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Emerging Nanostrategies to Combat Antibiotic-Resistant Urinary Tract Infections: A Review

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Abstract

Existing preclinical and clinical evidence for nanotechnology-based therapies in the treatment of antibiotic-resistant urinary tract infections (UTIs) is reviewed in this narrative study. Antibiotic-resistant UTIs represent a growing global health concern, necessitating the development of new therapeutic approaches. This review examines the application of nanotechnology against antibiotic-resistant UTIs and the capability of nanocarrier systems to improve drug delivery, target bacterial cells, and block biofilms. Different nanocarriers, including liposomes, silver nanoparticles (AgNPs), and gold nanoparticles (AuNPs), have been investigated for their distinctive properties that improve treatment efficacy. This review also discusses the mechanisms of action of these nanostrategies, including targeted drug delivery and enhanced penetration of antimicrobial agents. Safety considerations, including cytotoxicity and genotoxicity, as well as strategies to minimize side effects, are evaluated. Future research should focus on refining these technologies to overcome antibiotic resistance, ensuring safer and more effective clinical applications in UTI management.

Keywords: nanotechnology, antibiotic resistance, urinary tract infections, nanocarriers, drug delivery

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INTRODUCTION

Urinary tract infections (UTIs) are among the most prevalent bacterial infections, affecting millions worldwide. Studies show that around 70% of women will experience at least one UTI in their lifetime, and of these, approximately 30% will experience recurrent UTIs (rUTIs). Men and children are also predisposed to these infections, especially in cases involving urinary tract abnormalities or other medical conditions (1–4).

Antibiotics are the first choice for treating bacterial infections, including UTIs. The misuse and overuse of antimicrobials are the leading causes of antibiotic resistance, making it one of the top global threats to public health. Antibiotic resistance occurs when bacteria change and no longer respond effectively to medicines used to treat them. As a result of drug resistance, antibiotics become ineffective, bacterial infections become difficult to cure, and the risk of disease transmission and death increases. Antibiotic resistance in UTIs is of particular interest due to its frequent occurrence and its direct impact on treatment effectiveness. In light of the growing trend of antimicrobial resistance (AMR) in UTIs, the need for new, more effective clinical strategies for managing these infections is emphasized (4-6).

Nanotechnology, whose basic unit is the nanoparticle (NP), can play a significant role in the fight against infectious diseases and resistant pathogens. Their small size and specific electrical, magnetic, and binding properties can allow them to overcome common resistance mechanisms, including enzyme inactivation, reduced cell permeability, modification of target sites or enzymes, and increased efflux through overexpression of efflux pumps. Nanotechnology is becoming one of the most sought-after strategies for diagnosing, treating, and preventing UTIs due to its role in drug delivery and diagnostics (6–7).

Before reviewing the role of nanotechnology in UTI treatment, it is essential to discuss UTI pathophysiology and antibiotic resistance mechanisms. This section reviews major pathogens, their resistance patterns, and the course of the disease to establish a framework for evaluating new therapeutic options. Discussing these mechanisms will focus on how nanotechnology can enhance the treatment of UTIs, the advantages and limitations of such approaches, and their potential for clinical applications. It also explores the latest advancements in nanotechnology as a potential solution to antibiotic-resistant UTIs, offering a forward-looking perspective for future research avenues.

Unlike previous reviews that primarily summarized individual NP types, the present article integrates a comparative examination of liposomes, nanoemulsions, metal NPs, and polymeric nanocarriers, addressing their translational barriers, regulatory aspects, and safety evaluation.

This integrative approach highlights both the current clinical availability and the future

potential of nanotechnology in the treatment of resistant UTIs.

METHODS

The present review adopted a narrative approach, with structured elements to enable extensive coverage. A literature search was conducted in the PubMed, Scopus, ScienceDirect, and Google Scholar databases between January 2013 and June 2025. Search terms included "nanotechnology," "nanoparticles," "nanocarriers," "nanomedicine," "urinary tract infection," "antimicrobial resistance," "biofilm," and their respective combinations. The inclusion criteria were English-language, peer-reviewed articles that reported nanotechnology-based therapeutic or diagnostic strategies against UTIs, focusing on AMR mechanisms, safety, and translational potential. The exclusion criteria were conference abstracts, non-English articles, and papers lacking a nanotechnological context.

