The Review Of
DIABETIC
STUDIES
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# Emerging Disinfection Technologies In Infection Control: A Review Of Nano-Silver And Ozone-Based Approaches

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## Abstract

Nano-silver and ozone-based disinfection technologies have emerged as promising alternatives to traditional methods for infection control in healthcare settings. This review explores the scientific basis, mechanisms of action, applications, efficacy, and safety considerations of these technologies. Nano-silver exerts broad-spectrum antimicrobial activity through the release of silver ions and generation of reactive oxygen species, disrupting microbial cell membranes and DNA. Its incorporation into medical devices, textiles, and surface coatings provides sustained protection against pathogens. Ozone, a powerful oxidant, rapidly inactivates microorganisms by attacking cell walls and viral capsids. Its gaseous form allows comprehensive disinfection of air, water, and surfaces. Both technologies demonstrate efficacy against multidrug-resistant bacteria, viruses, and fungi, offering advantages over conventional disinfectants. However, challenges include potential cytotoxicity, environmental impact, and the need for standardized testing protocols. Integration of these technologies into infection control programs requires careful implementation, staff training, and compatibility with existing multi-barrier strategies. Future research should focus on developing composite systems, controlled-release nanomaterials, and eco-friendly approaches. Clinical trials are needed to validate their real-world impact on reducing healthcare-associated infections. As the threat of antimicrobial resistance grows, nano-silver and ozone-based disinfection offer promising tools for enhancing infection prevention and control in healthcare facilities.

## Keywords

Disinfection, Nano-silver, Ozone, Infection control, antimicrobial resistance, Healthcare-associated infections, Environmental hygiene.

## 1. Introduction

Healthcare-associated infections (HAIs) represent a critical global health challenge, contributing to substantial morbidity, mortality, and economic burden across healthcare systems. Approximately 1 in 10 patients worldwide is affected by HAIs, with higher rates observed in low- and middle-income countries and intensive care units. In the United States alone, HAIs affect an estimated 1.7 million individuals annually, resulting in economic losses ranging from \$8.3 billion to \$45 billion. The European region reports approximately 9 million HAIs each year, leading to 25 million additional hospital days and costs between 13 and 24 billion euros. These infections not only prolong hospital stays, increasing length of stay by an average of 8.3 days, but also elevate in-hospital mortality rates, with studies showing a significant rise from 7.8% in non-infected patients to 14.7% in those with HAIs. The burden is further exacerbated by the rising prevalence of multidrug-resistant organisms (MDROs), with an estimated 136 million healthcare-associated antibiotic-resistant infections occurring globally each year. This growing resistance, driven in part by the overuse and misuse of antimicrobials and disinfectants, underscores the urgent need for innovative infection control strategies (Gidey et al., 2023).

Traditional disinfection methods, including chemical agents (e.g., glutaraldehyde, sodium hypochlorite), ultraviolet (UV) radiation, and heat sterilization, have long been the cornerstone of infection prevention. However, these approaches present significant limitations. Chemical disinfectants can be corrosive, damaging sensitive medical equipment such as transesophageal echocardiography (TEE) probes, thereby compromising diagnostic accuracy and incurring substantial repair or replacement costs. They may also alter the dimensional stability of dental impressions and leave behind toxic residues, posing risks to both patients and healthcare workers. UV-C light, while effective in inactivating pathogens by damaging microbial DNA, requires direct line-of-sight exposure and may not penetrate shadowed areas, limiting its efficacy in complex environments. Furthermore, the prolonged contact times required for many chemical methods disrupt clinical workflows and increase operational costs. Critically, the sub-lethal or sub-inhibitory use of disinfectants can promote the development of antimicrobial resistance (AMR) through mechanisms such as efflux pump expression, biofilm formation, and cross-resistance, thereby undermining their long-term utility (Joshi et al., 2024).

The escalating crisis of AMR, which contributed to nearly 5 million deaths globally in 2019 and imposes an annual economic burden of approximately \$730 billion, is a primary driver for the development of alternative disinfection technologies. The paucity of new antimicrobial agents contrasts sharply with the growing demand for effective treatments against resistant pathogens. This gap, combined with the emergence of novel pathogens and the environmental persistence of resistance genes, necessitates a paradigm shift in infection control. In this context, nano-silver and ozone-based disinfection systems have emerged as promising alternatives. Nano-silver exerts potent antimicrobial effects through multiple mechanisms, including the release of silver ions that disrupt microbial cell membranes, inhibit enzymatic activity, and interfere with DNA replication. Its high surface-to-volume ratio enhances biocidal efficacy, and it has demonstrated effectiveness against a broad spectrum of pathogens, including multidrug-resistant Pseudomonas aeruginosa and Bacillus megaterium. Ozone, a powerful oxidant generated on-site, rapidly inactivates bacteria, viruses, and fungi by oxidizing cellular components without producing harmful chlorinated by-products. It is more effective than chlorine, acts three times faster, and decomposes into oxygen, leaving no residual contamination (Samreen et al., 2021).

