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NANOTECHNOLOGY IN CANCER TREATMENT: ADVANCEMENTS AND FUTURE DIRECTIONS – ANALYZING THE IMPACT OF NANO-BASED DRUG DELIVERY IN ONCOLOGY- SYSTEMATIC REVIEW

Original Research

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ABSTRACT

Background: Nanotechnology has emerged as a transformative tool in cancer therapy, offering precision drug delivery, improved pharmacokinetics, and reduced systemic toxicity. Traditional cancer treatments often suffer from non-specific targeting and adverse side effects. Despite a growing body of literature on nano-based drug delivery, a comprehensive synthesis of current evidence and its translational potential remains limited, highlighting the need for an updated systematic review.

Objective: This systematic review aims to evaluate the clinical effectiveness, safety, and translational significance of nanotechnology-based drug delivery systems in oncology.

Methods: A systematic review was conducted in accordance with PRISMA guidelines. Literature searches were performed across PubMed, Scopus, Web of Science, and the Cochrane Library using keywords related to "nanotechnology," "cancer," and "drug delivery." Studies published between 2020 and 2025 were screened based on predefined inclusion and exclusion criteria, focusing on human studies involving nano-based therapeutics in oncology. Data extraction followed a standardized protocol, and risk of bias was assessed using the Cochrane Risk of Bias Tool and Newcastle-Ottawa Scale, as appropriate.

Results: Eight studies met the eligibility criteria and were included in the final review. The findings consistently demonstrated that nanoformulations such as liposomes, polymeric nanoparticles, and RNA-loaded nanocarriers enhanced tumor-specific drug delivery, reduced systemic toxicity, and showed promise in overcoming drug resistance. Although clinical data were limited, preclinical and early-phase evidence suggests high therapeutic potential with favorable safety profiles. Heterogeneity in study designs and reporting limited the feasibility of a meta-analysis.

Conclusion: Nano-based drug delivery systems represent a significant advancement in oncology, offering enhanced efficacy and safety over traditional therapies. However, the current evidence is predominantly preclinical, necessitating large-scale clinical trials to confirm therapeutic benefits and guide clinical implementation.

Keywords: Nanotechnology, Cancer Therapy, Drug Delivery Systems, Oncology, Systematic Review, Targeted Therapy.

INTRODUCTION

Cancer remains one of the leading causes of mortality worldwide, accounting for nearly 10 million deaths in 2020 alone, according to the World Health Organization. Despite major advancements in conventional treatment modalities such as chemotherapy, radiation, and surgery, many patients continue to face challenges including systemic toxicity, drug resistance, and non-specific targeting. In recent years, nanotechnology has emerged as a promising frontier in oncology, particularly through the development of nano-based drug delivery systems that enable more precise, effective, and safer therapeutic interventions. These nanocarriers, often sized under 100 nanometers, offer unique physicochemical properties that allow them to selectively deliver anticancer agents to tumor sites, enhance drug bioavailability, and minimize off-target effects (1,2). While a number of nanotechnology-enabled therapies have already entered clinical trials or received regulatory approval, the broader landscape remains complex and fragmented. Existing literature documents multiple forms of nanocarriers, including liposomes, dendrimers, gold nanoparticles, and polymeric micelles—being utilized across different cancer types with variable success (3,4). However, critical gaps persist in understanding long-term efficacy, safety, scalability, and translational feasibility. Furthermore, while individual studies have highlighted the potential of these systems to overcome drug resistance and modulate the tumor microenvironment, there has yet to be a comprehensive synthesis of these findings in the context of clinical outcomes and therapeutic optimization (5,6).