A total of 900 records were identified across the four databases; after duplicate removal and screening, 20 studies were included in the final analysis based on the inclusion criteria. While not a systematic review, the current study followed the PRISMA 2020 guidance to maximize transparency in literature selection and synthesis (Figure 1). The included papers were evaluated regarding study type (in vitro, animal, or clinical), the presence of suitable controls and sample sizes, and the description of nanoparticle synthesis and characterization procedures. No formal risk-of-bias assessment was undertaken.

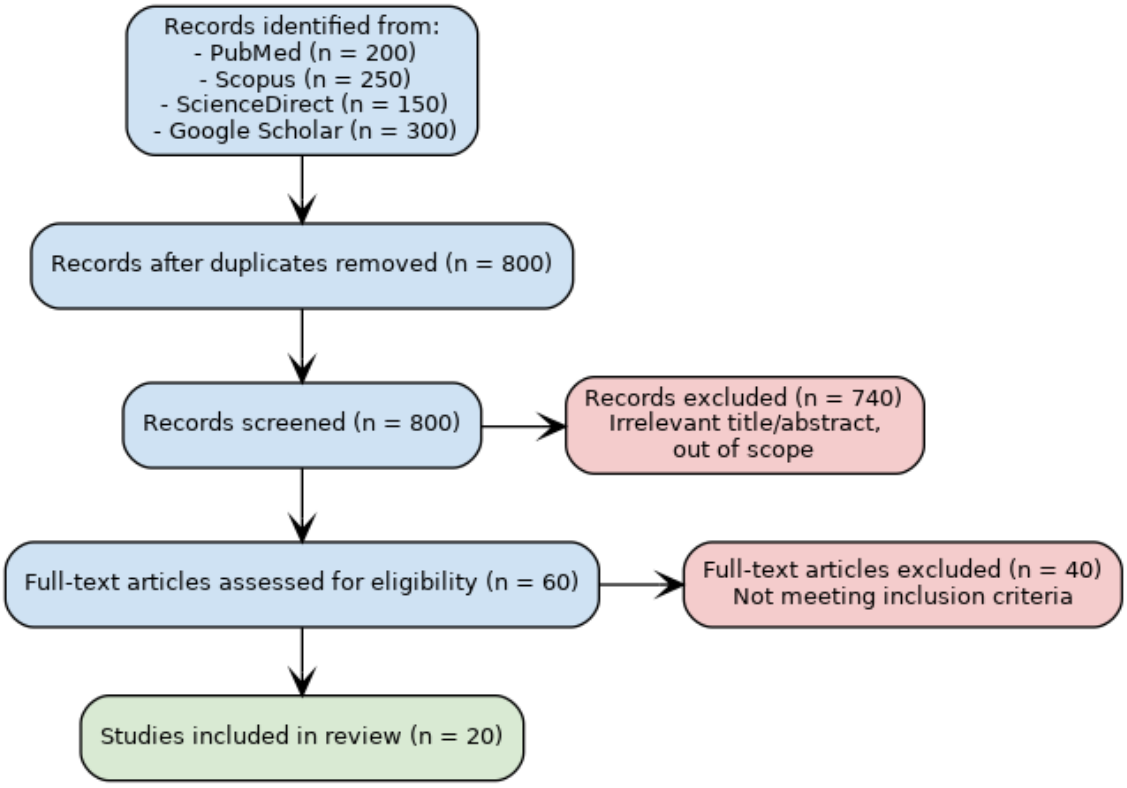

Figure 1. Literature selection process following the PRISMA 2020 framework

RESULTS

This review referenced over 20 peer-reviewed studies, clinical trials, and systematic reviews of nanotechnology-based strategies for antibiotic-resistant UTIs. The findings are summarized as follows:

Pathophysiology of UTIs

UTIs may occur as asymptomatic bacteriuria or as acute, chronic, or recurrent infections. Depending on the part of the urinary tract affected, acute UTIs are divided into upper and lower types.

Lower UTIs: include the infection of the bladder, urethra, and prostate.

Upper UTIs: infections of the kidneys (pyelonephritis, also termed acute bacterial tubulointerstitial nephritis under current nomenclature).

