2D Carbon Nanomaterials as Photoactive Antiviral and Antibacterial Agent

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Abstract

Antibiotic resistance has emerged as one of the most pressing global health challenges of the 21st century. According to the World Health Organization (WHO), the growing ineffectiveness of antibiotics in treating common infections such as pneumonia, tuberculosis, and gonorrhea is contributing to a silent pandemic that threatens to surpass the impact of recent global health crises. With an estimated 4.95 million deaths annually linked to antibiotic-resistant infections and projections suggesting a complete loss of effective antibiotics by 2050, there is an urgent need to develop alternative antimicrobial strategies that do not rely on conventional antibiotics.[1, 2]

Among the most promising approaches are antimicrobial coatings and phototherapy, which offer non-traditional mechanisms to combat microbial pathogens. In this context, we introduce a novel, metal-free, light-activated antimicrobial coating based on nitrogen-doped graphene acid (NGA), a recently developed graphene derivative with well-defined chemical composition and excellent colloidal stability. NGA is embedded in a polyvinyl alcohol matrix cross-linked with 1,4-boronic acid, forming a compact carbon-polymer composite that exhibits both photothermal and photodynamic activity under near-infrared (NIR) light irradiation.[2]

This dual functionality enables the coating to generate localized heat and reactive oxygen species (ROS), effectively neutralizing a broad spectrum of bacterial and viral pathogens. The NGA-based coating demonstrates strong antimicrobial efficacy against clinically relevant strains such as Staphylococcus aureus and Pseudomonas aeruginosa, which are commonly associated with skin infections and chronic wounds. Importantly, the coating maintains its antimicrobial performance over multiple irradiation cycles, shows no cytotoxic effects on skin cells, and possesses favourable properties such as strong adhesion, wettability, and reduced biofouling.

Benchmarking against a previously reported coatings highlights the superior performance of the NGA-based system, particularly in terms of biocompatibility, reusability, and environmental safety. To our knowledge, this is the first report of a fully metal-free, NIR-activatable antimicrobial coating with demonstrated efficacy in both antibacterial and antiviral applications. The use of NIR light, which penetrates soft tissues more effectively than UV or visible light, further enhances the clinical relevance of this technology.

Overall, this study presents a significant advancement in the development of next-generation antimicrobial materials. The NGA coating offers a sustainable, safe, and highly effective platform for preventing and treating infections, particularly in settings where antibiotic resistance is prevalent. Its potential applications span from wound dressings and medical device coatings to public health surfaces, making it a versatile tool in the fight against antimicrobial resistance.

References

[1] M. A. Salam, M. Y. Al-Amin, M. T. Salam, J. S. Pawar, N. Akhter, A. A. Rabaan, M. A. A. Alqueber Health 11 (2023): 1946.

[2] G. Reina, D. Panáček, K. Rathammer, S. Altenried, P. Meier, P. Navascués, Z. Baďura, P. Bürgisser, V. Kissling, Q. Ren, R. Zbořil, P. Wick EcoMat, (2025) e70009.

Figures

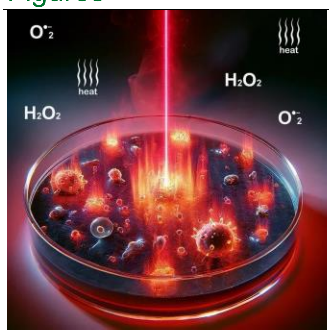

Figure 1: Scheme of the light induced antimicrobial activity of the NGA.