *Accounts of Chemical Research*, *56*(16), 2185-2196. https://doi.org/10.1021/acs.accounts.3c00279

Cheng, Y., Zhang, H., Wei, H., & Yu, C. (2024). Injectable hydrogels as emerging drug-delivery platforms for tumor therapy. *Biomaterials Science*, *12*(5), 1151-1170. https://doi.org/10.1039/d3bm01840g

Chira, S., Nutu, A., Isacescu, E., Bica, C., Pop, L., Ciocan, C., & Berindan-Neagoe, I. (2022). Genome editing approaches with CRISPR/Cas9 for cancer treatment: Critical appraisal of preclinical and clinical utility, challenges, and future research. *Cells*, *11*(18), 2781. https://doi.org/10.3390/cells11182781

Costa, F. P., Wiedenmann, B., Schöll, E., & Tuszynski, J. (2024). Emerging cancer therapies: Targeting physiological networks and cellular bioelectrical differences with non-thermal systemic electromagnetic fields in the human body – a comprehensive review. *Frontiers in Network Physiology*, *4*. https://doi.org/10.3389/fnetp.2024.1483401

Debela, D. T., Muzazu, S. G., Heraro, K. D., Ndalama, M. T., Mesele, B. W., Haile, D. C., Kitui, S. K., & Manyazewal, T. (2021). New approaches and procedures for cancer treatment: Current perspectives. *SAGE Open Medicine*, *9*. https://doi.org/10.1177/20503121211034366

Farhana, A., Alsrhani, A., Khan, Y. S., & Rasheed, Z. (2023). Cancer Bioenergetics and tumor microenvironments—Enhancing chemotherapeutics and targeting resistant niches through Nanosystems. *Cancers*, *15*(15), 3836. https://doi.org/10.3390/cancers15153836

Fei, W., Zhang, Y., Ye, Y., Li, C., Yao, Y., Zhang, M., Li, F., & Zheng, C. (2020). Bioactive metal-containing nanomaterials for ferroptotic cancer therapy. *Journal of Materials Chemistry B*, *8*(46), 10461-10473. https://doi.org/10.1039/d0tb02138e

Gao, S., Yang, X., Xu, J., Qiu, N., & Zhai, G. (2021). Nanotechnology for boosting cancer immunotherapy and remodeling tumor microenvironment: The horizons in cancer treatment. *ACS Nano*, *15*(8), 12567-12603. https://doi.org/10.1021/acsnano.1c02103

Ge, Z., & Liu, S. (2013). Functional block copolymer assemblies responsive to tumor and intracellular microenvironments for site-specific drug delivery and enhanced imaging performance. *Chemical Society Reviews*, *42*(17), 7289. https://doi.org/10.1039/c3cs60048c

Grinin, L., Grinin, A., & Korotayev, A. (2024). Nanotechnologies, robotics, artificial intelligence and other MANBRIC technologies in the long-term development. *World-Systems Evolution and Global Futures*, 403-457. https://doi.org/10.1007/978-3-031-56764-3_10

Huang, Y., Yao, K., Zhang, Q., Huang, X., Chen, Z., Zhou, Y., & Yu, X. (2024). Bioelectronics for electrical stimulation: Materials, devices and biomedical applications. *Chemical Society Reviews*, *53*(17), 8632-8712. https://doi.org/10.1039/d4cs00413b

Innao, V., Allegra, A. G., Musolino, C., & Allegra, A. (2020). New frontiers about the role of human microbiota in immunotherapy: The immune checkpoint inhibitors and CAR T-cell therapy era. *International Journal of Molecular Sciences*, *21*(23), 8902. https://doi.org/10.3390/ijms21238902

Jakóbisiak, M., Lasek, W., & Gołąb, J. (2003). Natural mechanisms protecting against cancer. *Immunology Letters*, *90*(2-3), 103-122. https://doi.org/10.1016/j.imlet.2003.08.005

Jin, H., Wang, L., & Bernards, R. (2022). Rational combinations of targeted cancer therapies: Background, advances and challenges. *Nature*

Reviews Drug Discovery, *22*(3), 213-234. https://doi.org/10.1038/s41573-022-00615-z

Jung, L., Narayan, P., Sreenivasan, S. T., & Narayan, M. (2020). Untangling the potential of carbon quantum dots in neurodegenerative disease. *Processes*, *8*(5), 599. https://doi.org/10.3390/pr8050599

Kasegn, M. M., Gebremedhn, H. M., Yaekob, A. T., & Mesele, E. (2025). The power of deoxyribonucleic acid and bio-robotics in creating new global revolution: A review. *Health Nanotechnology*, *1*(1). https://doi.org/10.1186/s44301-024-00002-0