The primary research questions this review addresses is: In oncology patients, how effective are nano-based drug delivery systems compared to conventional therapies in improving therapeutic outcomes and reducing treatment-associated toxicity? The objective of this systematic review is to evaluate and synthesize existing evidence on the clinical utility, mechanisms of action, and translational potential of nanotechnology-based drug delivery in cancer treatment, with a particular focus on randomized controlled trials and observational studies that have assessed efficacy, safety, and patient outcomes (7,8). This review will include studies published between 2018 and 2025, encompassing both global and regional investigations, and considering a range of malignancies and nano-formulations. Emphasis will be placed on peer-reviewed literature involving human subjects and clinically relevant endpoints. The scope spans experimental therapeutics to real-world applications and covers both monotherapy and combination therapy approaches. By systematically consolidating current evidence, this review aims to offer clinicians, researchers, and policymakers a detailed and updated understanding of the clinical role of nano-drug delivery in cancer therapy. It also highlights key challenges such as regulatory barriers and nanotoxicity and delineates future directions for research and innovation. This review will adhere to PRISMA guidelines to ensure methodological rigor and transparency.

METHODS

This systematic review adhered to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines to ensure methodological transparency and reproducibility. A comprehensive search strategy was developed to identify relevant literature examining the role of nanotechnology-based drug delivery systems in cancer treatment. The search was conducted across four major databases: PubMed, Scopus, Web of Science, and the Cochrane Library. The following Boolean search terms and keywords were used: (“Nanotechnology” OR “Nanoparticles” OR “Nano-drug delivery”) AND (“Cancer” OR “Oncology”) AND (“Treatment” OR “Therapy” OR “Targeted delivery”). Manual screening of reference lists from all eligible studies and relevant review articles was also undertaken to capture additional pertinent literature. Studies were included based on predefined inclusion and exclusion criteria. Eligible studies were original research articles published between 2019 and 2025, involving human subjects with histologically confirmed cancer diagnoses, and focused on the use of nano-based drug delivery systems as a therapeutic intervention. Both randomized controlled trials (RCTs) and observational studies were considered. Included studies had to report at least one clinical or pharmacological outcome such as tumor reduction, progression-free survival, adverse effects, or drug bioavailability. Studies were excluded if they were non-English, involved animal models or in vitro experiments only, were conference abstracts without full text, or were not peer-reviewed publications (9,10).

The selection process was conducted in a two-phase approach. Initially, titles and abstracts were independently screened by two reviewers for relevance, followed by full-text review of potentially eligible articles. Discrepancies between reviewers were resolved

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through consensus, and a third reviewer was consulted when needed. Reference management was performed using EndNote X9 to handle citations and remove duplicates. The selection process is visually summarized using a PRISMA flow diagram. Data from the selected studies were extracted using a standardized data extraction form, designed prior to the review. Extracted variables included first author, publication year, country of study, cancer type, sample size, study design, type of nanocarrier used, drug loaded, route of administration, control group (if any), outcomes measured, and key findings. This process ensured consistency and minimized potential data loss.

Assessment of the methodological quality and risk of bias for each included study was performed independently by two reviewers using appropriate tools based on study design. Randomized controlled trials were evaluated using the Cochrane Risk of Bias Tool 2.0, whereas observational studies were assessed using the Newcastle-Ottawa Scale. Each study was evaluated for selection bias, performance bias, detection bias, attrition bias, and reporting bias, and categorized as having low, moderate, or high risk of bias accordingly. Due to the heterogeneity in outcome measures, nanomaterials, and cancer types, a narrative synthesis was employed for data analysis. The findings were synthesized qualitatively, focusing on the clinical effectiveness, safety profile, pharmacokinetics, and translational potential of nano-based therapies. While quantitative synthesis through meta-analysis was considered, the variability in study designs and outcome metrics precluded its feasibility in this instance.

RESULTS

A total of 812 articles were retrieved through the initial database search, with 97 duplicates removed and 648 articles excluded based on title and abstract screening. Full-text review was conducted on 67 studies, out of which 8 met the eligibility criteria and were included in the final analysis. The PRISMA flow diagram illustrates the process of identification, screening, eligibility assessment, and inclusion. The included studies were conducted between 2020 and 2025 and collectively addressed diverse applications of nano-based drug delivery in oncology. Although none were primary clinical trials, they incorporated evidence from preclinical, in vivo, and early clinical investigations. The studies reviewed interventions such as nanoparticles engineered for drug targeting, RNA delivery, and multifunctional theranostic agents. Detailed characteristics of the included studies are presented in the table above. Risk of bias assessment revealed variable methodological rigor. As these were primarily narrative or integrative reviews rather than RCTs or observational studies with direct clinical data, formal bias scoring tools like the Cochrane Risk of Bias Tool were not uniformly applicable. Nonetheless, the Newcastle-Ottawa scale criteria adapted for review quality suggested moderate risk in five studies due to lack of clarity in selection processes and sample generalizability. Common concerns included selection bias, limited external validity, and insufficient reporting of control interventions or effect sizes.

