1.2.5.1 Chemical Structure and Mechanism of Action

Positively charged dendritic polymers, such as poly(amidoamine) dendrimers functionalized with amine or quaternary ammonium groups, have been widely studied for their potent antimicrobial properties. These polymers exhibit a highly branched structure with a high density of positively charged at their surface, which plays a critical role in their interaction with bacterial cells. First, the cationic groups on the polymer surface are attracted to the anionic components of the bacterial membrane, such as phospholipids and lipopolysaccharides. This interaction disrupts the membrane's integrity, leading to increased permeability and eventual leakage of intracellular contents. Meanwhile, the dense, multivalent nature of dendritic polymers enhances their binding affinity to bacterial cells compared to linear or less branched polymers. That allows the polymers to interact simultaneously with multiple sites on the bacterial membrane, further amplifying their antimicrobial efficiency (see Figures 1.6a, b). Moreover, the structure of dendritic polymers can be easily tuned by modifying their generation or surface functionalities, allowing for the optimization of their antimicrobial properties [105, 106].

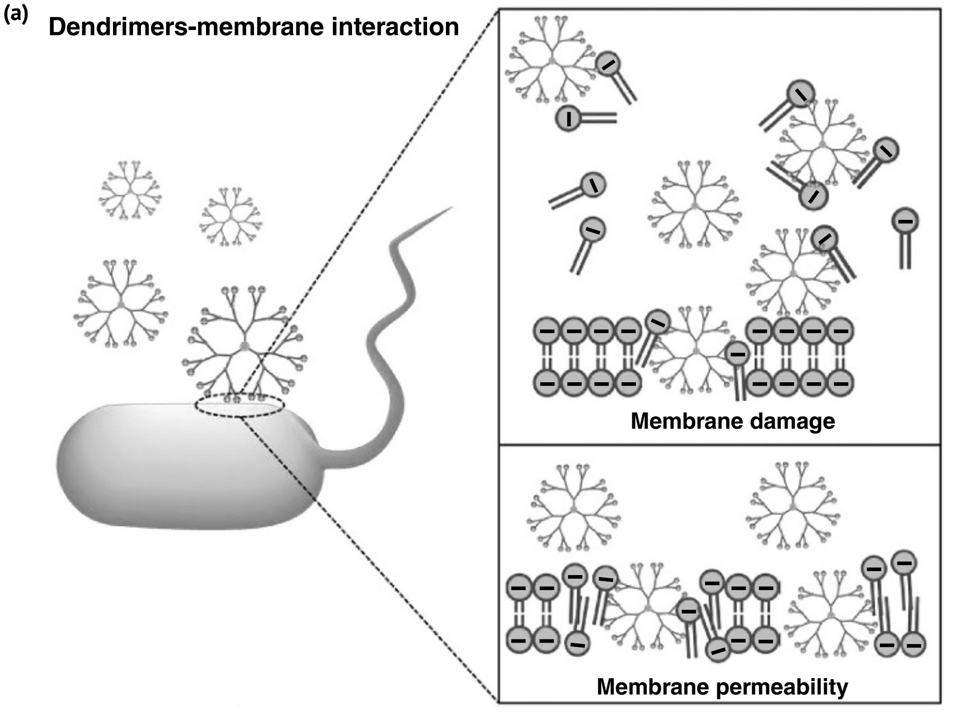

Figure 1.6 Illustration of dendritic polymer interactions with bacterial biofilms and their role in drug delivery. (a) The interaction of dendrimers with bacterial cells, which generally includes damage of bacterial cell membrane and membrane permeability by dendrimers. *Source:* Reproduced with permission of Elsevier [121]. (b) Dendritic systems presented a high efficacy against multidrug-resistant bacteria. *Source:* Reproduced with permission of the Royal Society of Chemistry [122]. (c) Heterofunctionalized poly-(amido-amine) dendrimers, as the drug carriers, with amide-conjugated vancomycin and incorporated Ag nanoparticles, showed a significant reduction in colony-forming units of a vancomycin-resistant *S. aureus* strain, while not inducing resistance in a vancomycin-susceptible strain. *Source:* Reproduced with permission of the Elsevier [110].

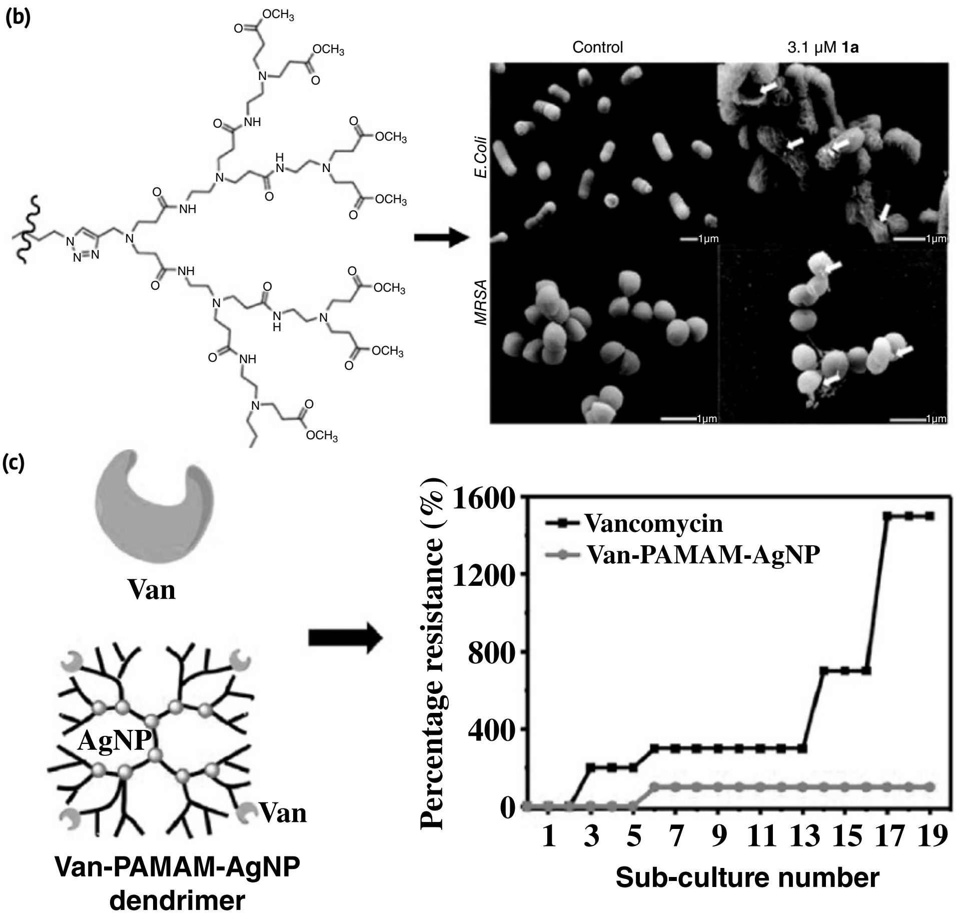

Figure 1.6 (Cont'd)

