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Article

Antimicrobial Urinary Catheters: Fabrication Strategies and Their Role in Preventing Catheter-Associated Urinary Tract Infections - A Narrative Review

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Abstract

Catheter-associated urinary tract infections (CAUTIs) are among the most frequent healthcare-associated infections, primarily caused by biofilm formation on catheter surfaces. This narrative review summarizes recent progress in antimicrobial urinary catheter development, focusing on substrate materials, functional agents, and fabrication strategies. Common substrates such as silicone, polyurethane, and thermoplastic elastomers provide biocompatibility and durability but require modification to achieve antimicrobial performance. Strategies including surface coatings (e.g., dip- and spray-coating, sol–gel, and layer-by-layer deposition), impregnation, composite blending, and hybrid designs have been investigated to deliver sustained antimicrobial release, antifouling resistance, and improved patient comfort. Coating-based methods enable localized control of active agents, while bulk modifications ensure durability despite surface wear. Emerging approaches highlight multifunctional systems integrating antimicrobial, antifouling, and lubricious properties, supported by precision techniques such as nanostructured coatings and bioinspired surface engineering. By linking material selection with fabrication design, this review underscores the need for scalable and cost-effective strategies that combine long-term antimicrobial protection, mechanical integrity, and regulatory compliance. Future research directions include hybrid fabrication methods, sustainable manufacturing, and clinical translation to reduce the global burden of CAUTIs.

Keywords: Antimicrobial urinary catheter; CAUTIs; Materials; Fabrication

INTRODUCTION

A urinary catheter is a flexible tube inserted into the bladder through the urethra to drain urine. Urinary catheters are utilized in various medical contexts, including surgical procedures, cases of urinary retention, and when patients cannot

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void naturally due to medical conditions [1]. It has been documented that approximately 20% of hospitalized patients use urinary catheters, and more than 70% of hospital-acquired urinary tract infections are related to catheter use [2]. There are several types of urinary catheters, each designed for specific purposes and patient needs. Examples of such devices include indwelling, intermittent, external, controlled drainage, and antimicrobial catheters [1], [3], [4]. Antimicrobial catheters are coated with antimicrobial agents to reduce the risk of catheter-associated urinary tract infections (CAUTIs) [4]. Figure 1 shows the mechanism and part of the urinary catheter.

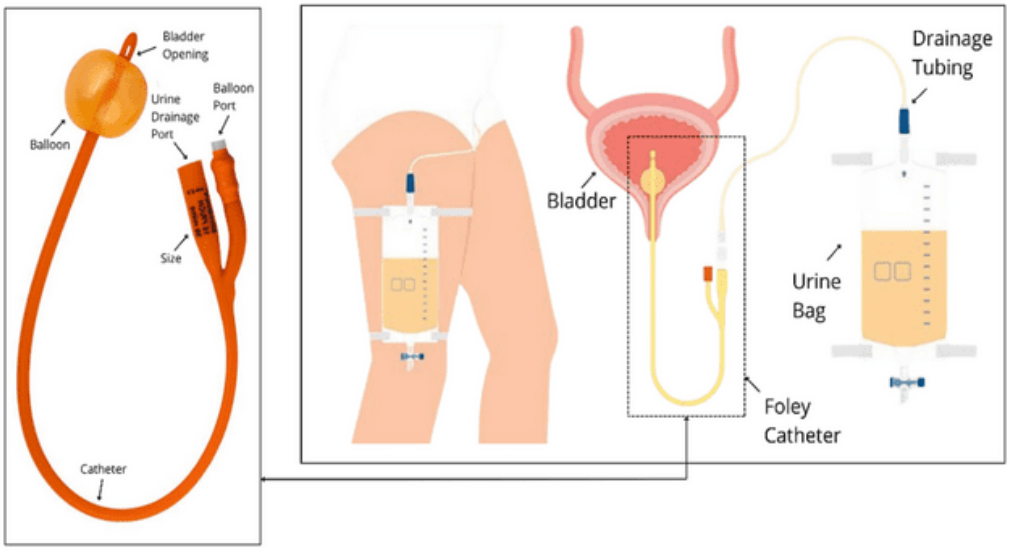


Figure 1. Mechanism of urinary catheter

CAUTIs represent a substantial global health challenge and are among the most prevalent nosocomial infections. These organisms are responsible for approximately 40% of all nosocomial infections and 80% of nosocomial urinary tract infections worldwide [5]. In intensive care units, the incidence rate has been documented to range from 1 to 4 cases per 1,000 catheter days, with bloodstream infections occurring at 1.4 per 10,000 patient days [6]. CAUTIs can lead to symptoms such as fever, hematuria, pain, and acute confusion, which have been shown to have a significant impact on patient morbidity [7]. Furthermore, there is a well-documented correlation between CAUTIs and prolonged hospital stays, as well as elevated in-hospital mortality rates [6].

CAUTIs are classified as nosocomial infections, with etiology attributed to microorganisms such as *Escherichia coli*, polymicrobial communities, and *Candida species* [8], [9], [10], [11]. The most prevalent causative agent is *Escherichia coli*, which is characterized by a high prevalence of multidrug-resistant strains, thereby complicating treatment regimens [7], [12]. Risk factors that can predispose patients to CAUTIs include prolonged catheter use, female

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gender, diabetes mellitus, mechanical ventilation, genetic or acquired deficiencies, and urinary catheter material and antimicrobial coatings [8], [9], [11], [13].

The type of catheter material and antimicrobial coatings are critical factors influencing the risk of CAUTIs. Traditional catheter materials, which are frequently composed of plastic, have been observed to impede the urinary tract's intrinsic defense mechanisms and facilitate bacterial colonization. These observations underscore the necessity for developing materials that can impede biofilm formation and mitigate infection risk [5]. Advancements in catheter materials, including synthetic spider silk and cobalt-containing bioactive glass, have been investigated for their antimicrobial properties. The objective of these materials is twofold: to enhance the mechanical strength and biocompatibility of catheters while concurrently providing antimicrobial action [14], [15]. Antimicrobial coatings on catheters, such as those containing silver, chlorhexidine, or nitric oxide, have been developed to reduce the risk of CAUTIs. These coatings prevent bacterial colonization and biofilm formation on the catheter surface, primarily contributing to infection [16], [17].

The development of novel fabrication strategies for antimicrobial catheters is imperative in preventing CAUTIs. Advancements in catheter materials and coatings have undergone a marked evolution over the past decade, progressing from rudimentary antimicrobial impregnation to sophisticated multifunctional surfaces that incorporate hydrogels, nanoparticles, and bioactive compounds [18], [19]. The practical significance of this research lies in its potential to enhance patient outcomes by reducing infection rates, biofilm formation, and catheter encrustation [17], [20]. A critical knowledge gap exists in understanding the comparative effectiveness of different materials and mechanisms, including antifouling versus bactericidal strategies, and their practical applications in clinical settings [2], [20]. Table 1 shows a critical examination of the extant literature, which reveals the necessity of a thorough overview regarding the advantages and disadvantages of this method.