The rationale for focusing on nano-silver and ozone lies in their ability to overcome the limitations of conventional methods while addressing the dual challenges of HAIs and AMR. Both technologies offer broad-spectrum efficacy, reduced environmental impact, and compatibility with sensitive equipment. Nano-silver can be integrated into various materials, from wound dressings to textiles, providing sustained antimicrobial protection. Ozone's gaseous form allows for comprehensive disinfection of air, water, and surfaces, including hard-to-reach areas, making it ideal for decontaminating personal protective equipment and indoor environments, particularly in the wake of the COVID-19 pandemic. This review aims to provide a comprehensive analysis of the mechanisms, applications, efficacy, and safety profiles of nano-silver and ozone-based disinfection technologies. It will evaluate their role in mitigating the spread of HAIs and AMR, compare them to traditional methods, and discuss current challenges, knowledge gaps, and future research directions for their integration into modern infection control protocols.

## 2. Principles of Disinfection and Infection Control

Disinfection and infection control are foundational elements in preventing the transmission of infectious agents within healthcare and community settings. They involve a series of processes designed to reduce or eliminate pathogenic microorganisms on surfaces, instruments, and in the environment, thereby protecting patients, healthcare workers, and the public. This section will explore the key principles underlying these processes, including an overview of disinfection, sterilization, and decontamination, the microbial inactivation mechanisms, classification of disinfection technologies, and the criteria that define effective disinfection (Yin et al., 2020).

### 2.1 Overview of Disinfection, Sterilization, and Decontamination Processes

Disinfection refers to the process of eliminating many or all pathogenic microorganisms, except bacterial spores, on inanimate objects or surfaces. It reduces the microbial load to a level considered safe for public health and clinical use. Sterilization is a more rigorous process that destroys all forms of microbial life, including highly resistant bacterial spores, rendering an object completely free of viable microorganisms. Finally, decontamination encompasses both cleaning and disinfection steps to remove organic and inorganic material and reduce microbial contamination to a safe level. These processes are carefully applied according to the Spaulding classification, which groups patient-care items as critical, semicritical, or noncritical based on infection risk and dictates the required level of disinfection or sterilization (Rutala & Weber, 2016).

### 2.2 Mechanisms of Microbial Inactivation

The effectiveness of disinfection and sterilization is dependent on how they inactivate microorganisms. The principal mechanisms include:

- **Oxidative Damage:** Agents like ozone and hydrogen peroxide produce reactive oxygen species that inflict damage on cellular components including lipids, proteins, and DNA, overwhelming microbial defense systems.
- **Cell Membrane Disruption:** Many chemical disinfectants, such as alcohols and quaternary ammonium compounds, disrupt the integrity of the microbial cell membrane, causing leakage of cellular contents and cell death.
- **Nucleic Acid Degradation:** Physical methods like ultraviolet and gamma radiation induce breaks in microbial DNA or RNA strands, preventing replication and transcription, effectively killing the microorganism.
- **Protein Denaturation:** Heat and certain chemicals denature essential microbial proteins, impairing enzymatic and structural functions critical to survival.

Some emerging technologies like nano-silver and ozone-based approaches rely heavily on oxidative mechanisms, enhancing microbial inactivation efficacy by targeting multiple cellular components simultaneously (Roohinejad et al., 2018).

### 2.3 Classification of Disinfection Technologies

Disinfection technologies are broadly categorized into:

- **Chemical Methods:** Use of chemical biocides such as chlorine compounds, alcohols, glutaraldehyde, and newer agents like nano-silver. These act via mechanisms like membrane disruption and oxidative stress.
- **Physical Methods:** Include heat (autoclaving, dry heat), radiation (UV, gamma rays), and filtration. These alter microbial structures or remove organisms physically.
- **Emerging Hybrid Systems:** Novel methods combining chemical and physical principles, such as plasma sterilization or ozone combined with ultraviolet light, seeking enhanced efficacy and safety profiles (Wang et al., 2020).