1.2.5.2 Applications

1.2.5.2.1 Medical Applications

Hyperbranched and dendritic polymers have found extensive use in medical devices and wound care. It is worth mentioning that the adhesion of pathogenic bacteria and the formation of biofilm on the implant are the most common causes of failure of medical devices. Thus, different types of amphiphilic dendrimers have been developed due to their superior antibacterial and antifouling activity. For example, a hierarchical surface integrating both a geminized cationic amphiphilic antibacterial upper layer and a zwitterionic antifouling sublayer has been developed. The hierarchical surface can eradicate almost all *S. aureus* and *E. coli* bacterial cells within 30 minutes. Moreover, this novel hierarchical surface holds great potential for the prevention of protein adhesion and biofilm formation on the surfaces, displaying a certain antifouling capacity, making the hierarchical platform a great potential candidate material for future applications in the field of implantable medical devices [107]. In wound healing, dendritic polymers functionalized hydrogel can provide both infection control and tissue repair, accelerating the healing process in chronic wound models. Cationic dendritic hydrogels were fabricated by chemically cross-linking trans-1,4-cyclohexanediamine with 1,3-dibromo-2-propanol using a condensation reaction. The prepared hydrogel possessed an inherent antibacterial ability that can kill effectively *S. aureus* and *E. coli*. Furthermore, *in vivo* experiments confirmed that the hydrogel can quickly stop bleeding, efficiently eradicate the bacterial infection, promote the conversion of macrophages from the pro-inflammatory M1 phenotype to the anti-inflammatory M2 phenotype, and accelerate collagen deposition and blood vessel formation, thereby promote rapid wound healing [108]. Additionally, hyperbranched polysaccharide derivatives have been employed in advanced wound dressings, where they demonstrated broad-spectrum antimicrobial activity and biocompatibility [109].

1.2.5.2.2 Drug Delivery Systems

The unique architecture of hyperbranched and dendritic polymers has been leveraged in drug delivery applications to enhance the solubility and stability of antimicrobial agents. First, the dendritic structure in dendritic polymers provides a large number of terminal functional groups on the polymer surface, which can be chemically modified to bind antimicrobial agents. Also, dendritic polymers have a well-defined, globular structure with internal cavities, which can encapsulate hydrophobic or hydrophilic drugs inside these cavities, protect them from enzymic degradation, and enhance their stability during transport. For example, heterofunctionalized, poly-(amido-amine) dendrimers were prepared as the delivery systems, to which vancomycin was covalently conjugated and Ag nanoparticles were physically loaded (see Figure 1.6c). The dual conjugation of vancomycin and Ag nanoparticles in PAMAM dendrimers showed a 6–7 log reduction in colony-forming units of a vancomycin-resistant *S. aureus*, while not inducing resistance in a vancomycin-susceptible strain. Moreover, that can also significantly faster and more effectively promote healing of a superficial wound infected with vancomycin-resistant *S. aureus* than traditional antibiotics [110]. Thus, hyperbranched polymeric micelles loaded with antibiotics can improve drug encapsulation efficiency and target delivery to infection sites, reducing systemic toxicity and improving therapeutic outcomes [111].

1.2.5.2.3 Environmental Applications

In water treatment, hyperbranched polymers functionalized with cationic groups have been incorporated into filtration membranes because of their high water permeability and low operation pressure, as a result, reducing the operation cost and energy consumption. For example, poly(tetrafluoroethylene) (PTFE) membrane has been grafted with hyper-branched poly(amidoamine) for the removal of Cu(II) cations from aqueous media. The experiment showed that relatively at low operation pressure (25 kPa), the water flux through the grafted PTFE membrane was higher than the PTFE membrane before modification due to the increase in its hydrophilicity. The grafted membrane was able to adsorb 1.42 g Cu^2/m^2 [112].

1.2.5.3 Recent Advances and Innovations

Dendritic polymers have emerged as a versatile class of macromolecules with significant advancements in recent years. Dendritic polymers play an increasing role in drug delivery systems. Researchers have developed dendrimers and hyperbranched polymers with stimuli-responsive properties, enabling controlled drug release triggered by pH, temperature, or enzymatic activity [113, 114]. For instance, dendritic polymers with acid-sensitive linkages have been designed to release chemotherapeutic agents selectively in acidic tumor microenvironments, minimizing systemic toxicity and enhancing therapeutic efficacy [114]. Additionally, surface functionalization with targeting ligands, such as antibodies or peptides has been used to improve the ability of these polymers to selectively deliver drugs to specific tissue sites [115].

In addition, energy storage and conversion have also benefited from the development of dendritic polymers. Their high surface area and ability to host functional groups make them ideal for use in batteries, fuel cells, and supercapacitors [116, 117]. For example, dendritic polymers have been employed as ion-conducting membranes or as supports for metal catalysts, which enhance the performance and stability of energy systems. Furthermore, their customizable structure enables the fine-tuning of conductivity and mechanical properties, addressing critical challenges in energy-related applications [118].

1.2.5.4 Advantages and Limitations

The primary advantage of dendritic polymers lies in their highly branched structure, which provides a large surface area with numerous terminal groups. These functional groups enable extensive chemical modification, allowing for tailored interactions with specific targets. That is particularly important in applications such as drug delivery, where functional groups can be used to conjugate therapeutic agents, targeting ligands, or stimuli-responsive moieties. Meanwhile, the interior cavities of dendritic polymers can provide spaces for encapsulating small molecules, including drugs, dyes, or catalysts. This encapsulation protects sensitive molecules from degradation, broadening the utility of dendritic polymers in drug delivery, imaging, and catalysis [119, 120].

However, some points also limit their further application in different fields. The synthesis of dendritic polymers often involves multiple iterative steps, including protection, activation, and deprotection reactions, which make the process time-consuming and may limit their large-scale production. Moreover, a potential cytotoxicity associated with dendritic polymers, especially those with cationic functional groups, raises concerns about their practicality for applications in the biomedical field. Surface modification of dendrimers with biocompatible molecules or groups such as PEG, has been employed to mitigate this issue, but they add complexity to the production process and increase production costs [120]. Thus, simplifying production methods and improving cost-effectiveness are critical for their broader adoption.

1.2.6 Hybrid Systems

Hybrid systems represent an innovative approach in the field of cationic polymers, which combines the inherent antimicrobial properties of cationic polymers with the unique functionalities of other materials, such as nanoparticles, natural extracts, and photodynamic agents [110, 123, 124]. By integrating multiple components, hybrid systems can achieve enhanced and broad-spectrum antimicrobial efficacy (see Figure 1.7). Thus, these systems have gained significant application in medical, environmental, and industrial sectors.