Table 1. Comparative general fabrication methods for antimicrobial urinary catheters

No.	Methods	Advantages	Disadvantages	Ref.
1.	Surface Coatings	These coatings can effectively reduce biofilm formation and bacterial colonization, providing immediate antimicrobial effects.	The potential for cytotoxicity and the development of microbial resistance are concerns. Additionally, the release of antimicrobial agents over time can diminish, reducing long-term effectiveness.	[21]
2.	Incorporation of Antimicrobial Agents	This method provides sustained antimicrobial activity and can be tailored to target specific pathogens.	The risk of developing resistance and potential adverse reactions in patients is a significant challenge. Moreover, the cost of production can be higher compared to traditional catheters.	[22]

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No.	Methods	Advantages	Disadvantages	Ref.
3.	Advanced Material Modifications	These methods can offer a broad spectrum of antimicrobial activity and are less likely to induce resistance compared to traditional antibiotics.	The complexity of fabrication and the need for precise control over material properties can limit their widespread application. Additionally, the long-term stability and safety of these materials require further investigation.	[15]
4.	Green Fabrication Techniques	This method is cost-effective and reduces environmental impact. It also provides effective antimicrobial properties without significant toxicity.	The scalability of these techniques for mass production and their long-term efficacy in clinical settings remain to be fully validated.	[23]

The review provides a conceptual framework integrating material science, microbiology, and clinical application perspectives. Key concepts include the formation of biofilms on catheter surfaces, the mechanisms of antimicrobial and antifouling coatings, and the interplay between material properties and microbial adhesion [24], [25], [26]. It is imperative to comprehend these relationships to facilitate the design of catheters that effectively prevent infection while maintaining biocompatibility and mechanical integrity [18], [27]. This review aims to provide a comprehensive narrative review of the fabrication strategies of antimicrobial urinary catheters from a biomaterials engineering and healthcare perspective to prevent CAUTIs. The review methodology entails thoroughly examining contemporary peer-reviewed studies that concentrate on materials and fabrication of catheters. The inclusion criteria emphasize studies with in vitro, in vivo, and clinical evaluations, while the exclusion criteria omit non-peer-reviewed and non-relevant reports. The findings have been organized thematically to address fabrication strategies of antimicrobial urinary catheters and their role in preventing CAUTIs [28], [29].

METHODS

The review methodology was designed to ensure transparency and reproducibility. Literature searches were conducted across major scientific databases, including PubMed, Scopus, and Web of Science, covering publications from 2015 to 2024 to capture the most recent advances in antimicrobial urinary catheter development. The primary keywords used were “antimicrobial urinary catheter” “catheter-associated urinary tract infections (CAUTIs),” “fabrication strategies,” “biomaterials,” and “surface modification”. Boolean operators and combinations of these keywords were applied to refine the search. Inclusion criteria consisted of peer-reviewed studies reporting in vitro, in vivo, or clinical evaluations of materials and fabrication techniques for urinary catheters. Both original research articles and high-quality reviews were considered. Exclusion criteria included non-peer-reviewed sources, conference abstracts without full

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papers, and publications not directly addressing catheter materials or fabrication methods. The collected studies were systematically screened and organized into thematic categories, focusing on material substrates, functional agents, fabrication techniques, and their role in preventing CAUTIs. This approach ensured a comprehensive and structured analysis of the field's current state.

PREVIOUS RESEARCH

Maijan et al. (2022) developed a one-step deep coating process to embed silver nanoparticles (AgNPs) into silicone-coated latex urinary catheters via protein-mediated in situ reduction. Immersion in silver nitrate allowed Ag^+ ions to penetrate 10–25 μm beneath the surface, producing a uniform nanoparticle distribution without toxic reagents. Characterization confirmed increased surface roughness and sustained silver ion release (0.44 mg/L) over 14 days. Antibacterial testing showed ~11 mm inhibition zones and 99.99–99.9999% reduction in S. aureus and E. coli adhesion within four hours. The deep penetration reduced the risk of coating delamination during use, ensuring prolonged antimicrobial performance. This approach minimizes processing complexity, reduces manufacturing cost, and supports eco-friendly production. Its sustained bactericidal effect clinical addresses biofilm-mediated CAUTIs during extended catheterization [30].

Kanti et al. (2022) evaluated spray coating as a scalable antimicrobial agent for urinary catheters. Uniform layers were formed on complex catheter geometries of silicone, latex, or polyurethane by atomising active formulations into fine droplets. Coated surfaces showed reduced adhesion of uropathogens and decreased biofilm formation, while increased hydrophobicity limited bacterial colonization. Spray coating enables precise thickness control, critical for balancing mechanical flexibility and drug release. The process is adaptable to multiple active agents, including metals and antibiotics. Its ability to uniformly coat large-scale catheter batches makes it highly suitable for commercial CAUTI prevention strategies [31].

Mei (2020) applied LbL deposition using hydrophilic polymers and tannic acid to construct stable multilayers on catheter surfaces. This approach allowed nanoscale control of coating architecture, achieving over four weeks of antibiofilm activity in vitro and in vivo against multiple uropathogens. The coating adhered well to different substrate materials without compromising flexibility. LbL films also demonstrated tunable release profiles, enabling tailored antimicrobial durations. The method is compatible with many bioactive molecules, increasing its versatility. Such customization makes LbL a promising platform for reducing CAUTI risk in various catheter applications [32].

Belfield et al. (2019) produced antimicrobial catheters by impregnating rifampicin, triclosan, and sparfloxacin into the catheter matrix. The process yielded sustained release for 12 weeks, preventing mineral encrustation and blocking colonization by MDR organisms, including MRSA, MRSE, and carbapenemase-

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producing E. coli. The absence of catheter blockage during prolonged testing demonstrated improved mechanical function. Because the antimicrobial agents are embedded within the bulk, surface wear does not compromise efficacy. This technique is particularly advantageous for long-term use where surface coatings might degrade. As a result, impregnation offers a dual solution to infection and blockage-related CAUTI complications [33].

Rathinam et al. (2021) utilized a sol–gel dip-coating method to incorporate eugenol into a nanoporous silica matrix on silicone catheter segments. The coating provided controlled release for more than 35 days, significantly inhibiting P. aeruginosa adhesion and biofilm development. Gene expression analysis confirmed downregulation of virulence-associated genes, and cytotoxicity test indicated biocompatibility. The sol–gel structure ensures a stable reservoir for the active agent while allowing gradual diffusion. This technique can be adapted to encapsulate multiple antimicrobial compounds simultaneously. Its long-lasting biofilm resistance directly supports CAUTI prevention during chronic catheterization [34].

Venkatesh et al. (2021) fabricated urinary catheters by uniformly blending AgNPs and ZnO nanoparticles into a silicone–polyurethane matrix using high-shear mixing. The composite exhibited improved hydrophilicity, preserved flexibility, and dual-phase antimicrobial ion release over 30 days. Antibacterial test showed >99.99% inhibition of E. coli and S. aureus. Embedding the nanoparticles in the bulk prevents loss of antimicrobial activity due to surface wear. The method also enhances mechanical stability, making it suitable for flexible catheters. This durable design reduces the need for frequent replacements, lowering CAUTI risk and healthcare costs [35].

Dai et al (2023) present the development of an antimicrobial hydrogel coating for urinary catheters using the coating over adhesive primer approach to enhance coating adhesion and durability. The process begins with the application of an adhesive primer layer composed of poly(vinyl acetate) (PVAc) containing the photoinitiator diphenylketone (BP) onto the silicone catheter surface, serving as a bonding interface between the hydrophobic substrate and the hydrogel. Subsequently, a mixture of hydrogel monomers, including acrylamide (AAm), 2-methacryloyloxyethyl phosphorylcholine (MPC), and zinc methacrylate (ZMA), along with a crosslinking agent, is polymerized via UV irradiation to form a thin, uniform, and firmly adhered hydrogel layer. This design enables the incorporation of antimicrobial agents such as Zn^{2+} ions or zwitterionic polymers within the hydrogel network, thereby providing not only lubrication and antifouling properties but also effectively inhibiting bacterial colonization responsible for catheter-associated urinary tract infections (CAUTIs) [18].

The widespread use of urinary catheters in medical care is frequently associated with catheter-associated urinary tract infections (CAUTIs), most of which result from the formation of multispecies bacterial biofilms on catheter

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surfaces. Polydimethylsiloxane (PDMS) is widely employed due to its high biocompatibility, mechanical stability, and chemical resistance; however, it remains susceptible to microbial adhesion. Various strategies have been explored to reduce infection risks, including coatings with antimicrobial metals and carbon-based materials such as graphene. Graphene exhibits exceptional mechanical, electrical, and thermal properties with its two-dimensional hexagonal lattice structure. It has demonstrated antibacterial activity against Gram-positive and Gram-negative bacteria through mechanisms such as physical membrane disruption and reactive oxygen species (ROS) induction. Chemical functionalization of graphene, such as nitrogen doping, can further enhance its antimicrobial properties and biocompatibility. In this context, incorporating nitrogen-functionalized graphene nanoplatelets (N-GNP) into a PDMS matrix has been shown to increase surface hydrophobicity and roughness, while significantly reducing total cell counts and biofilm biovolume in both single- and multispecies biofilms, with the most pronounced effect observed against Staphylococcus aureus. These findings highlight the potential of N-GNP/PDMS composites as protective coatings for urinary catheters to inhibit uropathogenic biofilm development [36].

