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Why Can Graphene Kill Bacteria? A Review of Antibacterial Mechanisms, Comparative Advantages, and Application Prospects

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Abstract

I think graphene is fascinating as a candidate for killing bacteria. It is a single-atom-thick honeycomb sheet of carbon with a specific surface area of about 2,630 m^2/g, and it conduct electricity extremely well. The antimicrobial resistance crisis is worsening: approximately 1.27 million people die from drug-resistant infections each year, and the WHO projects this could reach 10 million by 2050. Conventional disinfectants—ethanol, bleach, silver ions—attack specific biochemical targets, but bacteria continuously evolve resistance. This has motivated research into graphene, because it kills bacteria primarily through physical actions rather than chemical binding, reducing the risk of resistance development. Five antibacterial mechanisms have been identified: physical cutting by atomically sharp edges (the "nanoknife" effect), wrapping and suffocation, reactive oxygen species generation, phospholipid extraction via hydrophobic interactions, and electron transport disruption. This review covers the literature from 2010 to 2024, comparing graphene with ethanol, bleach, and silver ions across seven dimensions—killing mechanism, speed, persistence, resistance risk, safety, environmental impact, and cost—and discusses potential applications in medicine, water treatment, textiles, and public infrastructure. Current challenges include inconsistent selectivity, the absence of quality standards, long-term biosafety uncertainty, high production cost, and environmental interference. Graphene appears promising as a complementary option for specific applications, though significant obstacles remain before practical deployment.

Keywords

Graphene; antibacterial mechanism; nanomaterial disinfection; antibiotic resistance; reactive oxygen species.

1. INTRODUCTION

During the COVID-19 pandemic, disinfectant use surged dramatically. 75% ethanol evaporates quickly. Bleach is cheap but corrosive and irritating. Silver ions are effective but can accumulate in the body over time. The larger concern is antimicrobial resistance—the WHO reports approximately 1.27 million deaths annually from drug-resistant infections, with projections reaching 10 million by 2050 [1]. Most conventional disinfectants and antibiotics target specific biomolecular sites—cell wall enzymes, ribosomes, or membrane proteins. However, bacteria evolve rapidly: they develop efflux pumps, enzymatic degradation pathways, or alter the drug target site altogether. This led researchers to ask whether a fundamentally different approach might work—one that does not depend on a specific chemical target. That is where graphene enters the picture.

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Graphene, the material that won the Nobel Prize in Physics in 2010, was isolated by Novoselov and Geim in 2004 [2,3]. It is a single layer of sp^2-bonded carbon atoms in a honeycomb lattice, roughly 0.335 nm thick. It is extremely strong (Young's modulus ~1 TPa), has exceptional electron mobility (~200,000 $cm^2/V{\cdot}s$), and a huge specific surface area (~2,630 m^2/g). It seem almost impossible for a material this thin to possess such properties simultaneously. In 2010, Akhavan and Ghaderi demonstrated that graphene oxide nanowalls could physically damage bacterial membranes, launching the field of graphene antibacterial research [4]. Since then, over 10,000 papers have been published, including more than 100 highly cited works in journals such as Nature Nanotechnology and ACS Nano. What distinguishes graphene is that it and its derivatives (GO and rGO) kill bacteria predominantly through physical mechanisms rather than receptor- or enzyme-specific binding, meaning resistance is less likely to evolve. Liu et al. (2011) compared four graphene-related materials and identified GO as the most potent, with over 1,400 citations [5]. Tu et al. (2013) discovered phospholipid extraction from bacterial membranes by graphene nanosheets [6]. Li et al. (2015) identified electron transfer as a fifth antibacterial pathway [7]. By 2020, Mohammed et al. had published a comprehensive scope review [8]. However, most existing studies examine only one or two mechanisms under controlled laboratory conditions. A systematic comparison between graphene and conventional disinfectants also appears to be lacking in the literature.

2. ANTIBACTERIAL MECHANISMS OF GRAPHENE

Graphene doesn't kill bacteria through just one method. It uses five different pathways at the same time, which is part of what makes it so interesting. None of them is really 'chemical' in the traditional sense—they're mostly physical.