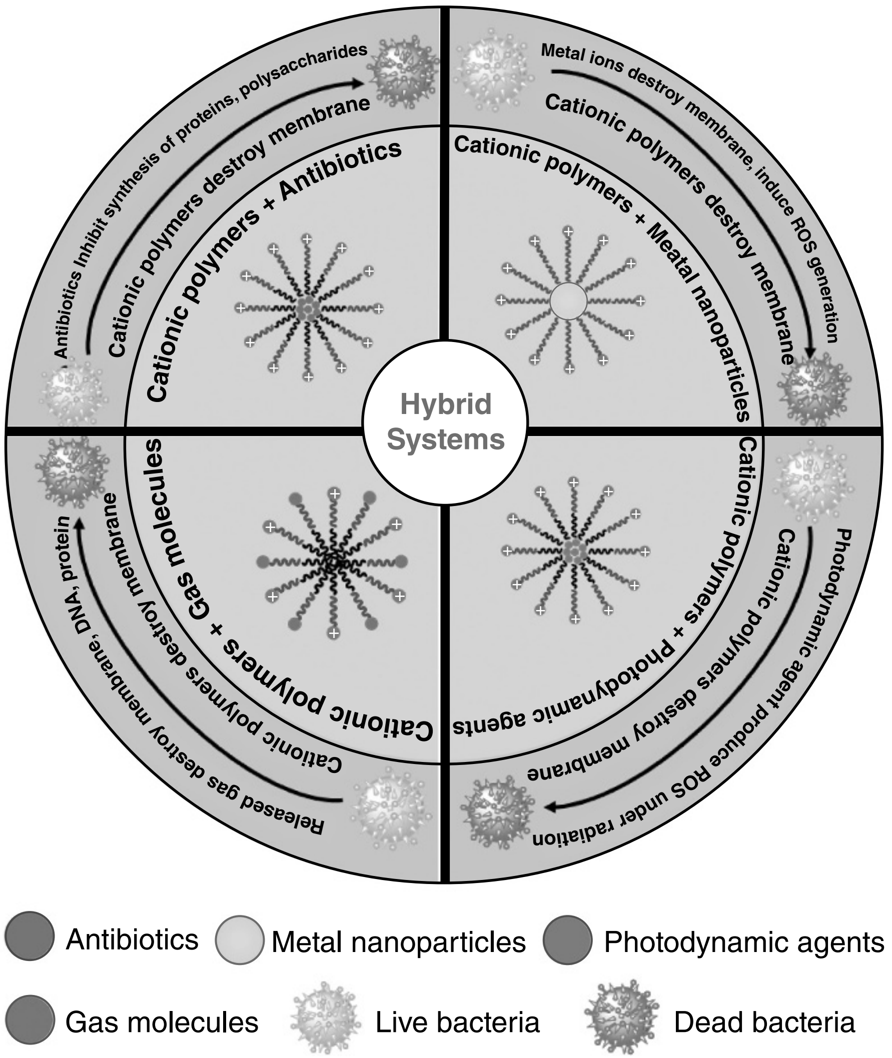

Figure 1.7 Illustration of hybrid systems combining cationic polymers and other methods for killing bacteria.

1.2.6.1 Chemical Structure and Mechanism of Action

Hybrid systems, integrating cationic polymers with additional components, can harness the advantages of each component and generate synergistic effects. For instance, when hybrid systems consist of cationic polymers with nanoparticles such as silver, gold, or zinc oxide nanoparticles, these nanoparticles can produce antimicrobial activity by releasing metal ions that disrupt bacterial metabolic pathways, while cationic polymers target and destroy bacterial membranes through electrostatic interactions [125, 126]. This dual action achieves synergistic antimicrobial efficiency and significantly reduces the development of resistant bacteria. Similarly, the incorporation of natural extracts into hybrid systems, such as essential oils, also provides complementary antimicrobial mechanisms. The essential oils can eradicate bacteria by inhibiting enzymatic pathways and disrupting membranes. On the other hand, cationic polymers can destroy bacterial membranes through electrostatic and hydrophobic interactions. As a result, these combined actions result in enhanced efficacy and reduced microbial resistance [127].

1.2.6.2 Applications of Hybrid Systems

1.2.6.2.1 Medical Applications

Hybrid systems incorporating cationic polymers and other systems have shown great promise in preventing biofilm formation and treating infections associated with medical devices. For example, cationic poly-(amido-amine) dendrimers were applied to physically load Ag nanoparticles to eradicate the infection resulting from vancomycin-resistant *S. aureus*. The hybrid systems showed a 6–7 log-units reduction of both *S. aureus* and *E. coli* while not inducing resistance in a vancomycin-susceptible strain. Moreover, that can also significantly faster and more effectively promote the healing of a superficial wound infected with vancomycin-resistant *S. aureus* than traditional antibiotics, presenting a great potential to be a coating for catheters and orthopedic implants [110]. In wound care, a hybrid system combining cationic polymers with photodynamic therapy agents provided dual-mode action, eradicating bacterial infection and preventing the formation of biofilms. For example, the photosensitizer Ce6-loaded polyethyleneimine-based micelle was constructed by a cationic dendritic polymer and physically loaded with photosensitizer Ce6. Cationic polymers can promote the interaction between photosensitizer and negatively charged bacteria, resulting in enhanced targeting of photosensitizer and lethality of photodynamic therapy, and remain active for a longer duration to prevent bacterial re-growth when removing the light. The hybrid system can reduce 4 log-units of Gram-negative *E. coli* with visible light irradiation for 5 minutes, which was usually insensitive to photosensitizers. Moreover, the cationic polymer and photodynamic combination also exerted significant inhibitory and ablative effects on fungi and biofilms [128].

1.2.6.2.2 Environmental Applications

Hybrid systems have been extensively employed in water treatment and environmental remediation. Graphene oxide-cationic polymer composites demonstrated high efficacy in removing bacterial contaminants and organic pollutants from wastewater, making them suitable for large-scale water purification systems [79]. For example, a kind of magnetic graphene oxide/cationic hydrogel hybrid system was synthesized for an organic dye acid red 88 (AR88) removal. Given the numerous cationic functional groups within its backbone, the hybrid system can adsorb component anionic AR88 uptake through electrostatic attraction. As a result, the cationic hybrid system exhibited an AR88 adsorption capacity of more than 1140.2 mg g^{-1} in a strongly alkaline solution (pH $>$ 10), which indicated that the hybrid system was a reusable adsorbent for the fast and highly efficient removal of AR88 from wastewater [129]. In industrial pipelines, hybrid coatings combining cationic polymers have been developed to maintain the pipeline body against corrosion and degradation by harsh environments. Acrylic-polyurethane hybrid coatings were prepared by mixing metal oxide pigment acrylic emulsion (AC) with polyurethane (PU) polymer using the traditional physical blend method. Subsequently, the modified acrylic emulsion (AC-PU) was then enriched with a novel mixed metal pigment of ($CoO.ZnO.Al_3O_4$) based on bauxite ore as a natural source of alumina. The results showed that the coating formulated with AC mixed with 15% polyurethane in the presence of the prepared pigment offered higher corrosion protection toward pipelines compared to the other formulations and the parent polymers [130].