### 2.4 Criteria for Effective Disinfection

Successful disinfection encompasses multiple factors:

- **Spectrum of Activity:** The agent or method must effectively target a broad range of microorganisms including bacteria, viruses, fungi, and when needed, resistant spores.
- **Material Compatibility:** Disinfectants must not degrade or damage the surfaces or instruments they are applied to, especially critical medical devices.
- **Safety:** Both for the user and the environment; agents should have minimal toxicity, cause no harmful residues, and be safe to handle with proper precautions.
- **Environmental Impact:** Effective disinfection that is also eco-friendly minimizes chemical residues, waste, and adverse ecological effects.

Evaluation of disinfectant efficacy often involves using indicator organisms or standard microbial tests to ensure killing rates of 90% or higher (natural bacteria) or 99.9% or higher with indicator bacteria (Mohapatra, 2017).

## 3. Nano-Based Disinfection: The Case of Nano-Silver

### 3.1 Scientific Basis and Mechanism of Action

Silver nanoparticles (AgNPs) possess unique physicochemical properties, including size (typically $<100$ nm), shape (e.g., spherical, triangular), surface charge, and surface coatings, which critically influence their antimicrobial activity. Smaller particles, especially those less than 20 nm, maximize surface area for interaction with microbial cells and enhance penetration, leading to greater bactericidal effects. Triangular nanoplates have shown higher antibacterial activity compared to spherical and rod-shaped particles due to their specific facet exposures (Dawadi et al., 2021).

The antimicrobial mechanisms of AgNPs are multifaceted: they disrupt bacterial cell membranes by interacting with sulfur-containing proteins; generate reactive oxygen species (ROS) that induce oxidative stress; interact with DNA to inhibit replication; and interfere with intracellular proteins and metabolic enzymes, culminating in microbial death. Additionally, pores created by AgNPs in bacterial membranes lead to cytoplasmic leakage, while apoptosis-like mechanisms can also be induced (Dhaka et al., 2023).

### 3.2 Synthesis and Characterization of Silver Nanoparticles

Silver nanoparticles can be synthesized by chemical reduction, biological (green) synthesis, and physical methods such as sonoelectrochemical techniques and photochemical reduction. Chemical methods (e.g., Tollens' process) allow control over particle size by varying reducing agents and reaction conditions. Biological synthesis uses organisms or extracts, offering eco-friendly and cost-effective routes, while physical methods involve energy input like ultrasound or radiation for reduction. Characterization techniques include Transmission Electron Microscopy (TEM) and Scanning Electron Microscopy (SEM) for morphology; Dynamic Light Scattering (DLS) for size distribution; X-Ray Diffraction (XRD) to assess crystallinity; Fourier Transform Infrared Spectroscopy (FTIR) for surface chemistry; and UV–Visible spectroscopy for surface plasmon resonance peak analysis (Abbas et al., 2024).

### 3.3 Antimicrobial Efficacy

AgNPs exhibit broad-spectrum antimicrobial properties against bacteria, viruses, and fungi. They are effective against multidrug-resistant organisms such as Methicillin-Resistant Staphylococcus aureus (MRSA), Vancomycin-Resistant Enterococci (VRE), and Acinetobacter spp. Their efficacy varies with formulation: dispersed in liquids, embedded in coatings or textiles, or integrated into wound dressings, each application enhances microbial contact and inhibition differently. AgNP coatings on textiles exhibit self-cleaning and long-lasting antibacterial effects relevant to hospital hygiene (Luceri et al., 2023).

### 3.4 Applications in Healthcare Settings

Nano-silver is incorporated into medical devices such as catheters and cardiovascular implants to prevent infection and biofilm formation. Commercial products like Silverline® catheters and Acticoat™ wound dressings leverage AgNPs' antimicrobial efficacy. In addition, AgNPs are used in hospital textiles, surface disinfectants, surgical masks, and filtration membranes to reduce microbial contamination and biofouling. AgNP-based biosensors and diagnostic tools also benefit from their sterilization potential and sensitivity (Ge et al., 2014).

### 3.5 Safety, Toxicity, and Environmental Concerns

Despite their benefits, AgNPs raise concerns about cytotoxicity to human cells, bioaccumulation, and environmental persistence. Cytotoxic effects stem from ROS generation, DNA damage, and apoptosis mediated by signaling pathways like IKK/NF-κB. Toxicity varies with dose, particle size, and exposure duration, with smaller particles generally more toxic. Safe concentration limits are proposed below 0.1 mg/L for water disinfection to minimize risks. Regulatory standards are evolving, balancing antimicrobial benefits against potential adverse effects and bacterial resistance induction debates (Ge et al., 2014).

