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Integrating Nanotheranostics, Omics, and Artificial Intelligence for Precision Multi-Organ Cancer Management: A Systematic Review

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Abstract:

Background: Cancer remains one of the leading global health challenges, characterized by profound heterogeneity at the genetic, molecular, and microenvironmental levels. Conventional therapies often fail due to late detection, therapeutic resistance, and systemic toxicity, underscoring the need for more precise and adaptable strategies.**Objective:** This systematic review synthesizes recent advances (2019–2024) in nanotheranostics, omics technologies, and artificial intelligence (AI), highlighting their convergence as a framework for precision multi-organ cancer management.**Methods:** Following PRISMA guidelines, a comprehensive literature search was conducted across PubMed, Scopus, Web of Science, ScienceDirect, and PMC. Eligible studies included original research on nanotheranostic platforms, omics-driven biomarker discovery, and AI-based oncology applications. Data were extracted on study design, cancer type, nanoplatform features, omics datasets, AI/ML models, and translational outcomes.**Results:** Nanotheranostics have advanced from multifunctional nanoparticles (e.g., gold nanoparticles, liposomes, polymeric systems) toward smart, stimuli-responsive platforms guided by AI and omics data. Omics approaches including genomics, transcriptomics, proteomics, metabolomics, and radiomics enable biomarker discovery, patient stratification, and target identification, while AI enhances nanoparticle design, predictive modeling, and real-time treatment adaptation. Applications span multiple cancers, including liver, breast, lung, pancreatic, and brain tumors. Challenges remain in overcoming tumor microenvironment heterogeneity, organ-specific barriers, biosafety concerns, and clinical translation, though early clinical studies report promising outcomes.

Keywords: Nanotheranostics, Omics, Artificial Intelligence, Multi-organ cancer, Precision oncology, Biomarker discovery, personalized therapy

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1. Introduction

Cancer is not a single disease but a complex and heterogeneous group of disorders, with variations at the genetic, epigenetic, and microenvironmental levels that influence progression and therapeutic response (Frontiersin). This diversity across organ systems such as liver, lung, breast, pancreatic, and brain cancers necessitates multimodal treatment strategies that combine surgery, chemotherapy, radiotherapy, targeted therapy, and immunotherapy to overcome therapeutic resistance and improve patient survival [1]. Nanotheranostics refers to multifunctional nanosystems engineered to integrate diagnostic imaging and targeted therapy in a single platform, thereby enabling precision oncology (PMC, NCBI). Omics sciences including genomics, transcriptomics, proteomics, and metabolomics generate high-dimensional datasets that uncover cancer-specific biomarkers and therapeutic targets. Artificial intelligence (AI), through machine learning and deep learning algorithms, provides the computational power to analyze these complex datasets, detect hidden patterns, and guide clinical decision-making in oncology.The convergence of omics-driven biomarker discovery, AI-based predictive modeling, and nanotheranostics holds immense potential for managing multi-organ cancers (ScienceDirect) [2]. By combining real-time molecular profiling with adaptive therapeutic delivery, clinicians can achieve early detection, patient stratification, and individualized treatment optimization. Such integrative frameworks not only enhance therapeutic efficacy but also minimize off-target toxicity, thereby laying the foundation for a new era of precision and personalized oncology. (Figure 1)