Poly(lactic acid) (PLA) is a biodegradable, bio-based thermoplastic polymer derived from renewable resources such as corn starch or sugarcane. It is characterized by high stiffness, good transparency, and ease of processing; however, its inherent brittleness, low thermal stability, and slow crystallization rate limit its application in demanding engineering and biomedical fields. To overcome these shortcomings, blending PLA with poly(ε-caprolactone) (PCL), a semi-crystalline biodegradable polyester with high ductility, low glass transition temperature, and good biocompatibility, has been extensively investigated. PLA/PCL blends combine the high modulus and strength of PLA with the flexibility and toughness of PCL, yielding materials with improved mechanical performance and thermal stability. Nevertheless, phase separation often occurs due to the limited miscibility between PLA and PCL, leading to heterogeneous morphologies that can adversely affect the overall properties. Strategies for compatibilization, incorporating chain extenders, reactive compatibilizers, or nanoparticle fillers, have improved interfacial adhesion and optimized the morphology of PLA/PCL blends. These modifications have been shown to tailor the blend properties for specific applications, including biomedical devices, packaging, and additive manufacturing, where the balance between strength, toughness, and biodegradability is critical [37].

Polymeric materials such as Tecothane—medical-grade polyurethane—are widely used in the fabrication of medical devices, including catheters and stents, due to their excellent mechanical properties, chemical stability, and biocompatibility. However, these materials are prone to microbial colonization and pathogenic biofilm formation, which are significant causes of implant-associated infections. Such infections, particularly those caused by Pseudomonas aeruginosa

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and Staphylococcus aureus, often necessitate surgical replacement of the device. However, this procedure does not guarantee the prevention of recolonization on the new implant. Conventional strategies, including catheter-surface impregnation with broad-spectrum antibiotics, have been linked to the emergence of antibiotic-resistant strains, particularly in bacteria adhering to implant surfaces.

An alternative and promising approach involves surface modification of biomaterials using antibacterial and anti-biofilm agents. Polyethyleneimine (PEI), which contains positively charged amine groups, exhibits strong electrostatic interactions with negatively charged bacterial cell walls, enabling potent antimicrobial activity. However, the intrinsic cytotoxicity of PEI toward human cells remains a challenge, necessitating modification strategies to mitigate its toxicity. One method involves immobilizing PEI onto Tecothane via itaconic acid as a chemical linker, using chemical grafting or electro-deposition techniques. This modification has significantly reduced biofilm formation, as evidenced by scanning electron microscopy (SEM) and bio-electrochemical measurements using cyclic voltammetry. Optimization studies revealed that grafting at 60 °C for six hours resulted in the highest efficiency. Consequently, PEI immobilization on Tecothane via itaconic acid presents a potential solution for preventing implant-associated infections without compromising the material's mechanical properties or biocompatibility [38].

Gayani et al. (2021) demonstrated using a spray deposition method to fabricate durable superhydrophobic polydimethylsiloxane (PDMS) surfaces for urinary catheter applications, aiming to reduce crystalline biofilm formation by Proteus mirabilis. In this approach, a trifluoropropyl polyhedral oligomeric silsesquioxane (TFP-POSS) solution in tetrahydrofuran (THF) was uniformly sprayed onto partially cured PDMS substrates under controlled temperature and nitrogen pressure, producing a micro/nanostructured coating with an exceptionally low surface energy (~1.9 mJ m^{-2}) and outstanding wetting properties (water contact angle ~167°, sliding angle ~2°). The resulting surfaces exhibited excellent self-cleaning performance, strong resistance to ultraviolet sterilization, and the ability to recover hydrophobicity through thermal or solvent-assisted healing. Under dynamic flow conditions simulating the urinary tract, TFP-coated PDMS significantly suppressed biofilm biomass, bacterial viability, and crystalline encrustation compared to unmodified silicone and siliconized latex, primarily due to the minimized formation of a conditioning layer and the enhanced removal of adhering particles by flow. This work highlights spray deposition as a scalable, non-biocide, and robust surface modification strategy for long-term antifouling performance in biomedical devices [29].

Onas et al. (2021) investigated the aging behavior of thermoplastic polyurethane (TPU) ureteral catheters subjected to prolonged implantation, using thermal curing as part of their manufacturing process to ensure mechanical stability and structural integrity. Catheters, explanted at intervals of 22 days, 29

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days, three months, and eight months, were characterized by thermogravimetric analysis (TGA), differential scanning calorimetry (DSC), and Fourier-transform infrared spectroscopy (FTIR) to assess changes in thermal and chemical properties over time. Results showed that thermal stability increased with usage duration, likely due to adsorption of urinary compounds onto the catheter surface, with TGA onset degradation temperatures rising from ~317 °C to ~341 °C. DSC analysis revealed distinct endothermal and exothermal transitions, with longer implantation times leading to more pronounced peaks, indicating structural rearrangement of hard segments within the polymer. FTIR spectra confirmed chemical changes, notably the disappearance of the C–O–C stretching band at eight months, suggesting degradation of ether linkages. These findings highlight that thermally cured TPU catheters undergo physical and chemical transformations during extended use, which may enhance thermal stability and alter the base polymer's structure, with implications for the design of long-term implantable devices [39].

Bovas et al. (2017) investigated the effect of extrusion process melt temperature on the surface characteristics of thermoplastic polyurethane (TPU) catheters made from Pellethane 2363-80AE. Catheters were produced using a single-screw extruder at melt temperatures ranging from 185 °C to 200 °C, with surface topography analyzed by optical microscopy and AFM, and wettability assessed via contact angle measurements. Results showed that lower melt temperatures (185–191 °C) produced rough, wavy surfaces with high surface roughness (Ra up to 318 nm) due to incomplete polymer melting, while higher melt temperatures (197–200 °C) yielded smooth, uniform surfaces with minimal roughness (Ra ~10.6 nm). Contact angle increased with smoother surfaces, indicating an inverse relationship between roughness and wettability. The optimal processing temperature was identified as 200 °C, producing homogeneous polymer melt, reduced surface defects, and desirable hydrophobicity, highlighting the critical role of precise melt temperature control in catheter extrusion [40].

Qiu et al. (2022) developed antibacterial thermoplastic polyurethane (TPU) composites by melt blending TPU with zinc oxide (ZnO) nanoparticles to enhance the performance of catheter materials. Using a twin-screw melt blending process, ZnO nanoparticles (1–5 wt%) were uniformly dispersed into the TPU matrix, followed by extrusion molding into test specimens. Scanning electron microscopy (SEM) confirmed good nanoparticle distribution at lower loadings, while higher loadings showed slight agglomeration. Mechanical testing revealed that tensile strength and elongation at break decreased slightly with increasing ZnO content, but hardness and thermal stability improved. Antibacterial tests against Escherichia coli and Staphylococcus aureus showed significant bacterial growth inhibition, especially at 3–5 wt% ZnO, due to Zn^{2+} ion release and reactive oxygen species generation. Water contact angle measurements indicated increased hydrophilicity with ZnO incorporation, potentially enhancing anti-biofouling behavior. This study demonstrated that melt blending is a practical and scalable

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method to fabricate TPU-based antimicrobial composites for catheter applications, balancing antibacterial efficacy with acceptable mechanical performance [41].