### 3.6 Limitations and Challenges

Challenges include high production costs and stability issues of AgNP formulations. Standardizing synthesis and testing protocols remains difficult, complicating comparisons between studies and clinical translation. Furthermore, there are knowledge gaps concerning the long-term ecological impact of AgNP release and accumulation in environments. Addressing these issues is critical for sustainable integration of nano-silver technologies in infection control (Duval et al., 2019).

## 4. Ozone-Based Disinfection

### 4.1 Overview and Mechanism of Action

Ozone (O8) is a triatomic molecule consisting of three oxygen atoms. It is a powerful oxidant with unstable physical and chemical properties that enable it to decompose rapidly, producing reactive oxygen species. This makes ozone highly effective in microbial inactivation processes. The principal mechanisms by which ozone disinfects include:

- **Oxidation of cell walls and membranes:** Ozone attacks and disrupts the lipid membranes and peptidoglycan layers of bacteria, leading to cell lysis.
- **Disruption of viral capsids and nucleic acids:** Ozone damages viral protein capsids and oxidizes viral RNA/DNA, rendering viruses noninfectious.

- **Denaturation of proteins and lipids:** Ozone interacts with proteins and unsaturated lipids in microorganisms, causing functional denaturation and loss of integrity.

These oxidative actions are facilitated both by direct ozone contact and indirectly by the formation of hydroxyl radicals during ozone decomposition, contributing to a broad-spectrum biocidal effect (Cenci et al., 2022).

### 4.2 Methods of Ozone Generation

Several technologies are used to generate ozone for disinfection:

- **Corona Discharge Systems:** Oxygen or air flows through a high voltage electrical field causing ionization of O2 molecules and formation of ozone. This method yields high ozone concentrations efficiently and is widely used in industrial and medical applications.
- **Ultraviolet (UV) Photolysis:** UV light at 254 nm wavelength splits O2 into single oxygen atoms, which then combine with other O2 molecules to form ozone. This method is simpler and less energy intensive but generates lower ozone concentrations and is less affected by humidity.
- **Electrolytic and Plasma-Based Generation:** Emerging techniques, including cold plasma ozone generation, use electrical discharges in liquids or gases at or near room temperature to produce ozone with potential environmental benefits.

Each method differs in ozone output, energy consumption, and operational complexity, with corona discharge generally preferred for large-scale or continuous applications, while UV methods suit smaller or more sensitive environments (Rangel et al., 2022).

### 4.3 Applications in Healthcare and Environmental Hygiene

Ozone-based disinfection has diverse applications including:

- **Air and HVAC Disinfection:** Ozone is used to decontaminate airborne pathogens in hospital ventilation systems, leveraging its gaseous nature to reach inaccessible areas.
- **Surface Decontamination:** Isolation rooms, ambulances, surgical theaters, and other high-risk areas are sanitized using ozone gas or ozonated water, effectively reducing bacterial, viral, and fungal contamination.
- **Sterilization of Medical Instruments and Water Treatment:** Ozone-treated water sterilizes instruments and purifies hospital water systems without chemical residues.
- **Food Industry and Pharmaceutical Cleanrooms:** Ozone is employed as a residue-free disinfectant to maintain sterile environments essential for these industries.

### 4.4 Efficacy Against Pathogens

Scientific studies report ozone's high efficacy against a broad range of pathogens:

- Bacteria (Gram-positive and Gram-negative) including Staphylococcus aureus and Escherichia coli are effectively inactivated at ozone concentrations around 25 ppm within 30 minutes exposure.
- Viruses such as SARS-CoV-2 and influenza virus are rapidly inactivated by ozone gas and ozonated water; SARS-CoV-2 can be inactivated within 1 minute with appropriate ozone water concentrations, supporting its use during the COVID-19 pandemic.
- Spores and fungal species also show susceptibility though generally require higher ozone exposure levels.

Comparisons indicate ozone has advantages over traditional chemical disinfectants due to its strong oxidation, broader antimicrobial spectrum, and lack of harmful residues. Optimization of ozone concentration and exposure time is crucial to maximize effectiveness while ensuring safety (Piletić et al., 2022).