1.2.6.2.3 Food Packaging

Hybrid systems have found applications in food packaging, where they inhibit the growth of foodborne pathogens and extend the shelf life of perishable goods. For example, cationic polymer films embedded with essential oils effectively reduce microbial contamination and preserve freshness during transportation and storage. Here, essential oil (LEO) was encapsulated with cationic chitosan (CS) to prepare a sustained-release natural essential oil nanocapsule. Subsequently, the as-prepared essential oil nanocapsules were added into grass carp collagen (GCC) as the film-forming matrix to prepare edible films. Edible GCC/CS-LEO films exhibited excellent morphology, oxygen permeability (OP), and superior antibacterial properties due to the presence of essential oil and CS. Importantly, GCC/CS-LEO film can be applied as chilled pork packaging with great preservative and antioxidant efficacy for 21 days [131].

1.2.6.3 Recent Advances and Innovations

Hybrid systems that combine cationic polymers with other materials represent a burgeoning area of research, which further enhances their functionality and broadens the application range. Herein, this section explores recent advances in the development and innovation of these hybrid systems.

One of the innovation directions is the integration of cationic polymers with metal nanoparticles, such as silver, gold, and zinc oxide nanoparticles. These hybrid systems not only can interact with bacterial membranes through the electrostatic interactions of cationic polymers, but also the metal ions released from the hybrid systems can yield a synergistic antibacterial effect [110].

Another significant advancement is the combination of cationic polymers with carbon-based nanomaterials, such as graphene oxide (GO) and carbon nanotubes (CNTs). These materials provide unique properties such as high surface area, electrical conductivity, and mechanical strength. For example, GO incorporated in hybrid systems physically disrupts bacterial membranes due to its sharp edges and high surface area, while cationic polymers disrupt bacterial membranes through electrostatic interactions with negatively charged microbial surfaces. The dual antibacterial mechanism ensures synergistic and effective eradication efficacy of bacterial infection [132].

In addition, the combination of photodynamic and/or photothermal agents with cationic polymers achieves controllable treatment against microbial infections by switching radiation sources between on and off state, improving treatment efficiency, and also minimizing toxic side effects on normal tissues [124, 132].

1.2.6.4 Advantages and Limitations

Hybrid systems excel in achieving multifunctional antimicrobial action, combining the strengths of cationic polymers with complementary components. Their versatility allows for tailored solutions across diverse applications. However, this combination is also a double-edged sword to some extent. From the perspective of clinical application, the combination of cationic polymers and other materials improves the antibacterial activity, but they also make the system more complicated, including material preparation, and purification, and thus may lead to a high cost. At the same time, when these hybrid systems are used in clinical practice, the components in this system may interact with the complex tissue environment and lead to unpredictable negative results. Thus, up to what extent this will affect clinical translation of the use of hybrid systems as a new, non-antibiotic-based infection control strategy remains to be seen.

1.3 Summary and Outlook

Cationic polymers have established themselves as versatile and powerful antimicrobial materials, addressing a wide range of challenges across medical, environmental, and industrial domains. Their ability to interact with negatively charged microbial membranes through electrostatic interactions and additional mechanisms such as oxidative stress and membrane disruption has made them an essential component in the fight against antimicrobial resistance. This chapter has explored their various classifications, applications, and advancements, with insights drawn from 132 key studies. Meanwhile, several key areas require continued research and development to fully harness the potential of cationic polymers.

1.3.1 Sustainability and Biodegradability

Developing biodegradable cationic polymers from renewable feedstocks not only aligns their use with global sustainability goals but also addresses the growing need for eco-friendly alternatives in various industries. That is particularly critical for applications in environmental systems, such as water treatment and soil remediation, as well as in consumer products like packaging and personal care items, where minimizing long-term ecological impacts is essential. By ensuring these materials degrade harmlessly after use, we can reduce environmental pollution, conserve resources, and contribute to a circular economy, making them a sustainable solution for modern challenges.

1.3.2 Targeted and Responsive Systems

Advances in stimuli-responsive materials can enhance the precision and efficiency of antimicrobial actions. These systems, capable of releasing antimicrobial agents in response to specific environmental triggers, will be instrumental in reducing off-target effects, enhancing therapy efficacy, and improving safety profiles.

1.3.3 Interdisciplinary Integration

The integration of cationic polymers with emerging technologies such as nanotechnology, artificial intelligence, and 3D printing can accelerate the development of next-generation materials. These interdisciplinary approaches will enable the design of more sophisticated and customizable antimicrobial solutions.

1.3.4 Scalability and Cost Reduction

Simplifying the synthesis and manufacturing processes of cationic polymers is essential for their commercial success. Collaborations between academia and industry will play a critical role in achieving cost-effective production at scale.

1.3.5 Expanding Applications

The versatility of cationic polymers can be further explored in emerging areas such as antimicrobial coatings for wearable electronics, self-sterilizing surfaces in public spaces, and advanced filtration systems for pandemics.

In conclusion, cationic polymers offer a promising solution to the growing threat of antimicrobial resistance, with their ability to adapt to diverse applications and evolving microbial challenges. By addressing current limitations and exploring innovative functionalities, these materials have the potential to transform antimicrobial strategies across sectors, ensuring a safer and more sustainable future.

References

1. Dhanda G, Acharya Y, and Haldar J. Antibiotic adjuvants: a versatile approach to combat antibiotic resistance. *ACS Omega*. 2023;8:10757–10783.
2. Alfei S and Schito AM. Positively charged polymers as promising devices against multidrug-resistant gram-negative bacteria: a review. *Polymers*. 2020;12:1195.
3. Si Z, Zheng W, Prananty D, et al. Polymers as advanced antibacterial and antibiofilm agents for direct and combination therapies. *Chem Sci*. 2022;13:345–364.
4. Song Q, Zhao R, Liu T, et al. One-step vapor deposition of fluorinated polycationic coating to fabricate antifouling and anti-infective textile against drug-resistant bacteria and viruses. *Chem Eng J*. 2021;418:129368.
5. Yuan J, Zhang D, He X, et al. Cationic peptide-based salt-responsive antibacterial hydrogel dressings for wound healing. *Int J Biol Macromol*. 2021;190:754–762.
6. Cai L, Ying D, Liang X, et al. A novel cationic polyelectrolyte microsphere for ultrafast and ultra-efficient removal of heavy metal ions and dyes. *Chem Eng J*. 2021; 410:128404.
7. Shaghaleh H, Hamoud YA, Xu X, et al. Thermo-/pH-responsive preservative delivery based on TEMPO cellulose nanofiber/cationic copolymer hydrogel film in fruit packaging. *Int J Biol Macromol*. 2021;183:1911–19124.
8. Pham P, Oliver S, and Boyer C. Design of antimicrobial polymers. *Macromol Chem Phys*. 2023;224:2200226.
9. Babutan I, Lucaci AD, and Botiz I. Antimicrobial polymeric structures assembled on surfaces. *Polymers*. 2021;13:1552.
10. Haktaniyan M and Bradley M. Polymers showing intrinsic antimicrobial activity. *Chem Soc Rev*. 2022;51(20):8584–8611.
11. Santoro O and Izzo L. Antimicrobial polymer surfaces containing quaternary ammonium centers (QACs): synthesis and mechanism of action. *Int J Mol Sci*. 2024;25:7587.