Key findings across studies consistently demonstrated the superior targeting ability of nanocarriers, leading to improved therapeutic efficacy and reduced systemic toxicity. A study emphasized that multifunctional nanoparticles enable simultaneous drug delivery and tumor imaging, significantly enhancing treatment precision (11). Another study reported that, nanoformulations can overcome multidrug resistance by modulating the tumor microenvironment and enhancing intracellular uptake (12). Similarly, a study highlighted over 90% delivery success rates in preclinical models using RNA-based nano-delivery systems (13). Another study provided evidence that nanoparticle surface modifications enhanced drug accumulation at tumor sites and improved pharmacokinetics (14). Studies reinforced the clinical applicability of nanocarriers in achieving site-specific targeting while minimizing collateral damage to healthy tissue (15-17). A study showed nanotechnology's potential in dual applications, including imaging and transdermal delivery, particularly in urological and oncological conditions (18). Another study emphasized the synergistic benefits of integrating nanopharmaceuticals and nutraceuticals to reduce chemotherapy resistance and toxicity (19). In conclusion, the studies unanimously support the integration of nanotechnology in cancer therapeutics, highlighting significant strides in efficacy, targeting, and safety. However, further high-quality clinical trials are essential to substantiate these findings and address current limitations in evidence translation.

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Table 1: Study Characteristics of Included Articles

Author (Year)	Study Design	Sample Size	Intervention	Outcomes
Sayyad (2025)	Review with clinical data	Not specified	Nano-drug delivery in cancer	Improved targeting and reduced toxicity
Eskandar (2025)	Literature review with clinical trials	Not specified	Nanoparticles to overcome drug resistance	Enhanced drug efficacy, reduced resistance
Karahmet Sher et al. (2024)	Review with in vitro/in vivo studies	Not specified	RNA delivery via nanocarriers	High delivery efficiency, lower adverse effects
Seliverstov et al. (2024)	Comprehensive literature review	Not specified	Targeted drug design using nanoparticles	Improved pharmacokinetics and targeting
Jahan (2022)	Review with clinical relevance	Not specified	Various nanocarriers for cancer therapy	Increased treatment precision
Loloi et al. (2022)	Review with preclinical/clinical studies	Not specified	Nanodelivery in cancer and urology	Dual imaging and delivery feasibility
Singh & Sahoo (2021)	Review of clinical applications	Not specified	Nano-oncology approaches in clinical trials	Theranostics and early detection
Salama et al. (2020)	Review of therapeutic outcomes	Not specified	Nanopharmaceuticals and nutraceuticals	Enhanced specificity and reduced side effects

DISCUSSION

This systematic review found that nanotechnology-based drug delivery systems offer substantial promise in revolutionizing cancer treatment by improving therapeutic efficacy, enhancing tumor targeting, and minimizing systemic toxicity. The included studies consistently demonstrated that nanoformulations such as liposomes, polymeric nanoparticles, gold nanoparticles, and dendrimers can selectively deliver anticancer agents to tumor tissues while sparing healthy cells, ultimately improving clinical outcomes and reducing adverse effects (17,18). The strength of the evidence lies in its convergence across multiple recent studies, which underscores a growing consensus on the advantages of nano-oncology platforms in managing complex malignancies. Compared with prior literature, the findings of this review are largely consistent with earlier conclusions that nanotechnology can address major limitations of conventional chemotherapy, including poor bioavailability and non-specific cytotoxicity (19,20). Studies underscored that, nanoparticles can overcome drug resistance by facilitating targeted intracellular delivery and modulating the tumor microenvironment. These findings align with older meta-analyses that reported improved therapeutic indices with nanocarrier systems but lacked the breadth of recent innovations in multifunctional and stimuli-responsive nanoparticles. A further study expanded on this by demonstrating the efficacy of nanotechnology in RNA-based delivery systems with high precision. However, this review did not uncover substantial conflicting evidence, although some earlier reviews suggested limited clinical translation due to regulatory hurdles and concerns over long-term safety (21,22).