### 4.5 Safety Considerations

While ozone is a potent disinfectant, safety protocols are essential:

- Ozone is a respiratory irritant; exposure at low levels can cause chest pain, cough, and throat irritation. Regulatory limits typically cap workplace exposure at 0.1 ppm over 8 hours, with indoor medical device ceilings around 0.05 ppm (Swanson et al., 2022).
- Safe operation requires controlled ozone generation, monitoring via sensors, and procedures such as evacuating people during treatment and ventilating the area post-treatment (Swanson et al., 2022).
- Engineering controls include automated ozone sensors triggering shutdowns to prevent excessive exposure and corrosion-resistant materials are necessary in ozone systems due to its oxidative nature (Swanson et al., 2022).

### 4.6 Limitations and Operational Challenges

Usage of ozone disinfection faces several challenges:

- Ozone can corrode certain materials, compromising some equipment and surfaces if not properly managed.
- High humidity and presence of particulates can reduce ozone efficacy.
- There is a lack of standardized disinfection protocols and certifications specifically for ozone treatments, complicating regulatory acceptance and uniform application.
- The initial investment and operational costs for ozone generators and required infrastructure may be high compared to conventional disinfectants (Domantovsky et al., 2022).

## 5. Comparative Analysis of Nano-Silver vs. Ozone Technologies

Nano-silver and ozone represent two emerging and promising disinfection technologies with distinct characteristics in their mechanisms, application modes, safety profiles, and environmental impacts.

Mechanism: Nano-silver exerts its antimicrobial effect primarily through the sustained release of silver ions ($Ag^+$) combined with the generation of reactive oxygen species (ROS). These silver ions interact with bacterial cell membrane proteins containing sulfur, disrupt enzymes by binding to phosphorus and sulfur-containing groups, and induce oxidative stress leading to microbial death. Additionally, the size and shape of silver nanoparticles influence their efficacy, with smaller particles (<20 nm) showing enhanced permeability and lethal action on bacteria via physical membrane disruption and oxidative damage. Conversely, ozone acts as a strong oxidant that causes oxidative damage by directly attacking the microbial cell wall, leading to cell wall disintegration (lysis). Upon decomposition in water or air, ozone generates secondary reactive species like hydroxyl radicals that contribute to broad-spectrum disinfection efficacy (Deshmukh et al., 2019).

Spectrum of Action: Both nano-silver and ozone demonstrate broad-spectrum antimicrobial activity against bacteria, viruses, and fungi. Nano-silver has been shown effective against a variety of pathogens, including enveloped and non-enveloped viruses, through direct interaction and structural disruption. Ozone extends its action to spores as well, offering sterilization potential important in healthcare and industrial applications. The gaseous or aqueous form of ozone enables it to penetrate surfaces and crevices that liquids or coatings may not reach (Epelle, Macfarlane, Cusack, Burns, Okolie, Mackay, et al., 2023).

Mode of Application: Nano-silver is typically applied via coatings, impregnated materials, liquids, or embedded within polymer systems. It is extensively used in wound dressings, medical device coatings, textiles, and surface disinfectants that provide sustained antimicrobial activity due to the slow release of silver ions. Ozone, on the other hand, is applied as a gas, mist, or dissolved in aqueous systems. Its gaseous form enables whole-room disinfection and surface sterilization without residue, while aqueous ozone solutions are used in water and wastewater treatment as well as surface sanitation in food processing and healthcare settings (Epelle, Macfarlane, Cusack, Burns, Okolie, Mackay, et al., 2023).

Safety Profile: The use of nano-silver raises concerns about cytotoxicity. Studies have reported that silver nanoparticles can cause cellular apoptosis, necrosis, and impairment of cell proliferation depending on dose and particle characteristics. Occupational exposure limits have been proposed, and regulatory bodies monitor safe handling practices due to potential skin sensitization and mutagenicity risks. Ozone presents respiratory irritation risks due to its oxidizing nature; acute exposure above recommended limits causes pulmonary effects such as congestion and irritation of mucosa. However, with controlled concentrations and ventilation, ozone is considered safe for disinfection purposes. Both technologies require careful management to mitigate health risks during application (Zhang et al., 2022).

Reusability/Residual Effect: Nano-silver provides long-lasting antimicrobial protection through persistent coatings that continuously release silver ions. However, its efficacy may decline over time with repeated exposure due to depletion of silver content. Ozone's strong oxidative property results in no residual disinfectant after it decomposes rapidly back to oxygen, leaving no lasting antimicrobial presence. This necessitates ozone application just prior to or during use for effective disinfection (Epelle, Macfarlane, Cusack, Burns, Okolie, Mackay, et al., 2023).