12 Hou S, Wang Y, Li J, et al. Effects of the number of cationic sites on the surface/interfacial activity and application properties of quaternary ammonium surfactants. *Colloids Surf A: Physicochem Eng Asp*. 2023;656:130523.

13 Namivandi-Zangeneh R, Wong EH, and Boyer C. Synthetic antimicrobial polymers in combination therapy: tackling antibiotic resistance. *ACS Infect Dis*. 2021;7:215–253.

14 Jumaah FN, Mobarak N, Hassan N, et al. Review of non-crystalline and crystalline quaternary ammonium ions: classification, structural and thermal insight into tetraalkylammonium ions. *J Mol Liq*. 2023;376:121378.

15 Luo H, Yin X-Q, Tan P-F, et al. Polymeric antibacterial materials: design, platforms and applications. *J Mater Chem B*. 2021;9:2802–2815.

16 Zhou C, Chia GW, and Yong K-T. Membrane-intercalating conjugated oligoelectrolytes. *Chem Soc Rev*. 2022;51:9917–9932.

17 Ghosh S, Mukherjee S, Patra D, et al. Polymeric biomaterials for prevention and therapeutic intervention of microbial infections. *Biomacromolecules*. 2022;23:592–608.

18 Chu X, Yang F, and Tang H. Recent advance in polymer coatings combating bacterial adhesion and biofilm formation. *Chin. J. Chem*. 2022;40:2988–3000.

19 Wang X-T, Deng X, Zhang T-D, et al. A versatile hydrophilic and antifouling coating based on dopamine-modified four-arm polyethylene glycol by one-step synthesis method. *ACS Macro Lett*. 2022;11:805–812.

20 Liu Y, Dong T, Chen Y, et al. Biodegradable and cytocompatible hydrogel coating with antibacterial activity for the prevention of implant-associated infection. *ACS Appl Mater Interfaces*. 2023;15:11507–11519.

21 Zhou Y, Jiang Y, Zhang Y, et al. Improvement of antibacterial and antifouling properties of a cellulose acetate membrane by surface grafting quaternary ammonium salt. *ACS Appl Mater Interfaces*. 2022;14:38358–38369.

22 Ma L, Chen Y, Ding Y, et al. High-performance antibacterial film via synergistic effect between uniformly dispersed TiO_2 nanoparticles and multifunctional quaternary ammonium cationic ligand. *Prog Org Coat*. 2021;157:106322.

23 Min T, Zhu Z, Sun X, et al. Highly efficient antifogging and antibacterial food packaging film fabricated by novel quaternary ammonium chitosan composite. *Food Chem*. 2020;308:125682.

24 Zhu Z, Zhang Y, Bao L, et al. Self-decontaminating nanofibrous filters for efficient particulate matter removal and airborne bacteria inactivation. *Environ Sci: Nano*. 2021;8:1081–1095.

25 Han W, Xu X-Q, Lian X, et al. A degradable quaternary ammonium-based pesticide safe for humans. *CCS Chem*. 2024;6:1499–1511.

26 Jiang Z, Yang R, Sheng Y, et al. Preparation and antibacterial ability of photodynamic antibacterial nanoparticles with ammonium cationic groups. *J Bioact Compat Polym*. 2024;39:301–316.

27 Huang K-X, Zhou L-Y, Chen J-Q, et al. Applications and perspectives of quaternized cellulose, chitin and chitosan: a review. *Int J Biol Macromol*. 2023;242:124990.

28 Ganewatta MS and Tang C. Controlling macromolecular structures towards effective antimicrobial polymers. *Polymer*. 2015;63:A1–A29.

29 T. Osimitz T and Droege W. Adverse outcome pathway for antimicrobial quaternary ammonium compounds. *J Toxicol Environ Health A*. 2022;85:494–510.

30 Tay J, Zhao Y, Hedrick JL, et al. Elucidating the anticancer activities of guanidinium-functionalized amphiphilic random copolymers by varying the structure and composition in the hydrophobic monomer. *Theranostics*. 2021;11:8977.

31 Singh D, Muhammad Irham L, Singh A, et al. Guanidinium-based integrated peptide dendrimers: pioneer nanocarrier in cancer therapy. *Protein Pept Lett* 2024;31:261–274.

32 Dey A, Yadav M, Kumar D, et al. A combination therapy strategy for treating antibiotic-resistant biofilm infection using a guanidinium derivative and nanoparticulate Ag(0) derived hybrid gel conjugate. *Chem Sci*. 2022;13:10103–10118.

33 Xu B, Jacobs MI, Kostko O, et al. Guanidinium group is protonated in a strongly basic arginine solution. *Chem Phys Chem*. (in press) 2025.

34 Fitch CA, Platzer G, Okon M, et al. Arginine: its pKa value revisited. *Protein Sci*. 2015;24:752–761.

35 Pan Y, Xia Q, and Xiao H. Cationic polymers with tailored structures for rendering polysaccharide-based materials antimicrobial: an overview. *Polymers*. 2019;11:1283.

36 Yu Z, Li Q, Liu Y, et al. Malleable, ultrastrong antibacterial thermosets enabled by guanidine urea structure. *Adv Sci*. 2024;24:2402891.

37 Pang C, Li B, Tu Z, et al. Self-assembled borneol-guanidine-based amphiphilic polymers as an efficient antibiofilm agent. *ACS Appl Mater Interfaces*. 2024;16:38429–38441.

38 Villanueva ME, González JA, Rodríguez-Castellón E, et al. Antimicrobial surface functionalization of PVC by a guanidine-based antimicrobial polymer. *Mater Sci Eng. C*. 2016;67:214–220.

39 Morata-Moreno N, Pérez-Tanoira R, del Campo-Balguerias A, et al. A new guanidine-core small-molecule compound as a potential antimicrobial agent against resistant bacterial strains. *Antibiotics*. 2024;13:609.