Sivakumar et al. (2019) conducted a study to optimize the injection molding process for manufacturing nylon PA66 side arms in urinary catheters, with the dual objectives of improving product quality and reducing production costs. The authors applied the Taguchi method using an L9 orthogonal array to evaluate the influence of three key process parameters systematically—melt temperature (260 °C, 270 °C, 280 °C), injection pressure (60 MPa, 70 MPa, 80 MPa), and cooling time (10 s, 15 s, 20 s)—on the quality of molded parts. The experimental results, analyzed through ANOVA, revealed that melt temperature significantly influenced minimizing defects (notably shrinkage, warpage, and dimensional inaccuracies), followed by injection pressure and cooling time. Optimal processing parameters were identified as 280 °C melt temperature, 80 MPa injection pressure, and 20 s cooling time, which produced side arms with minimal dimensional variation and surface defects. In addition, the optimized settings reduced cycle time, lowering overall manufacturing costs. The study highlights that systematic optimization of injection molding parameters using statistical tools can significantly enhance production efficiency and product reliability, making it a valuable approach for large-scale manufacturing of catheter components [42].

Table 2. Previous research on antimicrobial urinary catheter

No.	Fabrication	Materials	Finding	Refs.
1	Dip-coating	Rubber urethral catheter, silver nanoparticles (AgNPs)	One-step deep coating enabled AgNP impregnation within the catheter subsurface via protein-mediated in situ reduction, achieving uniform distribution up to 25 μm depth. Sustained silver ion release (0.44 mg/L, 14 days) resulted in ~11 mm inhibition zones and 99.99–99.9999% reduction of S. aureus and E. coli adhesion, offering scalable and low-cost CAUTI prevention.	[30]
2	Spray-coating	Various catheter polymers (e.g., silicone, latex, polyurethane) with antimicrobial agents	Spray atomization formed uniform antimicrobial layers on complex catheter geometries. Coatings reduced CAUTI-related pathogens 3 and catheter encrustation while enhancing hydrophobicity; suitable for scalable manufacturing.	[31]
3	Layer-by-later (LbL) deposition	Hydrophilic polymers and tannic acid	Sequential deposition produced stable, bacteria-resistant multilayers with long-term (>4 weeks) antibiofilm activity in vitro and in vivo. Compatible with diverse catheter substrates and geometries.	[32]

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No.	Fabrication	Materials	Finding	Refs.
4	Impregnation	Rifampicin, triclosan, and sparfloxacin	Antimicrobial agents impregnated into the catheter matrix provided sustained release for 12 weeks, prevented mineral encrustation, and inhibited colonization by MDR organisms (MRSA, MRSE, ESBL- and carbapenemase-producing E. coli), without catheter blockage.	[33]
5	Sol-gel coating	Silicone catheter segments and eugenol	Nanoporous silica matrix sustained eugenol release for >35 days, inhibiting P. aeruginosa adhesion and biofilm formation, downregulating virulence genes, and showing no cytotoxicity.	[34]
6	Composite blending	Silicone–polyurethane matrix blended with AgNPs and ZnO nanoparticles	High-shear blending yielded uniform nanoparticle dispersion (15–40 nm) throughout the bulk. Dual-phase Ag^{+}/Zn^{2+} release (30 days) achieved >99.99% bacterial inhibition, improved hydrophilicity, and preserved mechanical flexibility.	[35]
7	Coating over adhesive primer	Silicone rubber, PVAc primer + diphenylketone (BP), Hydrogel: AAm, MPC, ZMA, Crosslinker: N, N′-methylenebisacryl amide	Primer improved adhesion; UV-cured hydrogel formed a thin, uniform, durable layer; MPC enhanced lubrication, ZMA provided antimicrobial Zn^{2+}; reduced friction, increased wettability, inhibited bacterial growth (CAUTI prevention).	[18]
8	Photopolymerization	PDMS with Nitrogen-functionalized Graphene Nanoplatelets (N-GNPs)	Increased surface roughness and hydrophobicity while suppressing biofilm formation by uropathogenic bacteria; highest efficacy against Staphylococcus aureus.	[36]
9	Chemical grafting	Silicone urinary catheter with zwitterionic polymer grafting	Covalent bonding produced a superhydrophilic surface, reducing bacterial adhesion and biofilm thickness against E. coli and S. aureus.	[37]
10	Surface grafting	Polymer substrates with covalently attached antimicrobial agents	Improved hydrophilicity and reduced microbial adhesion; stable and durable antibacterial performance for medical devices.	[38]
11	Spray deposition	PDMS coated with TFP-POSS	Produced a superhydrophobic surface with ~167° water contact angle, UV sterilization resistance, self-healing	[29]

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No.	Fabrication	Materials	Finding	Refs.
			capability, and reduced biofilm formation and encrustation under flow conditions.	
12	Thermal curing (thermoplastic processing)	Thermoplastic polyurethane (TPU) Techoflex PU 93A B40	After prolonged use, TPU showed increased thermal stability over implantation time, internal structural changes, and ether bond degradation.	[39]
13	Extrusion	Thermoplastic polyurethane (Pellethane 2363-80AE)	Higher melt temperatures (up to 200 °C) produced smoother surfaces with lower roughness (~10.6 nm) and improved hydrophobicity, while lower temperatures caused incomplete melting and rough surfaces.	[40]
14	Melt blending	TPU blended with ZnO nanoparticles	ZnO addition improved antibacterial activity against E. coli and S. aureus, increased hardness and thermal stability, but slightly reduced tensile strength; higher ZnO loadings increased hydrophilicity.	[41]
15	Injection molding	Nylon PA66	Optimization using Taguchi and ANOVA identified melt temperature as the most significant factor; optimal parameters (280 °C, 80 MPa, 20 s) minimized defects and reduced production cost.	[42]

Based on the reviewed studies, a wide range of fabrication strategies—including surface coating (dip-coating, spray-coating, sol-gel, and primer-assisted coating), layer-by-layer deposition, impregnation, composite blending, photopolymerization, chemical grafting, and surface grafting—have demonstrated significant effectiveness in preventing catheter-associated urinary tract infections (CAUTIs) and reducing biofilm formation and encrustation. Coating-based approaches generally produce uniform antimicrobial layers with controlled release of active agents (e.g., Ag^{+}, Zn^{2+}, eugenol) for extended durations (>14 to 35 days), achieving over 99% inhibition against key pathogens such as *E. coli* and *S. aureus*. Bulk modification methods, including impregnation and composite blending, allow long-term antimicrobial protection (up to 12 weeks) without compromising mechanical flexibility and often prevent catheter blockage. Advanced surface modification techniques, such as photopolymerization and chemical grafting, can yield superhydrophilic or superhydrophobic surfaces that suppress bacterial adhesion and biofilm development while maintaining long-term stability. Thermoplastic processing methods (thermal curing, extrusion, melt blending, and injection molding) contribute to enhanced mechanical properties, thermal stability, and process optimization, with nanoparticle incorporation further improving antibacterial activity despite minor reductions in tensile strength. Combining appropriate base materials (e.g., silicone, polyurethane, nylon, PDMS) with

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fabrication techniques that integrate antimicrobial agents or tailor surface topography offers durable antibacterial performance, mechanical robustness, and strong potential for scalable industrial application in CAUTI prevention.

MATERIAL STRATEGIES ON ANTIMICROBIAL URINARY CATHETERS

Material Substrate (Tubing Catheter)

The choice of material for antimicrobial urine catheters is a fundamental factor in the device's clinical performance, affecting mechanical properties, flexibility, abrasion resistance, and biocompatibility. The right material plays a role in maintaining structural integrity and patient comfort. It determines the effectiveness of preventing biofilm formation and reducing the risk of catheter-associated urinary tract infections (CAUTIs), among healthcare facilities' most common nosocomial infections. In the development of modern catheters, the materials used can be classified into two main categories: substrate materials, which form the basic structure or body of the catheter, and functional materials, which are applied as protective layers or integrated into polymer matrices to provide additional properties such as antimicrobial activity, antifouling capabilities, or lubrication. The optimal combination of these two material categories enables the creation of multifunctional catheters that can fulfill clinical demands while minimizing the risk of infection [31][43].