UTIs can also be clinically classified into two types: complicated and uncomplicated UTIs. Complicated UTIs are more challenging to treat and occur in people with urinary tract problems or medical devices, while uncomplicated UTIs occur in healthy individuals and are easier to treat (8,9). Under normal conditions, urine is sterile and does not contain bacteria, viruses, or fungi. An infection occurs when microorganisms, usually bacteria from the digestive system, cling to the opening of the urethra and begin to multiply (10). Most UTIs are caused by bacteria that belong to the *Enterobacteriaceae* family (*Escherichia coli, Klebsiella pneumoniae, Proteus mirabilis, Citrobacter, and Enterobacter*), *Pseudomonas aeruginosa, Acinetobacter baumannii, Staphylococcus aureus, Staphylococcus saprophyticus, Streptococcus,* and *Enterococcus faecalis*. Persistent infections and recurrences are caused by bacterial reservoirs within the bladder lining, intracellular bacterial communities (IBCs), and the ability of some bacteria to enter a dormant state. *Escherichia coli (E. coli)* is responsible for the majority of UTIs. According to recent studies, there is an increasing resistance to antibiotics such as fluoroquinolones and third-generation cephalosporins due to mechanisms like the production of extended-spectrum beta-lactamases (ESBL). Klebsiella pneumoniae is known for producing ESBLs and exhibiting resistance to a wide range of beta-lactam antibiotics, including third-generation cephalosporins and carbapenems. This makes its treatment challenging. Staphylococcus saprophyticus commonly appears in young women and is sensitive to antibiotics. However, increasing resistance to trimethoprim-sulfamethoxazole is emerging, making treatment more difficult in some cases. *Enterococcus faecalis* most often resists aminoglycosides and beta-lactams, making treatment more difficult. Given the increasing number of antibiotic-resistant UTIs, conventional treatment approaches have increasingly become unsuccessful. Second, traditional treatment options currently available are outlined as their shortcomings and the reasons why alternative therapies are so desperately required (11).

Current Treatment Strategies for UTIs

The primary treatment for UTIs traditionally uses safe and cost-effective antibiotics. Currently, the most recommended therapies for UTIs are antibiotics such as trimethoprim-sulfamethoxazole, ciprofloxacin, ampicillin, nitrofurantoin, and fosfomycin. These antibiotics target a broad spectrum of pathogens responsible for UTIs, such as *Escherichia coli, Klebsiella pneumoniae, Proteus mirabilis, and Pseudomonas aeruginosa*. Empiric treatment of a symptomatic UTI should begin while a urine culture is conducted to assess antimicrobial susceptibility, which typically takes 48 hours. Acute cystitis in women is treated with a 3-day antibiotic course. Meanwhile, complicated UTIs (pyelonephritis, prostatitis) require extended treatment, lasting 10 to 21 days (2).

Despite the effectiveness of antibiotics, UTIs become progressively more challenging to treat due to the emergence of antibiotic-resistant bacteria, a significant issue. Among the key concerns is the resistance mechanism of the *Enterobacteriaceae* family, including *E. coli* and *K. pneumoniae*, namely plasmids that harbor extended-spectrum beta-lactamases (ESBLs). These plasmids rapidly spread resistance to third-generation cephalosporins and other antibiotics. Other members of the Enterobacteriaceae family produce class C beta-lactamases (AmpC enzymes), which are active against cephamycins and third-generation cephalosporins and are resistant to beta-lactamase inhibitors. The expression of AmpC enzymes is also associated with resistance to carbapenems in K. pneumoniae strains lacking a 42 kDa outer membrane protein (9). AMR causes a range of significant harms, including increased mortality, difficulty in controlling infectious diseases, higher healthcare costs, risk to advancements in modern medicine, and threats to global health security and the economy. With conventional therapies slowly losing their potency against multidrug-resistant bacteria, there is an emerging need for novel therapeutic approaches. Nanotechnology thus holds promise as a better alternative in enhancing the efficacy of drugs and targeting resistant pathogens. The following section discusses the shifting trends in UTI treatment strategies using nanotechnology (2).