40 Zhang C, Ying Z, Luo Q, et al. Poly (hexamethylene guanidine)-based hydrogels with long-lasting antimicrobial activity and low toxicity. *J Polym Sci A: Polym Chem*. 2017;55:2027–2035.

41 Rao Y, Zou X, Shen X, et al. Regulation of hydrophobic structures of antibacterial guanidinium-based amphiphilic polymers for subcutaneous implant applications. *Biomacromolecules*. 2023;25:89–103.

42 Peng K, Zou T, Ding W, et al. Development of contact-killing non-leaching antimicrobial guanidyl-functionalized polymers via click chemistry. *RSC Adv*. 2017;7:24903–24913.

43 Azarifar D, Ghaemi M, Golbaghi M, et al. Synthesis and biological evaluation of new pyranopyridine derivatives catalyzed by guanidinium chloride-functionalized γ-Fe_2O_3/HAp magnetic nanoparticles. *RSC Adv*. 2016;6:92028–92039.

44 Mogaki R, Hashim P, Okuro K, et al. Guanidinium-based "molecular glues" for modulation of biomolecular functions. *Chem Soc Rev*. 2017;46:6480–6491.

45 Oh S-H and Choi S-H. Upper critical solution temperature (UCST) behavior of polyguanidinium in aqueous media. *Macromolecules*. 2024;57:7449–7461.

46 Praveen K, Das S, Dhaware V, et al. pH-responsive "supra-amphiphilic" nanoparticles based on homoarginine polypeptides. *ACS Appl Bio Mater*. 2019;2:4162–4172.

47 Salama A and Hesemann P. Synthesis of N-guanidinium-chitosan/silica hybrid composites: efficient adsorbents for anionic pollutants. *J Polym Environ*. 2018;26:1986–1997.

48 Zhuang X, Hao J, Zheng X, et al. High-performance adsorption of chromate by hydrazone-linked guanidinium-based ionic covalent organic frameworks: selective ion exchange. *Sep Purif Technol*. 2021;274:118993.

49 Xue B, Wang F, Zheng J, et al. Highly stable polysulfone anion exchange membranes incorporated with bulky alkyl-substituted guanidinium cations. *Mol Syst Des Eng*. 2019;4:1039–1047.

50 Liang Y, Xia M, Yu Q, et al. Guanidinium-based ionic covalent organic frameworks for capture of uranyl tricarbonate. *Adv. Compos. Hybrid Mater*. 2022;34:1–11.

51 Jansone-Popova S, Moinel A, Schott JA, et al. Guanidinium-based ionic covalent organic framework for rapid and selective removal of toxic Cr (VI) oxoanions from water. *Environ. Sci. Technol*. 2018;53:878–883.

52 Geng Z, Ma S, Li Y, et al. Guanidinium-based ionic liquids for high-performance SO_2 capture and efficient conversion for cyclic sulfite esters. *Ind Eng Chem Res*. 2022;61:4493–4503.

53 Zhao Y, Wang Y, Wang X, et al. Recent progress of photothermal therapy based on conjugated nanomaterials in combating microbial infections. *Nanomaterials*. 2023;13:2269.

54 Liu Y-S, Wei X, Zhao X, et al. Near-infrared photothermal/photodynamic-in-one agents integrated with a guanidinium-based covalent organic framework for intelligent targeted imaging-guided precision chemo/PTT/PDT sterilization. *ACS Appl Mater Interfaces*. 2021;13:27895–27903.

55 Chen C-T, Weng C-C, Fan K-P, et al. Guanidinium-functionalized polymer dielectrics for triboelectric bacterial detection. *ACS Appl Mater Interfaces*. 2023;16:1502–1510.

56 Sahraro M, Yeganeh H, and Sorayya M. Guanidine hydrochloride embedded polyurethanes as antimicrobial and absorptive wound dressing membranes with promising cytocompatibility. *Mater Sci Eng C*. 2016;59:1025–1037.

57 Yu J, Zhang S, Dai Y, et al. Antimicrobial activity and cytotoxicity of piperazinium-and guanidinium-based ionic liquids. *J Hazard Mater*. 2016;307:73–81.

58 Schröder T, Niemeier N, Afonin S, et al. Peptoidic amino-and guanidinium-carrier systems: targeted drug delivery into the cell cytosol or the nucleus. *J Med Chem*. 2008;51:376–379.

59 Mitchell WR, Army Medical Bioengineering Research and Development Lab Fort Detrick MD. Biodegradation of guanidinium by aquatic microorganisms. *US Army Med Res Dev Command Tech Rep*. 1985;8506:1–26.

60 Texter J. Anion responsive imidazolium-based polymers. *Macromol Rapid Commun*. 2012;33:1996–2014.

61 O'Harra KE and Bara JE. Toward controlled functional sequencing and hierarchical structuring in imidazolium ionenes. *Polym Int*. 2021;70:944–950.

62 Chen J, Bao C, Han R, et al. From poly (vinylimidazole) to cationic glycopolymers and glyco-particles: effective antibacterial agents with enhanced biocompatibility and selectivity. *Polym Chem*. 2022;13:2285–2294.

63 Voloshina AD, Gumerova SK, Sapunova AS, et al. The structure–activity correlation in the family of dicationic imidazolium surfactants: antimicrobial properties and cytotoxic effect. *Biochim Biophys Acta*. 2020; 1864:129728.

64 Riduan SN and Zhang Y. Imidazolium salts and their polymeric materials for biological applications. *Chem Soc Rev*. 2013;42:9055–9070.

65 Zhou C, Sun M, Wang D, et al. *In vitro* antibacterial and anti-inflammatory properties of imidazolium poly (ionic liquids) microspheres loaded in GelMA-PEG hydrogels. *Gels*. 2024;10:278.

66 Hwang G, Koltisko B, Jin X, et al. Nonleachable imidazolium-incorporated composite for disruption of bacterial clustering, exopolysaccharide-matrix assembly, and enhanced biofilm removal. *ACS Appl Mater Interfaces*. 2017;9:38270–38280.

67 Liu Y, Zhou L, Xu X, et al. Combination of backbone rigidity and richness in aryl structures enables direct membrane translocation of polymer scaffolds for efficient gene delivery. *Biomacromolecules*. 2023;24:5698–5706.

68 Scialla S, Martuscelli G, Nappi F, et al. Trends in managing cardiac and orthopaedic device-associated infections by using therapeutic biomaterials. *Polymers*. 2021;13:1556.

69 Anandkumar B, George R, and Philip J. Efficacy of imidazolium and piperidinium based ionic liquids on inhibiting biofilm formation on titanium and carbon steel surfaces. *Anal Chim Acta*. 2020;1126:38–51.

70 Liang J, She J, He H, et al. A new approach to fabricate polyimidazolium salt (PIMS) coatings with efficient antifouling and antibacterial properties. *Appl Surf Sci*. 2019;478:770–778.