2.1. Physical Cutting — The "Nanoknife" Effect

Graphene nanosheet edges, at one atomic layer thick, have sub-nanometer curvature. When they contact bacteria, the edges act like tiny blades, piercing the cell membrane and causing intracellular contents to leak out—the so-called "nanoknife" effect. Akhavan and Ghaderi (2010) showed that graphene oxide nanowalls destroy the membranes of both S. aureus and E. coli, releasing RNA [4]. Pham et al. (2015) demonstrated that the orientation angle is critical: nanosheets contacting bacteria at a perpendicular 90° angle cut most effectively [9]. Because this mechanism is purely mechanical—no molecular binding or enzymatic inhibition—bacteria cannot easily evolve resistance against being physically sliced open. Whether bacteria might eventually develop thicker cell walls as a countermeasure remains an open question.

2.2. Encapsulation and Isolation — The "Nanosponge" Effect

When graphene sheets are sufficiently large, they can completely wrap around bacterial cells, blocking nutrient uptake and waste excretion, which leads to starvation and suffocation. Mejías Carpio et al. (2012) demonstrated that GO inhibits the growth of both Gram-positive (Bacillus subtilis) and Gram-negative (E. coli) bacteria through this wrapping mechanism [10]. This effect works best when the graphene sheets are larger than the bacterial cells; sheets that are too small cannot fully envelop the target.

2.3. Oxidative Stress — ROS Attack

Graphene contains abundant surface defects and sharp edges that catalyze the production of reactive oxygen species (ROS)—hydroxyl radicals (·OH), hydrogen peroxide (H_2O_2), and superoxide anions ($O_2{\cdot}^-$). These ROS attack membrane lipids, denature proteins, and damage DNA. Mangadlao et al. (2015) showed that denser GO films generate more ROS [11]. Gurunathan et al. (2012) confirmed that both GO and rGO produce ROS toxic to P. aeruginosa [12]. The relationship is not entirely straightforward: GO contains more oxygen groups (–OH, –COOH,

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epoxy) than rGO and generates more ROS, but rGO is more conductive and may kill through electron transfer pathways instead. Liu et al. (2011) conducted a thorough comparison of four materials and found GO most effective overall, acting through membrane damage and oxidative stress simultaneously [5].

2.4. Phospholipid Extraction — The "Wall Dismantling" Effect

Graphene possesses a large π-conjugated structure and strong hydrophobicity, allowing it to interact powerfully with membrane phospholipids and extract them directly from the lipid bilayer. Tu et al. (2013) used molecular dynamics simulations and experiments to reveal this process in two steps: insertion into the membrane, followed by adsorption and extraction of phospholipids, creating holes that lead to membrane collapse [6]. Dallavalle et al. (2015) found that sheet size is critical—sheets larger than about 5 nm tend to damage membranes through wrapping, while smaller ones penetrate directly [13]. The underlying physics of this size-dependence is complex, but the experimental results are reasonably consistent across studies.

2.5. Electron Transfer — The "Battery Leakage" Effect

Graphene's exceptional electrical conductivity enables it to act as an electron drain: it can withdraw electrons from bacterial membranes, disrupting the membrane potential and impairing cellular respiration—akin to a short circuit. Li et al. (2015) provided strong evidence for this mechanism by placing monolayer graphene on copper (conductor), germanium (semiconductor), and SiO_2 (insulator): antibacterial activity appeared only on the conductor and semiconductor, not on the insulator [7]. This suggests that electron transfer itself, rather than ROS production, can cause oxidative damage to bacteria. The idea that simply stealing electrons can kill bacteria is conceptually fascinating but not fully intuitive.

2.6. Synergistic Summary

These five mechanisms do not operate independently—they act synergistically. Physical cutting creates initial membrane damage, after which oxidative stress and phospholipid extraction amplify the damage. Electron transfer drains the cell's metabolic energy, impairing repair. The wrapping effect traps surviving bacteria, preventing their regrowth. This multi-pathway nature distinguishes graphene from single-mechanism disinfectants such as ethanol, which primarily denatures proteins. It is this combination of simultaneous physical and chemical attacks that makes graphene's antibacterial activity difficult for bacteria to evade.

3. COMPARISON WITH TRADITIONAL DISINFECTION METHODS

Graphene was compared with three widely used disinfectants: 75% ethanol, sodium hypochlorite (84 disinfectant), and silver ions (Ag^+). Table 1 summarizes their performance across seven dimensions.