Nanotechnology provides promising strategies for addressing antibiotic-resistant UTIs. Silver NPs (AgNPs) exhibit potent antimicrobial activity against resistant bacteria. These NPs destroy bacterial cell membranes, generate reactive oxygen species (ROS), and interfere with the DNA replication process, thus providing a potent bactericidal effect. Immunotherapy is designed to increase the host's immune response to infection. Vaccines for UTI pathogens and monoclonal antibodies against bacterial toxins are under investigation. These approaches have the potential to provide long-term protection and reduce the use of antibiotics (2,12).

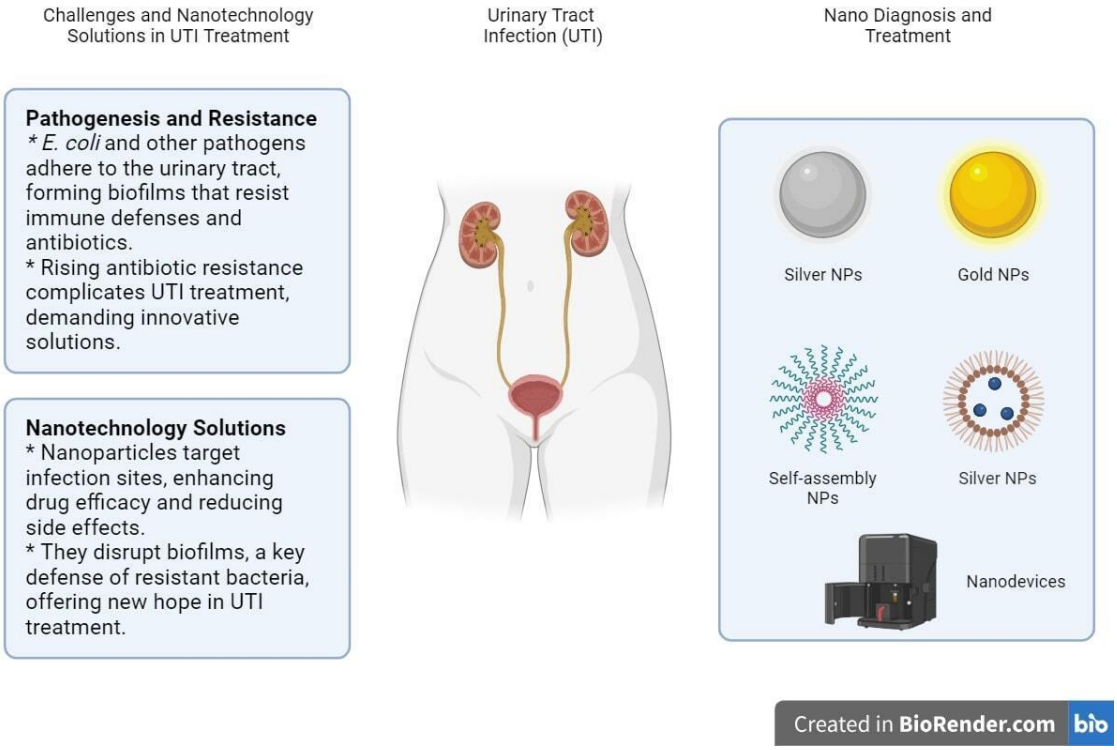

Figure 2. Nanotechnology Solutions for Overcoming Challenges in Antibiotic-Resistant Urinary Tract Infections (Prepared with Biorender).

Nanotechnology in Medicine

Basics of nanotechnology

Figure 2 illustrates the types of nanocarriers commonly used in medical applications, including their roles in diagnosing and treating UTIs and the mechanisms by which they address the challenges posed by antibiotic resistance.

Types of nanocarriers:

Liposomes: Spherical vesicles composed of one or more phospholipid bilayers. They can incorporate drugs, thus improving delivery to target sites of the body and reducing toxicity and side effects while improving therapeutic efficacy.

Dendrimers: Highly branched, star-shaped macromolecules with multiple surface functional groups, allowing them to carry several drug molecules simultaneously for drug delivery or imaging.

Metallic NPs: Include NPs from metals such as gold (Au) and silver (Ag). These NPs are used for their conductive, catalytic, and reactive properties. They find use in diagnostic (diagnostic imaging) and therapeutic applications (13).

Mechanisms of action in medical applications

Of all the medical uses of nanotechnology, its potential in dealing with resistant-to-antibiotic UTIs is one of the most important. Further discussions of critical nanostrategies useful against said infection are targeted drug delivery and biofilm disruption. Integrating

nanotechnology in medical settings suggests a promising direction for future health innovations, with ongoing research to overcome existing challenges and expand potential applications (Figure 2) (14).