71 Wang J, Ning J, Li S, et al. Multipurpose of zwitterionic poly (imidazolium)-based hydrogel coating for oil/water separation with long-term antibiofouling property. *Sep Purif Technol* 2022;295:121353.

72 Du H, Xu Q, Wang J, et al. Imidazolium-based poly (ionic liquid)/poly (vinyl alcohol) multifunctional supramolecular gels with self-healing, shape memory, and strain sensing. *J Mol Liq*. 2024;23:126586.

73 Kuddushi M, Pandey DK, Singh DK, et al. An ionic hydrogel with stimuli-responsive, self-healable and injectable characteristics for the targeted and sustained delivery of doxorubicin in the treatment of breast cancer. *Mater Adv*. 2022;3:632–646.

74 Mishra K, Devi N, Siwal SS, et al. Ionic liquid-based polymer nanocomposites for sensors, energy, biomedicine, and environmental applications: roadmap to the future. *Adv Sci*. 2022;9:2202187.

75 Anderson EB and Long TE. Imidazole-and imidazolium-containing polymers for biology and material science applications. *Polymer*. 2010;51:2447–2454.

76 Shamsuri AA, Daik R, and Md. Jamil SNA. A succinct review on the PVDF/imidazolium-based ionic liquid blends and composites: preparations, properties, and applications. *Processes*. 2021;9:761.

77 Qian W, Texter J, and Yan F. Frontiers in poly(ionic liquid)s: syntheses and applications. *Chem Soc Rev*. 2017;46:1124–1159.

78 Zhu M and Yang Y. Poly(ionic liquid)s: an emerging platform for green chemistry. *Green Chem*. 2024;26:5022–5102.

79 Guo J, Xu Q, Zheng Z, et al. Intrinsically antibacterial poly (ionic liquid) membranes: the synergistic effect of anions. *ACS Macro Lett*. 2015;4:1094–1098.

80 Zhou C, Sheng C, Gao L, et al. Engineering poly (ionic liquid) semi-IPN hydrogels with fast antibacterial and anti-inflammatory properties for wound healing. *Chem Eng J*. 2021;413:127429.

81 Dilxat D, Xie D, Wang J, et al. Molecular design of ultrafiltration membranes with antibacterial properties for the inactivation of antibiotic-resistant bacteria. *J Membr Sci*. 2024;690:122131.

82 Zhao S, Samadi A, Wang Z, et al. Ionic liquid-based polymer inclusion membranes for metal ions extraction and recovery: fundamentals, considerations, and prospects. *Chem Eng J*. 2024;24:148792.

83 Imdad S and Dohare RK. A critical review on heavy metals removal using ionic liquid membranes from the industrial wastewater. *Chem Eng. Process: Process Intensif*. 2022;173:108812.

84 Yan K, He B, Wu S, et al. Fabrication of poly (ionic liquid) hydrogels incorporating liquid metal microgels for enhanced synergistic antifouling applications. *ACS Appl Mater Interfaces*. 2024;23:11123.

85 Wang B, Wang P, He B, et al. Fabrication of ionic liquid-functionalized polystyrene nanospheres via subsurface-initiated atom transfer radical polymerization for anti-fouling application. *Prog Org Coat*. 2022;171:107044.

86 Bara JE, Hatakeyama ES, Gin DL, et al. Improving CO_2 permeability in polymerized room-temperature ionic liquid gas separation membranes through the formation of a solid composite with a room-temperature ionic liquid. *Polym Adv Technol*. 2008;19:1415–1420.

87 Cowan MG, Gin DL, and Noble RD. Poly (ionic liquid)/ionic liquid ion-gels with high “free” ionic liquid content: platform membrane materials for CO_2/light gas separations. *Acc Chem Res*. 2016;49:724–732.

88 Fallah Z, Zare EN, Khan MA, et al. Ionic liquid-based antimicrobial materials for water treatment, air filtration, food packaging and anticorrosion coatings. *Adv Colloid Interface Sci* 2021;294:102454.

89 Gaida B and Brzęczek-Szafran A. Insights into the properties and potential applications of renewable carbohydrate-based ionic liquids: a review. *Molecules*. 2020;25:3285.

90 Zhang D, Li Z, Yang L, et al. Architecturally designed sequential-release hydrogels. *Biomaterials*. 2023;23:122388.

91 Wang C, Chen P, Qiao Y, et al. pH-responsive superporogen combined with PDT based on poly Ce6 ionic liquid grafted on SiO_2 for combating MRSA biofilm infection. *Theranostics*. 2020;10:4795.

92 Henriques J, Pina J, Braga ME, et al. Novel oxygen-and curcumin-laden ionic liquid@ silica nanocapsules for enhanced antimicrobial photodynamic therapy. *Pharmaceutics*. 2023;15:1080.

93 Mecerreyes D. Polymeric ionic liquids: broadening the properties and applications of polyelectrolytes. *Prog Polym Sci*. 2011;36:1629–1648.

94 Correia DM, Fernandes LC, Martins PM, et al. Ionic liquid–polymer composites: a new platform for multifunctional applications. *Adv Funct Mater*. 2020;30:1909736.

95 Friess K, Izák P, Kárászová M, et al. A review on ionic liquid gas separation membranes. *Membranes*. 2021;11:97.

96 Salas R, Villa R, Velasco F, et al. Ionic liquids in polymer technology. *Green Chem*. 2025;17:897–908.

97 Flieger J and Flieger M. Ionic liquids toxicity—benefits and threats. *Int J Mol Sci*. 2020;21:6267.

98 Curreri AM, Mitragotri S, Tanner EE. Recent advances in ionic liquids in biomedicine. *Adv Sci* 2021;8:2004819.

99 Xue R, Chu X, Yang F, et al. Imidazolium-based polypeptide coating with a synergistic antibacterial effect and a biofilm-responsive property. *ACS. Macro Lett*. 2022;11:387–393.

100 Wang M, Shi J, Mao H, et al. Fluorescent imidazolium-type poly (ionic liquid) s for bacterial imaging and biofilm inhibition. *Biomacromolecules*. 2019;20:3161–3170.

101 Ni C, Zheng X, Zhang Y, et al. Multifunctional porous materials with simultaneous high water flux, antifouling and antibacterial performances from ionic liquid grafted polyethersulfone. *Polymer*. 2021;212:123183.

102 Dave K and Krishna Venuganti VV. Dendritic polymers for dermal drug delivery. *Ther Deliv* 2017;8:1077–1096.

103 Andrén OC, Ingverud T, Hult D, et al. Antibiotic-free cationic dendritic hydrogels as surgical-site-infection-inhibiting coatings. *Adv Healthc Mater*. 2019;8:1801619.