The choice of tubing material for antimicrobial urinary catheters is critical to their mechanical performance, patient comfort, and resistance to catheter-associated urinary tract infections (CAUTIs) [36]. Among the most widely used materials, silicone has long been considered a gold standard for long-term indwelling catheters due to its excellent biocompatibility, chemical inertness, and flexibility, which help minimize urethral trauma. Its thermal stability allows repeated sterilization without degradation, and its low reactivity reduces the likelihood of mineral encrustation. However, the hydrophobic nature of silicone promotes protein adsorption and bacterial adhesion, making it prone to biofilm formation unless modified with hydrophilic or antimicrobial coatings. Polydimethylsiloxane (PDMS), a specific form of silicone elastomer, offers similar benefits with enhanced elasticity and gas permeability, maintaining softness over extended periods. These properties make PDMS highly compatible with various antimicrobial surface treatments, although it shares the same susceptibility to microbial colonization due to hydrophobicity [44].

Polyurethane (PU) has emerged as another important substrate material, offering higher tensile strength, abrasion resistance, and reduced kink risk compared to silicone. Its flexibility can be tailored through adjustments in polymer composition, enabling customization for different clinical needs [45]. PU's smooth and transparent structure facilitates inspection for encrustation, yet its tendency to adsorb proteins more readily than silicone can accelerate biofilm formation if left

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unmodified. PU catheters are frequently paired with hydrophilic or antimicrobial coatings such as silver or hydrogel layers to address this. Natural latex, traditionally used for short- to medium-term catheters, remains valued for its low cost, high elasticity, and ease of manufacturing. However, the allergenic potential of latex proteins has led to reduced clinical preference, with most latex catheters now requiring silicone or hydrogel coatings to minimize direct tissue contact and prevent hypersensitivity reactions [46].

In recent years, thermoplastic elastomers (TPEs) have gained attention as cost-effective alternatives, combining the elasticity of rubber with the processing advantages of thermoplastics, such as ease of extrusion and molding. TPEs can be engineered to achieve specific hardness, elasticity, and chemical resistance, although long-term clinical evidence supporting their safety and performance remains limited [47]. Other high-performance thermoplastics, including polyetheretherketone (PEEK) and polyvinyl chloride (PVC), are used in specialized catheter designs [48]. PEEK offers exceptional strength and chemical stability for reinforced catheter segments. In contrast, PVC is inexpensive and widely available but limited by rigidity and the risk of plasticizer leaching, restricting its use primarily to short-term or disposable devices. Overall, while each substrate material offers distinct advantages, their ultimate performance in CAUTIs prevention depends heavily on surface modifications and compatibility with functional coatings that can counteract their inherent susceptibility to bacterial adhesion and biofilm development [49]. Table 3 and Figure 2 have been concluded for the term of the tubing material catheter.

Table 3. Classification of antimicrobial urinary catheter materials based on previous research

Material	Function of a Catheter	Key Properties	Advantages	Limitations
Silicone	Main tubing for long-term indwelling	Chemically inert, flexible, thermally stable	Excellent biocompatibility, autoclavable, and patient comfort	Hydrophobic surface prone to biofilm
PDMS	Flexible silicone variant	High gas permeability, elastic, inert	Retains softness, coating-compatible	Hydrophobic, requires surface modification
Polyurethane (PU)	Strong, durable tubing	High tensile strength, abrasion resistance	Tunable flexibility, durable under stress	Higher protein adsorption → biofilm risk
Natural Latex	Elastic tubing	High elongation, low cost	Easy processing, good flexibility	Allergy risk, needs a biocompatible coating
TPE	Alternative tubing material	Rubber-like elasticity, thermoplastic processability	Cost-effective, adaptable manufacturing	Limited clinical use, scarce long-term data

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Material	Function of a Catheter	Key Properties	Advantages	Limitations
Other thermoplastics (PEEK, PVC)	Specialty catheter tubing	High strength, chemical resistance	Niche applications	Less flexible, potential leaching (PVC)

Despite the range of substrate materials available for urinary catheter fabrication, none inherently possess strong and sustained antimicrobial or antifouling properties. Even materials with excellent biocompatibility, such as silicone and PDMS, remain vulnerable to protein adsorption and bacterial colonization due to their hydrophobic nature. At the same time, mechanically robust substrates like PU can still serve as favorable surfaces for biofilm development if left unmodified. Furthermore, materials such as natural latex, TPEs, and certain thermoplastics, although offering cost or processing advantages, often require additional surface treatments to address limitations in allergenicity, chemical stability, or long-term tissue compatibility. These inherent shortcomings highlight the critical role of additional functional materials, including antimicrobial agents, antifouling coatings, and lubricious layers, in transforming a structurally sound substrate into a clinically effective device capable of minimizing the risk of CAUTIs [7], [16]. The strategic integration of these functional layers onto or within the catheter substrate mitigates microbial adhesion and enhances patient comfort, device durability, and overall therapeutic outcomes. The following section discusses the various categories of functional materials used in antimicrobial urinary catheters, their mechanisms of action, and their integration strategies with different substrate types.

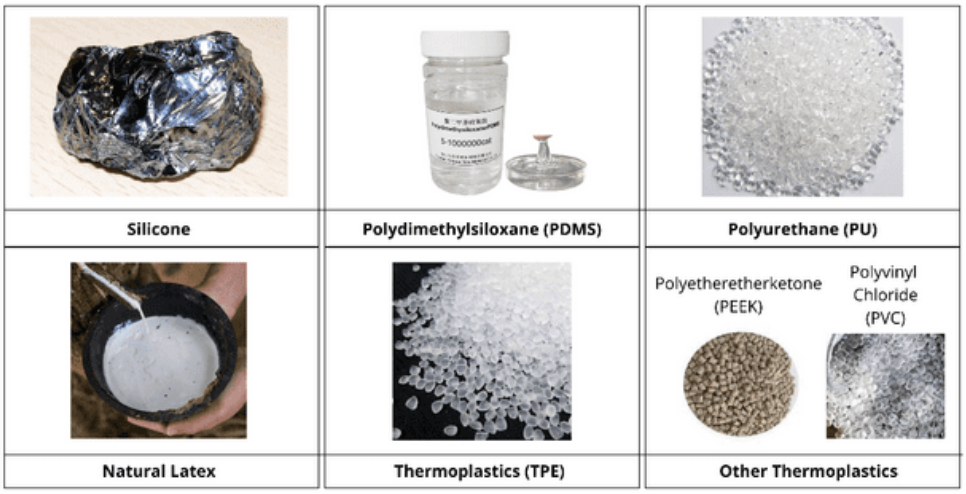


Figure 2. Materials substrate antimicrobial urinary catheter

Additional Materials

While the substrate of a urinary catheter determines its mechanical performance and biocompatibility, it rarely provides intrinsic antimicrobial or antifouling properties sufficient to prevent CAUTIs. Additional functional

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materials are integrated into or onto the catheter surface to address this limitation. These materials are selected to impart specific functionalities such as antimicrobial activity, antifouling behavior, or enhanced lubricity, and are typically applied through coating, impregnation, surface grafting, or composite fabrication techniques. The choice of functional material depends on its intended action mechanism and compatibility with the catheter's substrate.

Metal-based antimicrobial agents, particularly silver (Ag), have been widely employed due to their broad-spectrum activity against bacteria and fungi. Silver ions released from the catheter surface can disrupt bacterial cell walls, interfere with enzymatic systems, and damage nucleic acids [50]. Zinc (Zn) and copper (Cu) offer similar antimicrobial effects, though they are less frequently used in urinary catheters due to concerns over ion release control and potential cytotoxicity [51], [52]. Metal oxides such as zinc oxide (ZnO) and titanium dioxide (TiO_2) function primarily through reactive oxygen species (ROS) generation [53], [54], damaging microbial membranes and intracellular components. ZnO provides continuous antimicrobial activity without light, whereas TiO_2 often requires photoactivation to achieve maximal bactericidal effect [55].