Nanostrategies for UTIs

Liposomes and Nanoemulsions

Liposomes are lipid bilayer membrane vesicles that are spherical in shape and can encapsulate drugs, increasing their delivery at the site of action and therapeutic effect. Thermodynamically stable water-oil-surfactant mixtures, or nanoemulsions, provide effective delivery of hydrophobic drugs. These nanodelivery systems allow release control, reduce toxicity, and improve drug stability. Liposomes are synthesized through thin-film hydration, ethanol injection, and reverse-phase evaporation. At the same time, nanoemulsions are produced through high-energy methods such as ultrasonication, microfluidization, or high-pressure homogenization. These nanocarriers improve the distribution of antibiotics directly to infected tissues in UTI, significantly improving treatment outcomes against resistant strains (9,15).

Liposomes provide biocompatibility and the ability to encapsulate hydrophilic and hydrophobic drugs. However, their durability can be challenging because they may require cold storage. Nanoemulsions offer a high surface area for drug absorption but could have problems with stability over time (9,16).

Silver Nanoparticles (AgNPs)

AgNPs disrupt bacterial cell membranes, generating reactive oxygen species (ROS) and interfering with DNA replication, making them effective against a broad spectrum of bacteria, including antibiotic-resistant strains (9).

AgNPs can be synthesized through chemical reduction and green synthesis using plant extracts. In UTIs, AgNPs have demonstrated efficacy in inhibiting uropathogenic growth and reducing biofilm formation, a common cause of chronic infections (16).

The broad-spectrum antimicrobial activity of AgNPs is a significant advantage. However, their cytotoxic potential and the need for precise size and dose control to minimize side effects are vital concerns (9,17).

Gold Nanoparticles (AuNPs)

AuNPs are known for their biocompatibility and ease of functionalization. They can be conjugated with antibiotics or other therapeutic agents to improve drug delivery, targeting, and efficacy while reducing the required dose. AuNPs can also disrupt bacterial membranes and inhibit the growth of pathogens through photothermal effects (9,16).

AuNPs are synthesized through citrate reduction or green synthesis. In UTIs, AuNPs improve the distribution of antibiotics, especially against multidrug-resistant strains, by improving drug penetration and reducing bacterial resistance (9,17).

AuNPs offer excellent stability and low toxicity, making them suitable for various biomedical applications. However, the high cost of production and the need for precise functionalization are the constraining factors (9,16).

Other Nanostrategies

Quantum dots: NPs of semiconductors are used in diagnostics due to their unique optical characteristics. They can be conjugated with antibiotics or other molecules to detect specific uropathogens, thus providing rapid and sensitive diagnostic tools for UTIs (16).

Carbon nanotubes, with high surface area and unique electrical properties, are used in drug delivery and diagnostic applications. Functionalization of the nanotubes facilitates the precise targeting of bacteria, which increases the effectiveness and accuracy of UTI treatments (9).

Polymeric NPs, constructed from biodegradable polymers such as PLGA, encapsulate antibiotics, thus facilitating controlled release and targeted delivery. They reduce drug side effects and increase patient compliance by lowering the frequency of dosing (16).

These approaches are a promising means of improving UTI treatments, especially in the fight against antibiotic resistance. But durability, toxicity, and cost factors need to be addressed through more research and development (9,16,17).

Mechanisms of Action

Nanotechnology has opened new vistas for therapy because it precisely targets bacterial cells while overcoming their resistance mechanisms. Next, this review discusses a mechanism for the antimicrobial activity of NPs: biofilm disruption, interaction with microbial membranes, and enhancement of drug delivery.

Interaction with Bacterial Cells

Membrane and Biofilm Disruption

Membrane Disruption: Metallic NPs, including silver (AgNPs) and gold (AuNPs), bind to bacterial membranes, altering their permeability and causing cell lysis.

Generation of ROS: NPs create oxidative stress, damaging bacterial proteins, lipids, and DNA. This stress interferes with metabolic pathways through enzymatic activities and protein synthesis, which is disrupted when NPs infiltrate bacterial cells. Target-oriented action is achieved when functionalized NPs are attached with specific ligands or antibodies that selectively attach to bacteria's surface markers.