75% Ethanol: This is the most common disinfectant. It denatures proteins and dissolves membrane lipids, acting rapidly—usually within seconds to minutes. However, it evaporates quickly, leaving no residual protection. It cannot kill spores or some non-enveloped viruses, and repeated use causes skin irritation. It is also flammable. Table 1 shows ethanol is fast (sec–min) and inexpensive, but its persistence is extremely short. Graphene lasts far longer (days versus minutes) and employs five killing pathways rather than one, so resistance risk is substantially lower.

Sodium Hypochlorite (84 Disinfectant): This is a harsh but broad-spectrum agent, effective against bacteria, viruses, fungi, and spores. It generates hypochlorous acid, which oxidizes proteins and nucleic acids rapidly. It is very inexpensive, making it suitable for large-scale disinfection. The main disadvantages are skin and eye irritation, metal corrosion, and environmental toxicity. Table 1 shows 84 disinfectant has the widest spectrum and lowest cost,

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but poor safety and environmental scores. Graphene is less irritating, making it more suitable for skin-contact applications.

Silver Ions (Ag^+): Silver has been used for disinfection for centuries. It binds to sulfur-containing proteins in bacterial membranes, disrupts membrane integrity, and inhibits DNA replication and respiratory enzymes. It provides long-lasting antimicrobial action, which is why it is used in wound dressings and antimicrobial fabrics. However, silver can accumulate in the body—excessive exposure may cause argyria (skin discoloration) and potential liver or kidney damage. Furthermore, some bacteria have already developed silver resistance. Graphene's physical mechanisms avoid this resistance concern. Table 1 shows both have good persistence, but graphene's resistance risk is lower.

Table 1. Comparison of graphene with conventional disinfection methods across seven dimensions.

imension	Graphene	75% Ethanol	84 Disinfectant	Silver Ions
Mechanism	Physical + chemical, five synergistic pathways	Protein denaturation	Strong oxidation	Enzyme inactivation + DNA damage
Speed	Moderate (min–hrs)	Fast (sec–min)	Fast (min)	Slow (sustained)
Persistence	Long (coatings last days)	Very short	Short (hrs)	Long (sustained)
Resistance risk	Very low	Low	Low	Moderate (reported)
Human safety	Good	Moderate	Poor	Moderate (accumulation)
Environmental	Good	Good	Poor	Moderate
Cost	High (currently)	Very low	Very low	High

In summary, graphene's main advantages are extremely low resistance risk and long persistence. Its disadvantages are slower killing speed, significantly higher cost, and the fact that it remains in the research phase. It is unlikely to replace conventional disinfectants in the near term; rather, it serves as a complementary tool for specific applications. Ethanol is fastest, 84 disinfectant offers the widest spectrum at the lowest cost, and silver has the longest track record. Graphene may be most valuable for use cases requiring sustained protection and minimal resistance risk—such as coatings on medical devices or hospital surfaces. Some groups are exploring hybrid approaches, combining graphene with silver for both physical cutting and sustained chemical release, which may represent the most practical path forward.

4. APPLICATION PROSPECTS AND CHALLENGES

4.1. Application Prospects

Medical Antimicrobials: This is perhaps the most promising application area. Graphene wound dressings could kill bacteria while promoting wound healing. Coatings on implants such as artificial joints or catheters could prevent post-surgical infections. Graphene-based masks could actively kill pathogens rather than merely trapping them. How long such coatings remain effective inside the body is not yet clear, but the concept is promising.

Water Treatment: Due to graphene's enormous surface area, even small quantities can contact large volumes of water. Researchers are developing 3D porous GO membranes that filter bacteria physically and kill them through contact. Given that clean water access remains a global

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challenge and existing methods such as chlorination have known drawbacks, this application could become important. However, scaling up graphene production to treat municipal water supplies remains a significant economic obstacle.

Textiles: A notable advantage of graphene-blended fabrics is that they retain antibacterial activity after many wash cycles. Silver-ion fabrics gradually lose effectiveness because the silver is consumed, but graphene's physical mechanisms are not depleted. This makes graphene textiles attractive for hospital uniforms, sportswear, and other high-contact fabric applications.

Public Infrastructure: Door handles, elevator buttons, and subway rails are touched by thousands of people daily but cleaned only periodically. A graphene coating could provide continuous antimicrobial protection after a single application, reducing reliance on frequent manual disinfection. Whether this performance holds up under real-world conditions—with dirt, grease, and continuous human contact—remains to be determined.