Antibiotic-loaded coatings, such as those incorporating ciprofloxacin, gentamicin, or rifampicin, offer targeted bacterial inhibition through drug-specific biochemical pathways. These coatings can provide potent early-stage antimicrobial protection; however, they often suffer from burst release kinetics, limiting their long-term efficacy and raising concerns about antibiotic resistance [56]. In contrast, nitric oxide (NO) donor systems provide antimicrobial and anti-inflammatory benefits by disrupting bacterial communication (quorum sensing) and inhibiting biofilm formation, simultaneously reducing inflammatory responses in surrounding tissues. The challenge with NO systems lies in achieving controlled, sustained release over clinically relevant time frames [56].

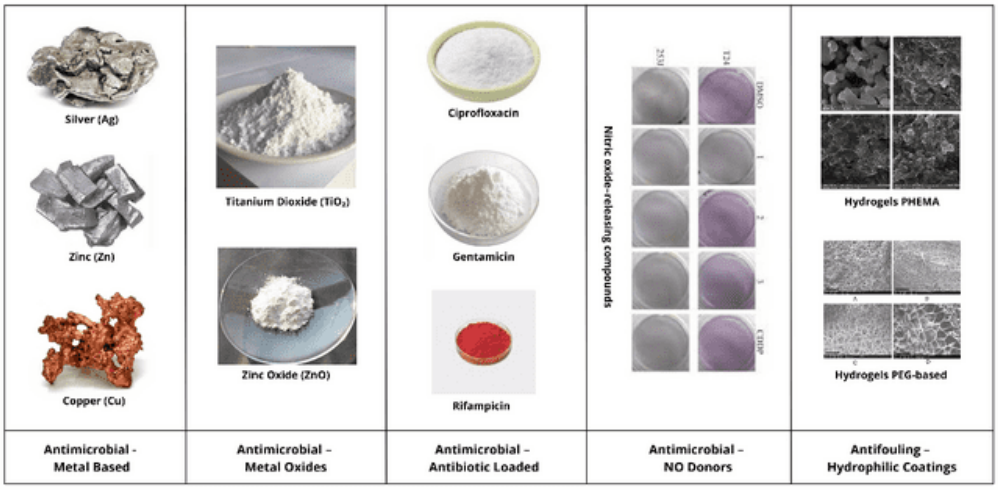
Antifouling strategies aim to prevent initial microbial adhesion by modifying the catheter's surface chemistry. Hydrophilic coatings, such as hydrogels based on poly(2-hydroxyethyl methacrylate) (PHEMA) or polyethylene glycol (PEG), create a hydrated barrier layer that resists protein adsorption and bacterial attachment while also reducing friction during insertion. Zwitterionic polymers, including poly(sulfobetaine methacrylate) and poly(carboxybetaine), use charged moieties to strongly bind water molecules, forming a stable hydration shell that effectively prevents nonspecific adhesion. These antifouling polymers demonstrate superior long-term stability but require more complex synthesis and surface grafting methods. Bioinspired adhesive layers, particularly polydopamine (PDA), serve as versatile platforms for immobilizing other functional agents while also improving coating adhesion to diverse substrates [57], [58].

Lubricious coatings, including silicone-based layers and hydrophilic hydrogel films, are primarily intended to reduce surface friction and improve patient comfort during catheterization. While not inherently antimicrobial, these

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coatings can be combined with antimicrobial agents to achieve multifunctional performance. Emerging approaches involve the incorporation of multifunctional nanomaterials, such as graphene oxide and carbon nanotubes (CNTs), which provide both mechanical reinforcement and antimicrobial activity. These materials can physically damage bacterial membranes while offering unique electrical or chemical properties, inhibiting microbial growth. Similarly, polymer–metal composites, such as polyurethane–silver or silicone–ZnO blends, integrate the substrate's structural benefits with the additive's antimicrobial propertiesproducing durable, synergistic effects [59].

The successful application of these functional materials depends heavily on their compatibility with the chosen catheter substrate. Hydrophobic surfaces such as silicone or PDMS often require activation via plasma treatment or chemical oxidation to achieve strong coating adhesion. In contrast, higher-energy surfaces like polyurethane allow more straightforward bonding. Latex substrates typically require full barrier coatings to mitigate allergen exposure, and specialty thermoplastics such as PEEK or PVC may necessitate surface roughening for effective functionalization. Therefore, the strategic pairing of substrate and functional material plays a decisive role in optimizing the catheter's clinical performance and its ability to prevent CAUTIs [60]. Table 4 and Figure 3 show the classification of additional materials for urinary catheter tubing.



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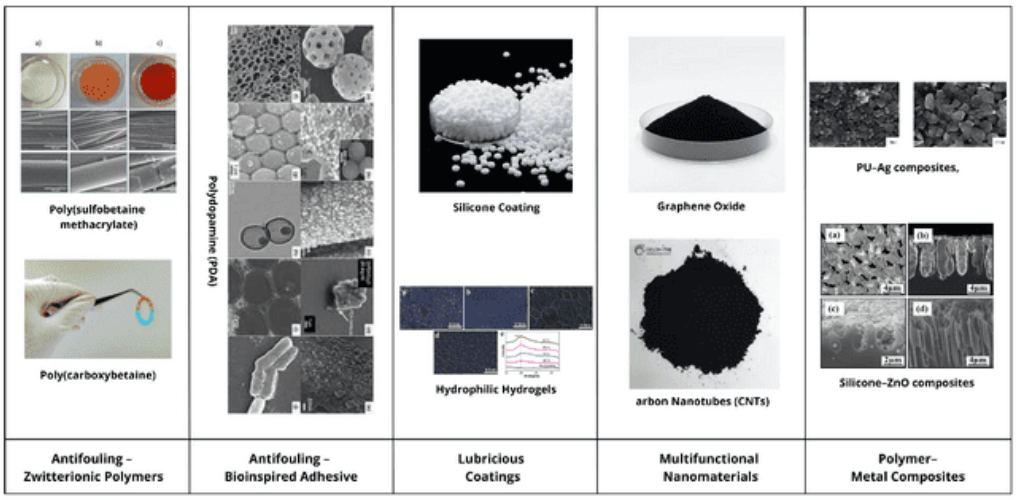


Figure 3. Additive materials antimicrobial urinary catheter

Table 4. Classification of additional materials for urinary catheter tubing

Function Category	Material Examples	Mechanism of Action	Advantages	Limitations
Antimicrobial – Metal-based	Silver (Ag), Zinc (Zn), Copper (Cu)	Ion release disrupts bacterial cell membranes, proteins, and DNA	Broad-spectrum activity, effective against bacteria and fungi	Potential cytotoxicity if ion release is uncontrolled; higher cost (Ag)
Antimicrobial – Metal Oxides	Zinc Oxide (ZnO), Titanium Dioxide (TiO_2)	ROS generation damages microbial cells	Stable, long-lasting activity can be combined with polymers	TiO_2 requires light activation for optimal effect
Antimicrobial – Antibiotic-loaded	Ciprofloxacin, Gentamicin, Rifampicin	Direct inhibition of bacterial growth via drug-specific mechanisms	High efficacy against targeted pathogens	Risk of antibiotic resistance; burst release limits duration
Antimicrobial – NO Donors	Nitric oxide–releasing compounds	Diffuses into biofilm, disrupts bacterial signaling, and is anti-inflammatory	Dual antimicrobial and anti-inflammatory effects	Controlled, sustained release is technically challenging
Antifouling – Hydrophilic Coatings	Hydrogels (PHEMA, PEG-based)	Form a hydration layer preventing protein/bacterial adhesion	Improves patient comfort, reduces biofilm formation	Swelling, long-term degradation
Antifouling – Zwitterionic Polymers	Poly(sulfobetaine methacrylate), Poly(carboxybetaine)	Hydration shell blocks nonspecific adhesion	Highly effective antifouling, stable hydration layer	Complex synthesis and surface grafting