Biofilm Penetration and Degradation: Small-sized NPs easily infiltrate biofilms, thus breaking the protective barriers against antibiotics. Enzyme-functionalized NPs degrade biofilm components like extracellular DNA and proteins.

Adhesion Inhibition: NPs prevent bacterial adhesion, reducing biofilm formation.

Enhanced Drug Delivery and Resistance Bypass

Targeted Delivery: Liposomes and other nanocarriers deliver drugs to infection sites with high specificity, minimizing side effects.

Controlled Release: Nanocarriers offer sustained release of drugs, maintaining effective concentrations.

Resistance Overcoming: NPs bypass bacterial efflux pumps, enhancing antibiotic efficacy.

Synergy with Antibiotics: NP-antibiotic combinations enhance penetration and antimicrobial efficacy.

Immune Modulation and Host Response

Some nanocarriers enhance immune responses by increasing phagocytosis and inflammation reduction, allowing bacterial clearance.

These mechanisms, taken together, demonstrate the potential of nanotechnology in overcoming antibiotic resistance and form a basis for new therapeutic methods against UTIs.

Clinical Applications and Studies

Targeted Drug Delivery

As promising as nanotechnology has been at the cellular and molecular levels, its application must be observed in translational and clinical settings. The section below outlines recent clinical studies that validate nanocarriers efficacy in treating UTIs and their translation into medical practice (18).

Safety and Toxicity

Like any other emerging medical technology, nanotechnology raises critical questions of safety and toxicity. In this regard, regulatory frameworks are significant in ensuring the responsible application of nanocarriers in clinical practice. The following section discusses the current regulatory landscape and ethical considerations regarding nanomedicine.

Cytotoxicity and genotoxicity

Due to their small size and high reactivity, nanocarriers can interact in biological systems in a way that can cause cytotoxicity and genotoxicity. Cytotoxicity refers to the nanocarriers ability to damage or kill cells, which can be analyzed through a series of *in vitro* assays. For example, studies have shown that silver NPs can induce cytotoxic action by generating reactive oxygen species (ROS), thus leading to oxidative stress, lipid peroxidation, DNA damage, apoptosis, and necrosis. Factors that affect cytotoxicity are particle size, concentration, and duration of exposure. Genotoxicity, on the other hand, is the capacity of NPs to induce damage to genetic material, leading to mutations, chromosome breakage, and carcinogenesis. NPs can interact with DNA directly or induce oxidative damage by producing ROS, leading to the degradation of genetic material. The NP size, shape, and surface charge are essential in determining their genotoxic potential (19).

Strategies to reduce side effects

Reduction of side effects of nanocarriers can be attained through the following strategies:

Surface modification: One strategy includes modifying the surface of NPs to reduce reactivity. Encapsulating NPs with biocompatible materials such as polyethylene glycol (PEG) can reduce their interaction with cellular components, thus minimizing cytotoxicity and genotoxicity.

Controlled Release Systems: Incorporating NPs into controlled release systems can enable control over their release within the body, ensuring that they reach the target site in a controlled manner and reducing systemic toxicity.

Use of Antioxidants: Since ROS generation is an essential mechanism of toxicity caused by NPs, co-administration of antioxidants has been explored as a strategy to combat oxidative stress and reduce cytotoxic and genotoxic effects.

Regulatory Guidelines: Regulatory guidelines are the major drivers in ensuring the safe application of NPs in medicine. Regulatory guidelines need to be developed to standardize NP toxicity testing, establish safe exposure levels, and ensure NPs in consumer products are assessed for safety. As nanocarriers hold great promise in medicine, their cytotoxicity and genotoxicity hazards need to be assessed with caution. Thorough toxicity testing, dose-response experiments, and side effect reduction strategies can leverage the advantages of nanocarriers while reducing their risks. Continued research and regulation will play critical roles in ensuring the safe integration of nanocarriers into clinical practice (20).

DISCUSSION

This review presents the dynamic future of nanotechnology in resolving the clinical dilemma of multidrug-resistant UTIs. The traditional antibiotic treatment has gradually lost its effectiveness because of mechanisms of resistance like β-lactamase production, efflux pump overexpression, and biofilm production (21). Nanotechnology provides a multifaceted strategy by enhancing antimicrobial delivery, evading the routes of resistance, and allowing site-selective release of drugs. The available literature at present, however, remains mostly preclinical, needing careful interpretation and further translational validation (22).