104 Arkas M, Vardavoulias M, Kythreoti G, et al. Dendritic polymers in tissue engineering: contributions of PAMAM, PPI PEG and PEI to injury restoration and bioactive scaffold evolution. *Pharmaceutics*. 2023;15:524.

105 Alkarri S, Bin Saad H, and Soliman M. On antimicrobial polymers: development, mechanism of action, international testing procedures, and applications. *Polymers*. 2024;16:771.

106 Scorciapino MA, Serra I, Manzo G, et al. Antimicrobial dendrimeric peptides: structure, activity and new therapeutic applications. *Int J Mol Sci*. 2017;18:542.

107 Chen T, Zhao L, Wang Z, et al. Hierarchical surface inspired by geminized cationic amphiphilic polymer brushes for super-antibacterial and self-cleaning properties. *Biomacromolecules*. 2020;21:5213–5221.

108 Cheng S, Wang H, Pan X, et al. Dendritic hydrogels with robust inherent antibacterial properties for promoting bacteria-infected wound healing. *ACS Appl Mater Interfaces*. 2022;14:11144–11155.

109 Li N, Yang L, Pan C, et al. Naturally occurring bacterial cellulose-hyperbranched cationic polysaccharide derivative/MMP-9 siRNA composite dressing for wound healing enhancement in diabetic rats. *Acta Biomater*. 2020;102:298–314.

110 Jiang G, Liu S, Yu T, et al. PAMAM dendrimers with dual-conjugated vancomycin and Ag-nanoparticles do not induce bacterial resistance and kill vancomycin-resistant *Staphylococci Acta Biomater*. 2021;123:230–243.

111 Cook AB and Perrier S. Branched and dendritic polymer architectures: functional nanomaterials for therapeutic delivery. *Adv Funct Mater*. 2020;30:1901001.

112 Sajid M, Nazal MK, Baig N, et al. Removal of heavy metals and organic pollutants from water using dendritic polymers based adsorbents: a critical review. *Sep Purif Technol*. 2018;191:400–423.

113 Guo Y, He X, Williams GR, et al. Tumor microenvironment-responsive hyperbranched polymers for controlled drug delivery. *J Pharm Anal*. 2024;23:101003.

114 Wei X, Luo Q, Sun L, et al. Enzyme-and pH-sensitive branched polymer–doxorubicin conjugate-based nanoscale drug delivery system for cancer therapy. *ACS. Appl Mater Interfaces*. 2016;8:11765–11778.

115 Paleos CM, Tsiourvas D, Sideratou Z, et al. Drug delivery using multifunctional dendrimers and hyperbranched polymers. *Expert Opin Drug Deliv*. 2010;7:1387–1398.

116 Zeigler DF, Candelaria SL, Mazzio KA, et al. N-type hyperbranched polymers for supercapacitor cathodes with variable porosity and excellent electrochemical stability. *Macromolecules*. 2015;48:5196–5203.

117 Flouda P, Bukharina D, Pierce KJ, et al. Flexible sustained ionogels with ionic hyperbranched polymers for enhanced ion conduction and energy storage. *ACS Appl Mater Interfaces* 2022;14:27028–27039.

118 Balogun E, Cassegrain S, Mardle P, et al. Nonconformal particles of hyperbranched sulfonated phenylated poly (phenylene) ionomers as proton-conducting pathways in proton exchange membrane fuel cell catalyst layers. *ACS Energy Lett*. 2022;7: 2070–2078.

119 Namata F, Sanz del Olmo N, Molina N, et al. Synthesis and characterization of amino-functional polyester dendrimers based on Bis-MPA with enhanced Hydrolytic Stability and inherent Antibacterial properties. *Biomacromolecules*. 2023;24:858–867.

120 Holmes AM, Heylings JR, Wan K-W, et al. Antimicrobial efficacy and mechanism of action of poly (amidoamine)(PAMAM) dendrimers against opportunistic pathogens. *Int J Antimicrob Agents*. 2019;53:500–507.

121 Skrzyniarz K, Takvor-Mena S, Lach K, et al. Molecular mechanism of action of imidazolium carbosilane dendrimers on the outer bacterial membrane–from membrane damage to permeability to antimicrobial endolysin. *J Colloid Interface Sci*. 2024;665:814–824.

122 Skrzyniarz K, Kuc-Ciepluch D, Lasak M, et al. Dendritic systems for bacterial outer membrane disruption as a method of overcoming bacterial multidrug resistance. *Biomater. Sci*. 2023;11:6421–6435.

123 Jiang G, Wu R, Liu S, et al. Ciprofloxacin-loaded, pH-responsive PAMAM-megamers functionalized with S-Nitrosylated hyaluronic acid support infected wound healing in mice without inducing antibiotic resistance. *Adv Healthc Mater*. 2024;13:2301747.

124 Shi E, Bai L, Mao L, et al. Self-assembled nanoparticles containing photosensitizer and polycationic brush for synergistic photothermal and photodynamic therapy against periodontitis. *J Nanobiotechnol*. 2021;19:1–15.

125 Atta AM, Al-Lohedan HA, Ezzat AO, et al. Synthesis of zinc oxide nanocomposites using poly (ionic liquids) based on quaternary ammonium acrylamidomethyl propane sulfonate for water treatment. *J Mol Liq*. 2017;236:38–47.

126 Ng LY, Mohammad AW, Leo CP, et al. Polymeric membranes incorporated with metal/metal oxide nanoparticles: a comprehensive review. *Desalination*. 2013;308:15–33.

127 Froiio F, Ginot L, Paolino D, et al. Essential oils-loaded polymer particles: preparation, characterization and antimicrobial property. *Polymers*. 2019;11:1017.

128 Wang Q, Shi Q, Li Y, et al. Visible light-regulated cationic polymer coupled with photodynamic inactivation as an effective tool for pathogen and biofilm elimination. *J Nanobiotechnol*. 2022;20:492.

129 Dong S and Wang Y. Removal of acid red 88 by a magnetic graphene oxide/cationic hydrogel nanocomposite from aqueous solutions: adsorption behavior and mechanism. *RSC Adv*. 2016;6:63922–63932.

130 Mohamed M, Ahmed N, Mohamed W, et al. Novel water-based coatings of acrylic-polyurethane reinforced with mixed metal pigment for oil and gas pipelines protection. *Prog Org Coat*. 2020;149:105941.

131 Jiang Y, Lan W, Sameen DE, et al. Preparation and characterization of grass carp collagen-chitosan-lemon essential oil composite films for application as food packaging. *Int J Biol Macromol*. 2020;160:340–351.

132 Khalil WF, El-Sayyad GS, El Rouby WM, et al. Graphene oxide-based nanocomposites (GO-chitosan and GO-EDTA) for outstanding antimicrobial potential against some *Candida* species and pathogenic bacteria. *Int J Biol Macromol*. 2020;164:1370–1383.