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Function Category	Material Examples	Mechanism of Action	Advantages	Limitations
Antifouling – Bioinspired Adhesive	Polydopamine (PDA)	Strong adhesion to substrate, platform for further functionalization	Compatible with various coatings, stable in many conditions	Potential degradation in prolonged exposure to physiological fluids
Lubricious Coatings	Silicone coating, Hydrophilic hydrogels	Reduce surface friction during insertion and use	Lower patient discomfort, easier insertion	Wear and tear may reduce lubricity over time
Multifunctional Nanomaterials	Graphene oxide, Carbon nanotubes (CNTs)	Mechanical reinforcement + antimicrobial activity	Strong, conductive, synergistic antimicrobial effect	Dispersion control in polymers is difficult
Polymer–Metal Composites	PU–Ag composites, Silicone–ZnO composites	Combines substrate strength with antimicrobial activity	Enhanced durability, broad-spectrum antimicrobial	Complex fabrication and cost factors

In summary, additional functional materials play a pivotal role in transforming a structurally sound urinary catheter substrate into a clinically effective device capable of resisting biofilm formation and reducing the incidence of CAUTIs. However, successfully integrating these functional layers depends on their inherent antimicrobial or antifouling efficacy and compatibility with the substrate's chemical composition, surface energy, and physical properties. As highlighted in Table 5, different substrate materials present unique challenges and opportunities for coating adhesion, durability, and functional performance. This interplay between substrate and functional material dictates the selection of fabrication techniques ranging from surface activation and dip-coating to in situ polymerization or composite blending that can ensure strong bonding, sustained activity, and minimal alteration of the catheter's mechanical or biocompatibility profile. Therefore, understanding these compatibility parameters forms the foundation for developing optimized fabrication strategies, which will be discussed in the following section.

Table 5. Compatibility of additional functional materials with different substrate tubing

Substrate Material	Compatible Additional Materials	Notes on Compatibility
Silicone	Silver, ZnO, TiO_2, Antibiotic coatings, NO donors, Hydrogels, Zwitterionic polymers, Polydopamine	A hydrophobic surface requires surface activation (e.g., plasma treatment) before coating; it has excellent long-term stability once modified.

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PDMS	Similar to silicone: Silver, ZnO, TiO_2, Antibiotic coatings, NO donors, Hydrogels, Zwitterionic polymers, Polydopamine	High coating adhesion after surface oxidation; maintains flexibility with most coatings.
Polyurethane (PU)	Silver, ZnO, TiO_2, Antibiotic coatings, Hydrogels, Zwitterionic polymers, Polydopamine, Polymer–metal composites	Higher surface energy than silicone → better coating adhesion; risk of degradation with some solvents used in coating processes
Natural Latex	Silicone coating, Hydrogel coating, Silver impregnation	Coating acts as a barrier to prevent allergen exposure; hydrophilic coatings improve comfort
Thermoplastic Elastomers (TPE)	Silver, ZnO, TiO_2, Hydrogels, Zwitterionic polymers	Coating adhesion depends on specific TPE chemistry; surface pre-treatment is often needed
PEEK	Silver nanoparticles, TiO_2, Graphene oxide	Requires roughening or plasma activation for strong coating adhesion
PVC	Silver, ZnO, Antibiotics	Often used for short-term catheters; compatibility is limited by potential plasticizer migration affecting coating stability

FABRICATION STRATEGIES ON ANTIMICROBIAL URINARY CATHETERS

The fabrication of antimicrobial urinary catheters is a multifaceted process that combines the creation of a mechanically robust and biocompatible substrate with the effective integration of functional materials to prevent microbial adhesion and biofilm formation [61]. The fabrication strategy selection depends on the substrate's physicochemical properties, type and function of the additional material, and the intended clinical application [62]. Since the substrate alone rarely offers intrinsic antimicrobial properties, fabrication approaches must ensure strong adhesion of functional coatings and preservation of catheter flexibility, patient comfort, and biocompatibility [19].

The first critical step in many fabrication workflows is surface activation and modification, particularly for substrates with low surface energy such as silicone and PDMS. While biocompatible and flexible, these materials present hydrophobic surfaces that hinder coating adhesion. Plasma treatment, corona discharge, or chemical oxidation can introduce polar functional groups, increase wettability, and enable strong bonding with hydrophilic or antimicrobial layers. In contrast, polyurethane (PU), which possesses higher surface energy, generally allows better direct adhesion, although mild activation can improve coating uniformity and longevity. For substrates like natural latex, thermoplastic elastomers (TPEs), or PVC, surface primers and barrier coatings are applied both

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to enhance compatibility with functional materials and to address specific clinical risks such as allergen exposure or plasticizer migration [63], [64].

After surface preparation, coating techniques are the most common method for functionalizing urinary catheters. Due to their simplicity and scalability, methods such as dip-coating and spray-coating are widely used for applying silver nanoparticles, antibiotic films, or hydrophilic hydrogels. More advanced approaches, such as layer-by-layer (LbL) assembly, enable precise control over coating thickness and allow for the sequential deposition of multiple functional layers, for example, an antifouling hydrogel base followed by an antimicrobial topcoat [65]. For applications requiring durable performance, chemical grafting or in situ polymerization can covalently bond functional polymers, such as zwitterionic materials or PEG derivatives, to the catheter surface, ensuring long-term stability even under continuous fluid exposure [66].

In applications where a sustained release of antimicrobial agents is desired, impregnation and loading methods are employed. These techniques involve incorporating active agents—such as silver ions, antibiotics, or nitric oxide donors—into the catheter matrix or onto its surface [31]. Conventional soaking allows passive diffusion of active molecules into the polymer, while supercritical CO_2-assisted impregnation offers deeper penetration without leaving harmful solvent residues. Drug-loaded polymer carriers, microcapsules, or nanoparticles can be embedded within the catheter wall, releasing the active agents gradually to maintain long-term antimicrobial activity without compromising flexibility [67].

Beyond surface-based approaches, composite fabrication integrates functional materials directly into the bulk of the catheter substrate during manufacturing. Melt blending, extrusion, and injection molding allow antimicrobial agents such as silver nanoparticles, ZnO, or graphene oxide to be uniformly distributed within the polymer matrix. This strategy ensures that antimicrobial properties persist even if the catheter's surface becomes scratched or worn [68], [69]. However, composite approaches require precise control over additive dispersion and concentration to avoid altering the mechanical or biocompatibility profile of the base material.

Recent developments have moved toward hybrid and multifunctional strategies that combine multiple fabrication techniques to maximize efficacy. For example, a catheter may be extruded as a polymer silver composite to provide intrinsic antimicrobial protection, followed by surface grafting of a hydrophilic hydrogel to reduce friction and prevent initial bacterial adhesion. Similarly, a polydopamine adhesive layer can be applied to enhance coating adhesion, then functionalized with nitric oxide donors for dual antimicrobial and anti-inflammatory benefits. Such multifunctional designs recognize that CAUTIs prevention is a multifactorial challenge, requiring simultaneous microbial colonization, biofilm formation, and patient comfort management.

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A consolidated overview of these fabrication methods, including their compatible substrates, advantages, and limitations, is presented in Table 6. This summary enables direct comparison of different approaches, linking the choice of strategy to the type of functional material and the substrate's physical and chemical characteristics. By aligning fabrication techniques with the compatibility profiles described earlier in Table 3, manufacturers can design catheters that meet mechanical and biocompatibility requirements and provide clinically effective infection prevention. The integration of materials science and fabrication engineering underpins the development of next-generation antimicrobial urinary catheters.