Head-to-head appraisal

One-to-one comparisons reveal dissimilar benefit–risk profiles. AgNPs exhibit swift bactericidal and antibiofilm activity *in vitro* but possess a narrow safety margin; AuNPs are safer but more expensive and susceptible to equal activity by conjugation or adjunct photothermal activation. Liposomal and PLGA formulations offer improved therapeutic index and biocompatibility but slower activity. No carrier is superior—choice relies on the site of infection, desired release profile, and practicality of hybrid formulations (22–24).

Quantitative safety and translation

Antibacterial activity of AgNPs resides at 10–50 μg/mL, and cytotoxicity increases above ≈ 100 μg/mL; AuNPs accommodate higher doses at the

expense of increasing production complexity. Liposomal and PLGA systems elevate the therapeutic index but accommodate variable IC_{50}/CC_{50} reporting and urinary pharmacokinetics. Clinical assessment remains in the non-UTI indication, confirming that translational data for urinary delivery are still insufficient (22–25).

Economic and accessibility factors

The production of metal NPs is cost-inefficient, and lipoid and polymeric delivery systems are limited by cold-chain and storage requirements. Cost-effectiveness for UTIs relies on reduced recurrence, faster healing, and feasibility in low-resource and primary-care environments. Health-economic and implementation studies must be conducted to define real-world feasibility (24,25).

While current evidence highlights the antibacterial potential of nanocarriers, much of it remains descriptive rather than comparative. Most studies rely on short-term *in vitro* assays, use variable synthesis protocols, and rarely quantify toxicity thresholds or pharmacokinetic behavior. As a result, apparent differences in performance across AgNPs, AuNPs, liposomes, and polymeric systems often stem from methodological bias rather than genuine therapeutic advantage. To move beyond proof-of-concept, future investigations should adopt standardized analytical frameworks, enabling robust cross-validation and translation of preclinical findings into clinical settings.

Comparative Evaluation of Nanocarrier Systems

Of the nanocarriers presented, the most efficacious bactericidal activity is shown by the metallic NPs (AgNPs, AuNPs), by membrane rupturing and the induction of oxidative stress. Silver NPs, for instance, show dose-dependent cytotoxicity, with antibacterial activity reached at 10–50 μg/mL, yet mammalian cytotoxicity in their case at over 100 μg/mL. Gold NPs possess improved biocompatibility and stability, although high synthesis cost and few extensive production scales for clinical implementation (22,23).

Liposomes and polymeric NPs (e.g., PLGA-based NPs) provide better, more controllable release kinetics and can co-encapsulate antibiotics and antioxidants to produce the maximum therapeutic index. Nanoemulsions are simpler to form and are particularly suitable for hydrophobic agents, though long-term stability and reproducibility are problematic. No individual system has universal optimization, so hybrid nanoplatforms or combinatorial formulation can offer the optimal trade-off among efficacy, safety, and cost (Table 1) (24).

Nanocarrier Type	Major Advantages	Limitations
Liposomes	Biocompatible; encapsulate both hydrophilic and hydrophobic drugs; enable controlled release	Require cold storage; moderate long-term stability
Silver nanoparticles (AgNPs)	Strong bactericidal and anti-biofilm activity; broad-spectrum efficacy	Dose-dependent cytotoxicity (>100 μg/mL); oxidative stress induction; cost and safety concerns
Gold nanoparticles (AuNPs)	Excellent biocompatibility and stability; allow functionalization with targeting ligands	High synthesis cost; limited scalability; need precise size control
Polymeric nanoparticles (PLGA, chitosan)	Biodegradable; tunable release profiles; low toxicity; scalable synthesis	Variable drug loading; slower release kinetics; limited in vivo data
Nanoemulsions	Simple formulation; high surface area for drug absorption; suitable for hydrophobic agents	Stability issues over time; temperature sensitivity

Table 1. Comparative strengths and limitations of major nanocarrier systems used in antibiotic-resistant urinary tract infections

In general, these comparative remarks highlight that efficacy cannot solely determine the fitness of a nanocarrier platform. The therapeutic potential of the metal systems is balanced by dose-limiting toxicity and expense, while the nanocarriers based on lipids and polymers, although nontoxic, struggle with loading efficiency against the payload and *in vivo* stability. These findings indicate that the translational effectiveness shall rely less on the composition of individual NP and rely more upon the merging of physicochemical optimization with *in vivo* validation in clinically appropriate models.