Kashani, G. K., Naghib, S. M., Soleymani, S., & Mozafari, M. (2024). A review of DNA nanoparticles-encapsulated drug/gene/protein for advanced controlled drug release: Current status and future perspective over emerging therapy approaches. *International Journal of Biological Macromolecules*, *268*, 131694. https://doi.org/10.1016/j.ijbiomac.2024.131694

Khafaga, A. F., Gaballa, M., Karam, R., Shoulah, S. A., Shamma, R. N., Khalifa, N. E., Farrag, N. E., & Noreldin, A. E. (2024). Synergistic therapeutic strategies and engineered nanoparticles for anti-vascular endothelial growth factor therapy in cancer. *Life Sciences*, *341*, 122499. https://doi.org/10.1016/j.lfs.2024.122499

Leone, R. D., & Powell, J. D. (2020). Metabolism of immune cells in cancer. *Nature Reviews Cancer*, *20*(9), 516-531. https://doi.org/10.1038/s41568-020-0273-y

Li, Y., Li, X., Wei, L., & Ye, J. (2024). Advancements in mitochondrial-targeted nanotherapeutics: Overcoming biological obstacles and optimizing drug delivery. *Frontiers in Immunology*, *15*. https://doi.org/10.3389/fimmu.2024.1451989

Li, Y., Zheng, X., & Chu, Q. (2021). Bio-based nanomaterials for cancer therapy. *Nano Today*, *38*, 101134. https://doi.org/10.1016/j.nantod.2021.101134

Liu, B., Zhou, H., Tan, L., Siu, K. T., & Guan, X. (2024). Exploring treatment options in cancer: Tumor treatment strategies. *Signal Transduction and Targeted Therapy*, *9*(1). https://doi.org/10.1038/s41392-024-01856-7

Ma, C., & Gurkan-Cavusoglu, E. (2024). A comprehensive review of computational cell cycle models in guiding cancer treatment strategies. *npj Systems Biology and Applications*, *10*(1). https://doi.org/10.1038/s41540-024-00397-7

Mazumdar, H., Khondakar, K. R., Das, S., Halder, A., & Kaushik, A. (2024). Artificial intelligence for personalized nanomedicine; from material selection to patient outcomes. *Expert Opinion on Drug Delivery*, *22*(1), 85-108. https://doi.org/10.1080/17425247.2024.2440618

Morganti, S., Tarantino, P., Ferraro, E., D'Amico, P., Duso, B. A., & Curigliano, G. (2019). Next generation sequencing (NGS): A revolutionary technology in Pharmacogenomics and personalized medicine in cancer. *Advances in Experimental Medicine and Biology*, 9-30. https://doi.org/10.1007/978-3-030-24100-1_2

Nguyet, N. T., Hai Yen, L. T., Van Thu, V., Lan, H., Trung, T., Vuong, P. H., & Tam, P. D. (2018). Highly sensitive DNA sensors based on cerium oxide nanorods. *Journal of Physics and Chemistry of Solids*, *115*, 18-25. https://doi.org/10.1016/j.jpcs.2017.11.023

Pei, Z., Lei, H., & Cheng, L. (2023). Bioactive inorganic nanomaterials for cancer theranostics. *Chemical Society Reviews*, *52*(6), 2031-2081. https://doi.org/10.1039/d2cs00352j

Pollock, J. F., & Healy, K. E. (2008). Biomimetic and bio-responsive materials in regenerative medicine: intelligent materials for healing living tissues. In *Strategies in regenerative medicine: Integrating biology with materials design* (pp. 1-58). New York, NY: Springer, New York.

Rainey, J., Vander Stoep, C., & Holley, M. (2024). Chronic kidney disease reversal: Case study. *Journal of Cardiovascular Medicine and Cardiology*, *11*(4), 068-079. https://doi.org/10.17352/2455-2976.000211

Ramezani, G., Stiharu, I., Van de Ven, T. G., & Nerguizian, V. (2023). Advancement in biosensor technologies of 2D MaterialIntegrated with cellulose—Physical properties. *Micromachines*, *15*(1), 82. https://doi.org/10.3390/mi15010082

Richard, P. U., Duskey, J. T., Stolarov, S., Spulber, M., & Palivan, C. G. (2015). New concepts to fight oxidative stress: Nanosized three-dimensional supramolecular antioxidant assemblies. *Expert Opinion on Drug Delivery*, *12*(9), 1527-1545. https://doi.org/10.1517/17425247.2015.1036738