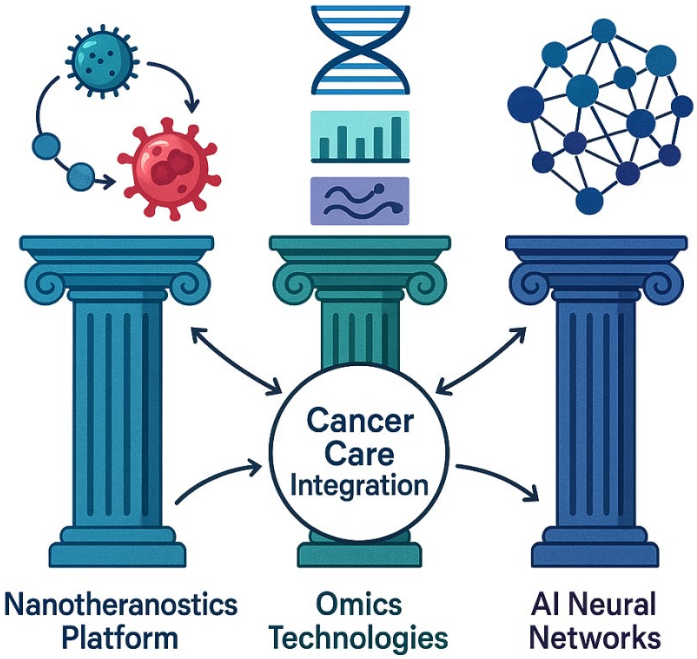

Figure 1: Conceptual diagram showing the integration of nanotheranostics, omics technologies, and AI in cancer care

2. Methodology

2.1 Systematic Review Design Criteria

This systematic review was conducted according to PRISMA guidelines, focusing on publications between January 2019 and December 2024 to capture the most recent advances in nanotheranostics, omics technologies, and artificial intelligence (AI) for cancer management (ScienceDirect). Studies were eligible if they reported original data or systematic analyses related to the integration of at least one of the following: nanotheranostics, omics-based biomarker discovery, or AI-driven oncology applications. Review articles, commentaries, conference abstracts, and non-English publications were excluded.

2.2 Literature Search Strategy

A comprehensive literature search was performed across multiple databases, including PubMed, Scopus, Web of Science, ScienceDirect, and PMC (NCBI)**.** Search terms combined controlled vocabulary (MeSH) and free-text keywords such as nanotheranostics, multi-organ cancer, omics, artificial intelligence, machine learning in oncology,*and* precision oncology. Boolean operators (AND, OR) and filters (publication year, language) were applied to refine results. Additional studies were identified through citation tracking and reference list screening.

2.3 Data Extraction and Synthesis Methods

Two independent reviewers extracted relevant data, including study design, cancer type, nanotheranostic platform, omics datasets analyzed, AI/ML models employed, and key clinical/therapeutic outcomes. Discrepancies were resolved through discussion with a third reviewer. Data synthesis was performed narratively and, where possible, quantitatively through meta-analysis. Findings were organized thematically across cancer types and methodological approaches to highlight trends, gaps, and translational potential.

3.Omics in Cancer Nanotheranostics

The advent of high-throughput technologies has introduced a diverse set of omics approaches that play crucial roles in cancer nanotheranostics (ScienceDirect). Genomics identifies somatic mutations and copy number variations that define cancer subtypes. Transcriptomics profiles gene expression signatures associated with tumor progression and drug resistance. Proteomics deciphers protein-level alterations, signaling cascades, and post-translational modifications, while metabolomics maps metabolic reprogramming as a hallmark of malignancy. More recently, radiomics has emerged as a non-invasive computational tool that extracts quantitative imaging features linked to molecular phenotypes, thereby bridging diagnostic imaging with omics-informed therapies [3].

Omics datasets provide the foundation for biomarker discovery, enabling identification of cancer-specific molecular signatures that can be leveraged for nanotheranostic targeting

(ExplorationPub). These biomarkers inform patient stratification, ensuring that individuals are matched to therapeutic strategies most likely to yield favorable outcomes. Furthermore, omics-driven analyses uncover drug targets and resistance pathways, guiding the design of nanosystems that deliver therapeutic payloads directly to malignant cells while sparing healthy tissues [4].

The true potential of omics lies in multi-omics integration, where genomic, transcriptomic, proteomic, metabolomic, and radiomic data are combined to construct a holistic molecular landscape of cancer. Advanced computational approaches and AI models synthesize these layers of information to predict disease trajectory, optimize nanoparticle functionalization, and tailor therapy at the individual patient level. This integration represents a cornerstone for personalized nanotheranostics, moving beyond one-size-fits-all treatments toward precision oncology [5]. (Figure 2)