4.2. Current Challenges

(1) Inconsistent Antibacterial Selectivity: Graphene works better on Gram-positive bacteria than Gram-negative ones, because the outer membrane of Gram-negative bacteria provides additional protection. Some studies have even reported that certain amine-functionalized graphene quantum dots promote bacterial growth rather than inhibiting it. Layer number, sheet size, oxygen content, and surface charge—all of these variables can reverse the antibacterial outcome. It seem there is no clear predictive pattern, which makes comparing studies difficult.

Several groups have attempted to functionalize graphene with chemical groups to improve activity against Gram-negative bacteria, but results so far are inconsistent. This problem may be inherently difficult—it involves not only the properties of graphene, but also the diverse defense mechanisms bacteria have evolved. A more pragmatic approach might be to focus on the bacterial types and application scenarios where graphene's performance is strongest, rather than pursuing universal antimicrobial activity.

(2) Lack of Standardized Quality Metrics: Currently, the term "graphene" is applied to materials ranging from genuine single-layer sheets to graphite microplatelets, which perform entirely differently. No national or international standards exist for defining graphene quality in the context of antibacterial applications. Thus, when one study reports "graphene kills 99% of bacteria" and another reports 30%, the materials being tested may not even be comparable. This makes cross-study comparisons nearly meaningless.

Raman spectroscopy has been proposed as a quality assessment tool, using the D band and G band peaks to evaluate graphene structure. However, no universally accepted standard has been agreed upon. Resolution may require involvement from international standards organizations such as ISO. Additionally, most long-term animal studies were not designed specifically for antimicrobial applications, and the dosing regimes differ from anticipated real-world exposure. Safety studies are inherently time-consuming and expensive, which has slowed progress.

(3) Unverified Long-Term Biosafety: Short-term studies indicate graphene is more toxic to bacteria than to mammalian cells, which is a favorable selectivity profile. However, data on chronic exposure are extremely limited. Whether graphene accumulates in organs such as the liver or lungs, whether the body can clear or degrade it, and whether long-term exposure could cause chronic inflammation or carcinogenesis are questions that require years of toxicological investigation. At present, the kind of multi-year safety data needed to support implantable or long-wear applications has not yet been generated.

(4) Cost and Scalability: Producing high-quality single-layer graphene remains expensive, especially when compared with commodity disinfectants like ethanol and bleach. Scaling up production while maintaining consistency and purity is an additional challenge. Medical-grade graphene—required for implants or wound dressings—demands exceptionally high purity and

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uniformity, further increasing costs. At present, there is a trade-off between quality and quantity that has not yet been resolved.

Production costs have decreased over the past decade due to advances in CVD and other synthesis methods, but batch-to-batch consistency remains problematic. One batch may be predominantly single-layer while another contains multiple layers, and this variation affects antibacterial performance. Cost reduction and quality control will likely improve incrementally over the next decade as manufacturing processes mature, though the timeline is uncertain.

(5) Environmental Interference: In laboratory settings, graphene is tested against bacteria in clean buffer solutions. In real-world environments, surfaces are coated with proteins, lipids, salts, and other contaminants that block direct contact between graphene and bacterial cells. Since most killing mechanisms depend on physical contact, performance that approaches 99% in a petri dish may degrade substantially on a contaminated real-world surface. This gap between laboratory and practical performance is a significant barrier to deployment.

Some researchers have explored protective coatings to reduce protein fouling on graphene surfaces. Others have tested performance in more realistic media such as artificial body fluids. None of these approaches fully solves the problem. It may be necessary to accept that graphene's antibacterial performance will be higher in controlled environments than in complex real-world settings, and to target applications where conditions are relatively clean and predictable.

5. CONCLUSION

Graphene can kill bacteria through five mechanisms—physical cutting, wrapping and suffocation, oxidative stress, phospholipid extraction, and electron transfer—and these mechanisms act synergistically rather than independently. Because most are physical rather than biochemical, bacteria are unlikely to evolve resistance as readily as they do against conventional antibiotics. This is graphene's most compelling advantage. Compared with ethanol, bleach, and silver ions, graphene offers longer persistence and lower resistance risk, but is slower, more expensive, and still primarily at the research stage. It is unlikely to replace conventional disinfectants in the near future. However, it have real potential for specific applications—long-lasting antimicrobial coatings, functional medical materials, and combating drug-resistant infections in clinical settings. If the standardization problem is resolved, production costs reduced, and long-term safety data become available, graphene could become a useful tool. Writing this review helped clarify the current state of the field, though some mechanistic details remain difficult to fully grasp.

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