Saminathan, A., Zajac, M., Anees, P., & Krishnan, Y. (2021). Organelle-level precision with next-

generation targeting technologies. *Nature Reviews Materials*, *7*(5), 355-371. https://doi.org/10.1038/s41578-021-00396-8

Shi, J., Sun, C., Liang, E., & Tian, B. (2021). Semiconductor nanowire-based cellular and subcellular interfaces. *Advanced Functional Materials*, *32*(11). https://doi.org/10.1002/adfm.202107997

Solaini, G., Baracca, A., Lenaz, G., & Sgarbi, G. (2010). Hypoxia and mitochondrial oxidative metabolism. *Biochimica et Biophysica Acta (BBA) - Bioenergetics*, *1797*(6-7), 1171-1177. https://doi.org/10.1016/j.bbabio.2010.02.011

Sun, B., Bte Rahmat, J. N., & Zhang, Y. (2022). Advanced techniques for performing photodynamic therapy in deep-seated tissues. *Biomaterials*, *291*, 121875. https://doi.org/10.1016/j.biomaterials.2022.121875

Sun, W., Luo, Z., Lee, J., Kim, H., Lee, K., Tebon, P., Feng, Y., Dokmeci, M. R., Sengupta, S., & Khademhosseini, A. (2019). Organ-on-a-Chip: Organ-on-a-Chip for cancer and immune organs modeling (Adv. Healthcare mater. 4/2019). *Advanced Healthcare Materials*, *8*(4). https://doi.org/10.1002/adhm.201970014

Thorat, N. D., Tofail, S. A., Von Rechenberg, B., Townley, H., Brennan, G., Silien, C., Yadav, H. M., Steffen, T., & Bauer, J. (2019). Physically stimulated nanotheranostics for next generation cancer therapy: Focus on magnetic and light stimulations. *Applied Physics Reviews*, *6*(4). https://doi.org/10.1063/1.5049467

Wang, J., Zhao, W., Zhang, Z., Liu, X., Xie, T., Wang, L., Xue, Y., & Zhang, Y. (2024). A journey of challenges and victories: A bibliometric worldview of Nanomedicine since the 21st century. *Advanced Materials*, *36*(15). https://doi.org/10.1002/adma.202308915

Wang, L., Liu, Y., Li, W., Jiang, X., Ji, Y., Wu, X., Xu, L., Qiu, Y., Zhao, K., Wei, T., Li, Y., Zhao, Y., & Chen, C. (2011). Selective targeting of gold Nanorods at the mitochondria of cancer cells: Implications for cancer therapy. *Nano Letters*, *11*(2), 772-780. https://doi.org/10.1021/nl103992v

Wang, R., Huang, Z., Xiao, Y., Huang, T., & Ming, J. (2023). Photothermal therapy of copper incorporated nanomaterials for biomedicine. *Biomaterials Research*, *27*(1). https://doi.org/10.1186/s40824-023-00461-z

Wang, X., Li, C., Wang, Y., Chen, H., Zhang, X., Luo, C., Zhou, W., Li, L., Teng, L., Yu, H., & Wang, J. (2022). Smart drug delivery systems for precise cancer therapy. *Acta Pharmaceutica Sinica B*, *12*(11), 4098-4121. https://doi.org/10.1016/j.apsb.2022.08.013

Wong, X. Y., Sena-Torralba, A., Álvarez-Diduk, R., Muthoosamy, K., & Merkoçi, A. (2020). Nanomaterials for Nanotheranostics: Tuning their properties according to disease needs. *ACS Nano*, *14*(3), 2585-2627. https://doi.org/10.1021/acsnano.9b08133

Wrześniewski, K., Weymann, I., Zaleski, K., Coy, E., Kempiński, M., Schönherr, H. P., ... & Tarapov, S. (2019). Quench dynamics of spin in magnetic impurity systems. https://mtpr.amu.edu.pl/former-seminars/

Wu, X., Li, Y., Wen, M., Xie, Y., Zeng, K., Liu, Y., Chen, W., & Zhao, Y. (2024). Nanocatalysts for modulating antitumor immunity: Fabrication, mechanisms and applications. *Chemical Society Reviews*, *53*(5), 2643-2692. https://doi.org/10.1039/d3cs00673e

Zang, X., Song, J., Li, Y., & Han, Y. (2022). Targeting necroptosis as an alternative strategy in tumor treatment: From drugs to nanoparticles. *Journal of Controlled Release*, *349*, 213-226. https://doi.org/10.1016/j.jconrel.2022.06.060