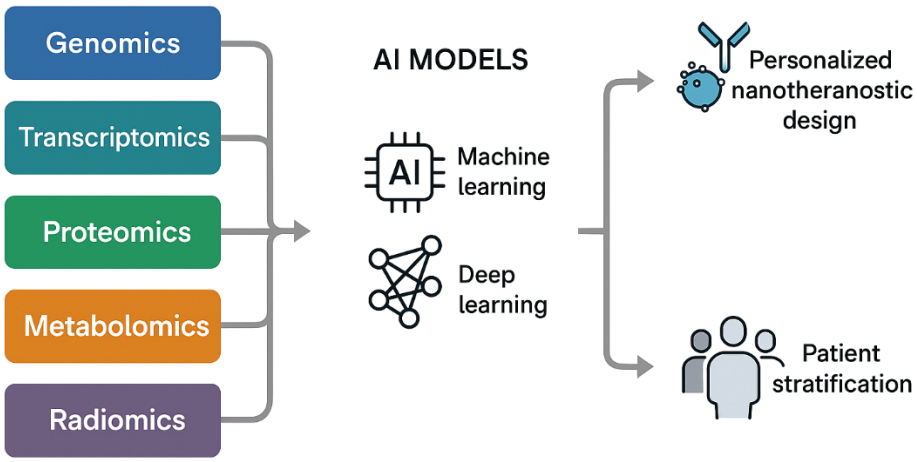

Figure 2: Conceptual diagram of multi-omics integration pipeline feeding into AI models for personalized nanotheranostics

4.Artificial Intelligence Applications

Artificial intelligence has emerged as a transformative tool in the design and optimization of nanoparticles, enabling more efficient drug delivery, surface modification, and tumor-targeting strategies (PMC, NCBI) [6]. By simulating nanoparticle–biological interactions, AI algorithms can predict circulation stability, biodistribution, and cellular uptake. This accelerates the development of nanotheranostic systems with enhanced therapeutic efficacy and reduced systemic toxicity.Machine learning (ML) and deep learning (DL) approaches are increasingly employed for predictive modeling in oncology. These methods analyze large-scale patient datasets to forecast disease progression, therapy response, and resistance mechanisms (PMC, NCBI) [7]. Such predictive power enables treatment personalization, where nanoparticle-based interventions can be adapted to the unique molecular and clinical profiles of individual patients

[8].The integration of AI with omics datasets and medical imaging provides unprecedented opportunities for early diagnosis and therapy optimization**.** DL algorithms can extract subtle imaging features invisible to the human eye, while ML pipelines process complex multi-omics datasets to reveal actionable biomarkers. Together, these approaches enhance the precision of nanotheranostics, ensuring that both diagnostic imaging and therapeutic delivery are fine-tuned to patient-specific needs [9].

5. Nanotheranostics Platforms and Strategies

Nanotheranostics are centered on multifunctional nanoparticles that simultaneously perform diagnostic imaging and therapeutic delivery within a single platform (PMC, NCBI). Such dual-capability systems enable real-time monitoring of drug distribution and therapeutic response, minimizing systemic toxicity while improving treatment precision [10]. For example, nanoparticles functionalized with contrast agents (e.g., MRI or fluorescence probes) allow clinicians to visualize tumor localization while concurrently releasing chemotherapeutic or gene-silencing payloads.The next generation of nanotheranostics leverages AI algorithms and omics-derived biomarkers to engineer smart nanoparticle systems (Nature) [11]. These platforms are responsive to specific physiological stimuli such as pH, redox gradients, or enzyme activity and are further optimized through AI-assisted modeling. By integrating omics datasets, smart nanoparticles can be tailored to patient-specific tumor signatures, ensuring personalized and adaptive therapy [12]**.**

Several nanomaterials have already demonstrated clinical and preclinical utility as nanotheranostic agents (Wiley Online Library). Gold nanoparticles offer surface plasmon resonance properties for imaging and photothermal therapy [13]. Liposomes are biocompatible carriers capable of encapsulating both imaging probes and drugs. Polymeric nanoparticles provide tunable size, charge, and degradability for controlled drug release. Collectively, these platforms exemplify the diverse strategies available for constructing effective nanotheranostic systems [14].