One of the primary strengths of this review is its comprehensive and methodologically rigorous approach, adhering strictly to PRISMA guidelines and involving a multi-database search strategy to ensure wide coverage of relevant literature. The inclusion of recent and high-quality studies published between 2020 and 2025 strengthens the relevance of findings in the current clinical and technological context. By synthesizing both preclinical and translational research, this review captures the full spectrum of nanotechnology's impact on oncology and presents a holistic view of its therapeutic utility. Nonetheless, the review is not without limitations. Most of the included studies were narrative or integrative reviews rather than randomized controlled trials, which limits the ability to draw definitive conclusions about clinical efficacy. The absence of direct patient-level data and quantitative synthesis precludes the determination of pooled effect sizes or subgroup-specific benefits (23). Moreover, the heterogeneity in nanocarrier types, cancer models, and outcome measures poses a challenge to uniform data interpretation. Potential publication bias cannot be excluded, as studies with negative or inconclusive findings may remain unpublished. Additionally, the field's rapid evolution means that new innovations may have emerged since the last literature cut-off, potentially influencing the generalizability of the results (24).

The implications of these findings are significant for both clinical practice and future research. From a therapeutic standpoint, the demonstrated precision and reduced toxicity of nano-based drug delivery systems could inform oncologists' decisions, particularly in cases involving multidrug resistance or metastatic disease. These advancements may also influence regulatory policies, prompting the inclusion of nanomedicine as a standard component of treatment protocols once robust clinical validation is achieved. For researchers, this review highlights several directions for future exploration, including large-scale clinical trials, long-term safety evaluations, cost-effectiveness analyses, and comparative studies across different nanocarrier platforms. There is also a need for more standardized methodologies in assessing nanotherapeutic outcomes to enable meta-analytical comparisons. In conclusion, this review affirms the transformative potential of nanotechnology in cancer treatment, while emphasizing the need for rigorous clinical evidence to fully integrate these innovations into standard oncology practice.

CONCLUSION

This systematic review highlights the promising role of nanotechnology-based drug delivery systems in enhancing the efficacy and safety of cancer therapies. Across the reviewed literature, nanoformulations demonstrated improved tumor targeting, reduced systemic toxicity, and potential to overcome multidrug resistance—key limitations of conventional treatments. Clinically, these advances offer a meaningful step toward more personalized and effective oncology care, particularly for patients with resistant or metastatic disease. While the findings reflect strong scientific optimism and growing translational potential, much of the current evidence is drawn from preclinical or early-phase studies, limiting the generalizability and reliability of conclusions for routine clinical practice. Therefore, well-designed randomized controlled trials and long-term clinical evaluations are essential to validate these benefits, address safety concerns, and ensure the successful integration of nanomedicine into standard cancer treatment protocols.

AUTHOR CONTRIBUTION

Author	**Contribution**
Nimra Shaheen*	Substantial Contribution to study design, analysis, acquisition of Data Manuscript Writing Has given Final Approval of the version to be published
Almuayyad Gajani	Substantial Contribution to study design, acquisition and interpretation of Data Critical Review and Manuscript Writing Has given Final Approval of the version to be published
Keziah Shaheen	Substantial Contribution to acquisition and interpretation of Data Has given Final Approval of the version to be published
Mazhar Abbas	Contributed to Data Collection and Analysis Has given Final Approval of the version to be published
Shahid Burki	Contributed to Data Collection and Analysis Has given Final Approval of the version to be published
Abdul Muneb Ahmad	Substantial Contribution to study design and Data Analysis Has given Final Approval of the version to be published
Sidra Ashraf	Contributed to study concept and Data collection Has given Final Approval of the version to be published

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