Critical Appraisal and Translational Gaps

Despite encouraging experimental results, heterogeneity in evidence prevents cross-comparison. Most studies vary particle synthesis procedures, size distributions, and antimicrobial tests, resulting in non-standardized measures of efficacy. Scant few have undertaken head-to-head correlations or long-term animal models for assessing toxicity.

The clinical translation is in its initial stage—scant NP-based antibacterial formulations are still in early-stage trials, all against wounds or skin infections, not UTIs. Furthermore, dose–response relationships and urine environment pharmacokinetics are uncharacterized,

prematurely halting the escalation of doses in a rational manner.

Safety concerns remain paramount: oxidative stress, DNA damage, and mitochondrial disruption are recurrent findings in cytotoxicity assays. Nonetheless, advances in surface functionalization (e.g., PEGylation) and controlled-release matrices have been shown to mitigate adverse effects and prolong circulation times (22).

Another significant limitation of the current evidence is the reproducibility and transparency in the design of experiments. Most publications lack crucial information like NP characterization parameters, stability, and statistical reproducibility. Complying with reporting requirements like the Minimum Information Reporting in Bio–Nano Experimental Literature (MIRIBEL) guidelines can improve the reliability and comparability of nanomedicine research appreciably.

Economic and Regulatory Considerations

Scalability and cost-effectiveness of nanomedicines are further translational obstacles. The synthesis of metallic NPs involves costly precursors and rigorous purification, and liposomal and polymeric formulations frequently entail cold-chain storage—impractical logistically in resource-poor environments. Implementing good manufacturing practice (GMP) regulations and agency-based regulatory harmonization, as exemplified by the EMA, FDA, and OECD, will, however, be critical in preparing nanomedicines for commercialization. Ethical guidelines should mirror these advances to provide transparency in the evaluation of toxicities, coupled with fair distribution of future nanotherapeutics. Overall, these studies demonstrate that whereas nanotechnology has transformed laboratory therapeutics, clinical availability remains limited by agency-based regulations, economic, and safety challenges (22,25-28).

Strengths and Limitations

The review's biggest virtue lies in comparative integration among the classes of nanocarriers, both emphasizing therapeutic potential as well as regulatory constraints. The review bridges preclinical evidence and opportunities for translation, offering a general vision of nanostrategies against recalcitrant UTIs.

The study design variability and reporting practices in the literature limit the ability to compare the efficacy endpoints directly. Future meta-analyses will come to the fore to measure therapeutic performance and safety margins in the NP systems.

The current data synthesis unmistakably points to the transition of NP research from descriptive NP design to hybrid and functionalized nanosystems that can provide concurrent antibacterial and/or anti-inflammatory activity. The transition hints at the maturation of the field wherein scalability, safety profiling, and mechanistic elucidation assume equal significance as the intensity of the antimicrobial activity. The future development

will rely on the cross-disciplinary merging of microbiology, nanotechnology, toxicology, and pharmaceutical production.

CONCLUSION

Antibiotic-resistant UTIs constitute a current global health challenge. Nanotechnology provides useful avenues to enhance antimicrobial delivery, disrupt biofilms, and evade bacterial resistance mechanisms. Among the explored platforms, liposomal and polymeric nanocarriers exhibit optimal safety and temporal release control. In contrast, metal NPs possess intense bactericidal activity yet are limited by the potential for toxicity and cost ceilings.

Translation to the clinic will require standardized NP characterization, harmonized safety thresholds, and appropriate manufacturing practices. The inclusion of machine learning and artificial intelligence has the potential to accelerate NP design, as well as predictive safety modeling.

Despite the encouraging laboratory results, the area still lags regarding the gap in experimental efficacy and clinical usefulness. Closing the translational gap needs to be the next strategy of nanotechnology-based anti-infective research.

The future of UTI treatment will depend upon weighing innovation against affordability—translating nanotechnological promise into available, safe, and sustainable therapies.

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