Table 6. Summary of fabrication strategies for antimicrobial urinary catheters

Functional Material Type	Compatible Substrate	Fabrication Strategy	Key Advantages	Limitations / Considerations
Silver (Ag), Zn, Cu nanoparticles	Silicone, PDMS, PU, Latex, TPE	Dip-coating, Spray-coating, Layer-by-layer (LbL) deposition, Impregnation	Broad-spectrum antimicrobial, long-lasting	Need controlled ion release to avoid cytotoxicity; coating adhesion depends on substrate activation.
Metal oxides (ZnO, TiO_2)	Silicone, PDMS, PU, PEEK	Dip-coating, Sol–gel coating, Composite blending (extrusion, molding)	Stable activity, ROS generation	TiO_2 often needs light activation; dispersion uniformity is critical in composites.
Antibiotic coatings (ciprofloxacin, gentamicin, rifampicin)	Silicone, PDMS, PU, PVC	Impregnation, Layer-by-layer assembly, Polymer carrier embedding	High initial antimicrobial effect	Risk of burst release and antibiotic resistance
Nitric oxide donors	Silicone, PDMS, PU	Impregnation with NO donor polymers, Coating over adhesive primer (e.g., PDA)	Dual antimicrobial & anti-inflammatory effect	Challenging sustained release control
Hydrophilic hydrogels (PHEMA, PEG)	Silicone, PDMS, PU, Latex	Dip-coating, Photopolymerization, Chemical grafting	Reduces friction, antifouling, and improves comfort	Potential swelling or degradation in long-term use
Zwitterionic polymers	Silicone, PDMS, PU	Surface grafting, LbL assembly	Strong antifouling via hydration shell	Complex synthesis, higher cost
Polydopamine (PDA)	Silicone, PDMS, PU, Latex, PEEK	Dip-coating (self-polymerization), Spray deposition	Strong universal adhesion, primer for further coating	May degrade over very long exposure to physiological fluids

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Functional Material Type	Compatible Substrate	Fabrication Strategy	Key Advantages	Limitations / Considerations
Lubricious coatings (silicone, hydrogel films)	Latex, PU, PVC	Dip-coating, Thermal curing	Lower friction, improved insertion	Not inherently antimicrobial; may require a dual-functional layer
Nanomaterials (Graphene oxide, CNTs)	PU, PEEK, Silicone	Composite blending, Electrophoretic deposition	Mechanical reinforcement + antimicrobial	Dispersion control is a critical cost factor
Polymer–metal composites	PU, Silicone, TPE	Melt blending, Extrusion, Injection molding	Integrated antimicrobial + mechanical performance	Uniform dispersion is needed to maintain mechanical integrity

In conclusion, the selection and optimization of fabrication strategies for antimicrobial urinary catheters must be approached as a multidimensional design process, where substrate compatibility, functional material properties, and manufacturing feasibility converge to define clinical performance [15], [22], [43], [70]. As outlined in Table 6, each fabrication method offers distinct advantages, whether in achieving sustained antimicrobial release, enhancing antifouling resistance, or improving patient comfort. However, each also presents limitations that must be carefully managed through engineering and material science solutions. Integrating hybrid and multifunctional approaches signals a shift toward more sophisticated catheter designs capable of addressing the complex pathophysiology of CAUTIs. Future research will likely focus on scalable fabrication methods that enable precise control over surface chemistry and microstructure, ensuring regulatory compliance and cost-effectiveness for widespread clinical adoption. By bridging advances in biomaterials with innovative manufacturing technologies, the next generation of urinary catheters holds the potential to significantly reduce infection rates, extend device longevity, and improve patient outcomes.

DISCUSSION

While multiple fabrication strategies have been proposed for antimicrobial urinary catheters, several important research gaps and limitations remain. Coating-based approaches such as dip-coating, spray-coating, sol–gel deposition, and layer-by-layer assembly demonstrate strong initial antimicrobial activity and tunable drug release. However, their performance often declines over time due to coating delamination, burst release kinetics, or cytotoxicity concerns. Moreover, varying coating adhesion across different catheter substrates limits their universal applicability. Impregnation and bulk modification methods (e.g., incorporating antibiotics, silver nanoparticles, or hybrid composites) provide more durable

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antimicrobial effects since efficacy is maintained even after surface wear. However, these approaches face challenges in controlling uniform dispersion, avoiding mechanical property degradation, and minimizing the risk of antimicrobial resistance. The potential emergence of multidrug-resistant organisms particularly limits antibiotic-based impregnation.

Advanced strategies, including multifunctional nanomaterials, zwitterionic coatings, and bioinspired surface engineering, show promise in simultaneously delivering antimicrobial, antifouling, and lubricious effects. However, these technologies remain preclinical, with limited data on long-term biocompatibility, large-scale manufacturing, and regulatory approval. From a translational perspective, the scalability and cost-effectiveness of these fabrication strategies are critical barriers to clinical adoption. Many promising laboratory techniques (e.g., nanostructured coatings, plasma-based activation) are resource-intensive and difficult to adapt for mass production. Furthermore, few comparative clinical trials have systematically evaluated different strategies' long-term efficacy and safety in preventing CAUTIs. A summary of strengths, limitations, and research gaps for each major fabrication method is presented in Table 7, providing an integrated overview that complements the descriptive findings in earlier sections.

Table 7. Research gaps and limitations of antimicrobial catheter fabrication strategies

Fabrication Method	Strengths	Main Limitations / Gaps
Surface Coatings (dip-coating, spray, sol–gel, LbL)	Controlled antimicrobial release, simple and scalable	Risk of delamination, burst release, reduced long-term efficacy, cytotoxicity concerns
Impregnation (antibiotics, silver, etc.)	Sustained release, effective against MDR strains	Risk of resistance, difficulty in dose control, and potential toxicity
Composite Blending / Bulk Modification	Antimicrobial effect maintained despite surface wear, durable	Nanoparticle dispersion challenges, altered mechanical properties, and cost
Chemical Grafting & Surface Modification	Strong adhesion, long-term stability	Complex synthesis, limited scalability, high cost
Multifunctional / Nanomaterial Strategies	Combine antimicrobial, antifouling, and lubricious effects	Preclinical stage, uncertain long-term safety, regulatory hurdles
Thermoplastic Processing (extrusion, injection, melt blending)	Improved mechanical stability, scalable for industry	Limited antimicrobial activity unless combined with coatings or fillers

Overall, future research should focus on: (i) integrating multifunctional coatings with durable bulk modifications, (ii) addressing antibiotic resistance through non-traditional antimicrobial agents, (iii) developing standardized testing protocols that reflect clinical conditions, and (iv) advancing scalable, regulatory-compliant fabrication methods. Addressing these challenges will be essential to translate promising laboratory innovations into effective clinical solutions for reducing the global burden of CAUTIs.

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CONCLUSION AND FUTURE PERSPECTIVE

Antimicrobial urinary catheters represent a critical innovation in the ongoing effort to reduce the incidence of CAUTIs, one of the most prevalent healthcare-associated infections worldwide. This review highlights that the effectiveness of these devices depends on two fundamental factors: the intrinsic properties of the substrate material and the successful integration of additional functional layers or agents. While substrate materials such as silicone, polyurethane, and thermoplastic elastomers offer mechanical robustness and biocompatibility, they rarely possess inherent antimicrobial properties. Therefore, functional materials—including silver-based agents, metal oxides, antibiotics, nitric oxide donors, hydrophilic hydrogels, and zwitterionic polymers—are indispensable in imparting targeted antimicrobial and antifouling effects.

Fabrication strategies, ranging from surface activation and coating techniques to impregnation, composite blending, and hybrid multifunctional approaches, must be carefully matched to the chemical nature and the physical requirements of the chosen substrate. This review summarizes that this compatibility determines the antimicrobial layer's stability and effectiveness, and the catheter's overall clinical performance. Therefore, the convergence of material selection and fabrication engineering forms the foundation for developing catheters that deliver long-term infection prevention and patient comfort.

Three major trends will likely drive the next generation of antimicrobial urinary catheters. First, integrating multifunctional properties—combining antimicrobial, antifouling, and lubricious effects into a single, durable system—will be essential for addressing the multifactorial causes of CAUTIs. Second, precision fabrication methods, including additive manufacturing, bioinspired surface engineering, and nanostructured coatings, will allow more controlled functionalization while preserving mechanical and biocompatibility profiles. Third, sustainable and scalable production, focusing on cost-effectiveness and regulatory compliance, will be critical for enabling widespread adoption in clinical practice. Collaborative efforts between materials scientists, biomedical engineers, and clinicians will be key to translating laboratory innovations into commercially viable, high-performance catheters capable of significantly reducing the global burden of CAUTIs.

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