6. Multi-Organ Cancer Management

The integration of nanotheranostics and AI-driven analytics has shown promising applications in multiple organ-specific cancers (PMC, NCBI). In liver cancer, nanoparticles functionalized with targeting ligands improve drug accumulation in cirrhotic and vascularized tissues. Breast cancer applications include receptor-guided nanocarriers for HER2-positive subtypes and AI-assisted prediction of therapy resistance in triple-negative breast cancer [15]. For lung cancer**,** nanotheranostic systems enhance the precision of imaging-guided interventions, while AI models stratify patients for immunotherapy responsiveness. In pancreatic cancer, AI-guided nanoparticle design is being explored to penetrate the dense stromal barrier and improve drug delivery.Despite advances, several biological and physiological barriers hinder widespread application. The tumor microenvironment (TME) exhibits significant heterogeneity in vascularization, hypoxia, stromal density, and immune infiltration (Frontiersin) [16]. These variations influence nanoparticle penetration and therapeutic efficacy. Additionally, organ-

specific barriers such as the blood–brain barrier (BBB) in glioblastoma**,** pulmonary clearance in lung cancer, and fibrotic stroma in pancreatic tumors present unique challenges that necessitate highly adaptive nanotheranostic designs [17].

Recent translational research and early-phase clinical trials highlight the potential of nanotheranostics in multi-organ cancer management. Gold nanoparticle-based systems have entered clinical evaluation for photothermal therapy in head and neck cancers. Liposomal formulations with imaging probes are being tested in metastatic breast cancer to monitor treatment response in real-time [18]. Moreover, AI-assisted radiomic analyses are now being incorporated into multi-center studies to improve patient stratification and therapy personalization across organ-specific cancers. Collectively, these success stories underscore the feasibility of applying nanotheranostics and AI in diverse clinical contexts, moving the field closer to precision multi-organ oncology [19].

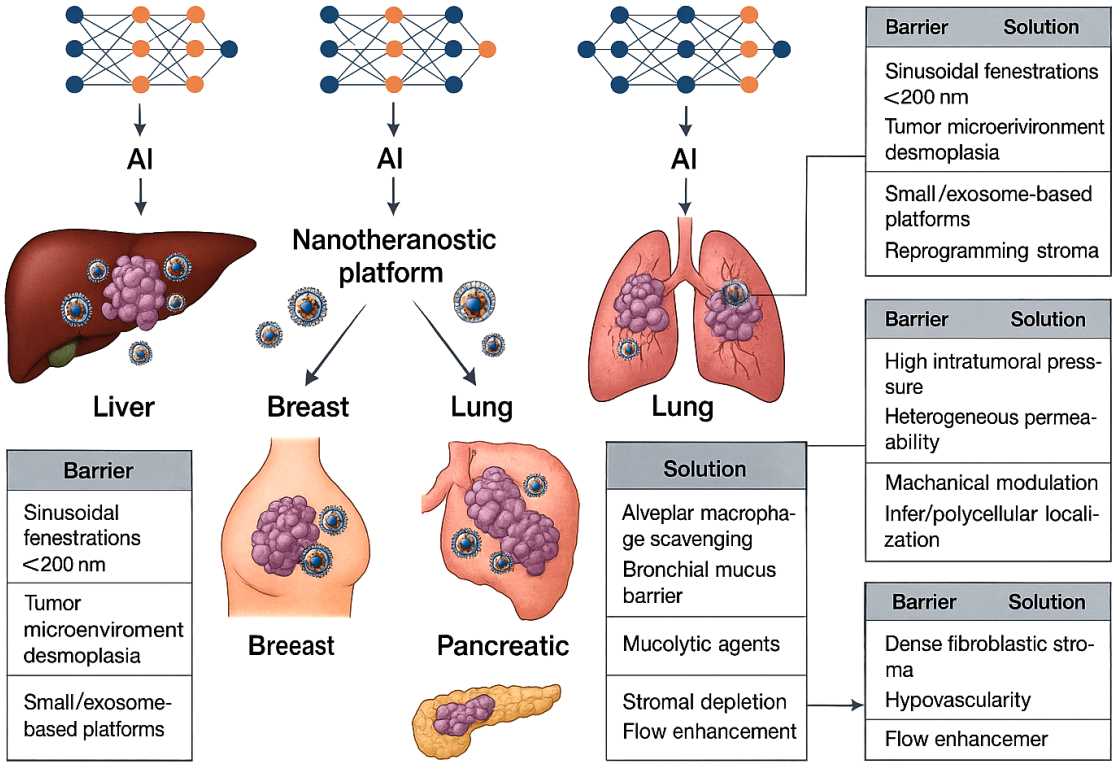

Figure 3: Schematic showing multi-organ applications of nanotheranostics and AIhighlighting liver, breast, lung, and pancreatic cancers with barriers

7. Safety, Monitoring, and Adaptive Protocols

Ensuring the biosafety of nanotheranostic systems is a central prerequisite for clinical translation. Key concerns include toxicity, long-term accumulation, and immunogenicity, which can vary depending on nanoparticle composition, size, and surface chemistry (PMC,

NCBI) [20]. Artificial intelligence (AI) models are increasingly applied to predict nanoparticle–host interactions by integrating data from preclinical studies, in silico simulations, and omics-driven toxicology datasets. These predictive frameworks accelerate safety evaluation and reduce reliance on prolonged in vivo testing [21].Traditional pharmacokinetic studies are insufficient for mapping the complex spatiotemporal dynamics of nanoparticles in the human body. AI-integrated monitoring platforms now enable real-time tracking of nanoparticle distribution, clearance, and tumor accumulation through multimodal imaging technologies (e.g., MRI, PET, fluorescence). By processing large imaging datasets, AI enhances sensitivity and precision in detecting subtle biodistribution patterns, thereby improving both diagnostic accuracy and therapeutic safety [22].

The future of nanotheranostics lies in adaptive treatment protocols guided by multimodal data integration (PMC, NCBI). Combining omics-derived biomarkers, imaging signals, and patient clinical data, AI-powered clinical decision support systems dynamically adjust therapy regimens in response to evolving tumor behavior. This approach ensures that nanotheranostic interventions remain personalized, minimizing off-target effects while maximizing therapeutic outcomes [23].

8. Limitations and Future Directions

Despite significant preclinical advances, the translation of nanotheranostics into clinical oncology remains limited. Barriers include the lack of standardized protocols for nanoparticle synthesis and characterization, insufficient long-term biosafety data, and variability in tumor microenvironment responses across patients. Furthermore, regulatory hurdles and the high cost of scaling nanotheranostic platforms hinder widespread adoption [24]. Most studies remain confined to in vitro or small animal models, with only a few progressing into early-phase clinical trials.To bridge these gaps, there is a strong need to integrate omics-driven biomarker discovery, AI-powered analytics, and advanced nanotheranostic platforms. Omics data should guide patient stratification, while AI can optimize nanoparticle design and predict therapeutic outcomes. Collaborative frameworks involving bioinformaticians, nanotechnologists, oncologists, and regulatory agencies are essential to accelerate clinical readiness [25]. Furthermore, developing open-access multi-omics databases will enhance reproducibility and global collaboration.Looking ahead, the convergence of nanotheranostics, omics, and AI will pave the way for personalized, multi-organ cancer theranostics. Adaptive treatment protocols, driven by continuous real-time monitoring and multimodal data integration, will allow therapies to evolve alongside tumor dynamics. The long-term vision is a clinically deployable ecosystem where diagnostic imaging, molecular profiling, and nanoparticle-mediated therapy are seamlessly integrated, offering a patient-specific, organ-spanning approach to cancer care [26].

9. Conclusion

This review highlights the transformative role of nanotheranostics when integrated with omics technologies and artificial intelligence in advancing precision oncology. By bridging diagnostic imaging with targeted therapy, nanotheranostic platforms offer unprecedented opportunities for real-time monitoring and patient-specific treatment. Omics-driven biomarker discovery and patient stratification, coupled with AI-based predictive modeling and clinical decision support, strengthen the capacity to address cancer heterogeneity across multiple organ systems. While challenges such as biosafety, tumor microenvironment complexity, and translational gaps remain, emerging clinical studies demonstrate the feasibility of these approaches in real-world oncology. Looking forward, the convergence of nanotechnology, omics sciences, and AI promises a paradigm shift toward adaptive, personalized, and multi-organ cancer management, paving the way for safer, more effective, and sustainable therapeutic strategies.

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