Cost and Implementation: Nano-silver technologies typically incur moderate to high costs due to the complexity of nanoparticle synthesis, incorporation into products, and regulatory compliance. Ozone generation systems require an upfront investment in generators and safety controls but tend to have moderate operational costs; maintenance and energy consumption influence implementation expenses depending on scale (Deshmukh et al., 2019).

Environmental Impact: Nano-silver poses environmental concerns related to nanoparticle pollution, bioaccumulation, and toxicity to aquatic organisms given its persistence and potential for release into ecosystems. Conversely, ozone has a short half-life and decomposes rapidly into molecular oxygen, resulting in low environmental residues. However, ozone’s high oxidative power requires careful emission control to avoid localized air quality impacts (Deshmukh et al., 2019).

Regulatory Challenges: Nano-silver faces evolving regulatory frameworks centered on nanomaterial safety, worker exposure limits, and consumer product approval. Occupational exposure guidelines are emerging but not fully standardized. Ozone usage is governed by occupational safety limits for inhalation exposure and environmental standards aimed at controlling emissions to safeguard human health and ecosystems. These regulatory considerations influence the widespread adoption and acceptance of both technologies (Epelle et al., 2023).

## 6. Integration Into Infection Control Programs

### 6.1 Role of Emerging Technologies in Supplementing Existing Protocols

Emerging disinfection technologies such as nano-silver and ozone are increasingly recognized for their complementary roles in enhancing traditional infection control protocols. Nano-silver, due to its potent and broad-spectrum antimicrobial properties, is used to coat medical devices, surfaces, and personal protective equipment (PPE) to provide continuous antimicrobial action. Its mode of action, releasing silver ions that disrupt microbial cell membranes and DNA, supplements standard chemical disinfectants by offering prolonged protection and reducing biofilm formation, which is a critical challenge in healthcare environments. Ozone, a powerful oxidizing agent, offers rapid and effective decontamination capabilities against bacteria, viruses, and fungi. Its gaseous and aqueous forms provide flexible applications for disinfecting air, surfaces, and medical equipment, supplementing manual cleaning and chemical disinfection protocols where human error or access limitations may compromise efficacy. Together, these technologies enhance multi-barrier strategies by providing different mechanisms of microbial eradication, improving overall infection prevention outcomes (Epelle, Macfarlane, Cusack, Burns, Okolie, Mackay, et al., 2023).

### 6.2 Implementation Models in Healthcare Facilities

Successful integration of nano-silver and ozone-based disinfection requires well-designed implementation models that consider healthcare facility workflows, infrastructure, and regulatory standards. Nano-silver coatings are incorporated into medical devices such as catheters and wound dressings through advanced manufacturing approaches, including polymer surface modifications and nano-coating techniques that maintain device biocompatibility while imparting antimicrobial efficacy. These applications tend to be passive, requiring minimal behavioral change by healthcare workers. Ozone disinfection systems, on the other hand, are implemented actively via dedicated equipment such as ozone chambers, misting systems, or generators for air and surface sanitation. Automated ozone decontamination units with controlled gas concentration and exposure times are designed to ensure effective microbial kill while minimizing personnel exposure risks. Some facilities integrate ozone disinfection for reusable semi-critical devices and environmental surfaces in ICU and operating rooms, complementing existing sterilization and cleaning cycles. The success of these models depends on clear protocols, appropriate equipment maintenance, and monitoring for residual ozone levels to ensure safety and effectiveness (Epelle, Macfarlane, Cusack, Burns, Okolie, Vichare, et al., 2023).

### 6.3 Staff Education and Safety Training

Education and safety training are pivotal in integrating nano-silver and ozone disinfection technologies into infection control programs. Healthcare workers must be trained on the scientific principles, applications, and limitations of these technologies to foster acceptance and proper use. For nano-silver, understanding its long-lasting antimicrobial effects and safety profile helps alleviate concerns about toxicity or environmental impact. Ozone disinfection requires rigorous training regarding occupational exposure limits, safe handling of ozone generators, and protocols to prevent inhalation risks, given ozone's oxidative potential. Training programs should include hazard communication, use of personal protective equipment (PPE), emergency procedures, and compliance with manufacturer instructions for use (IFU). Ongoing education ensures staff are aware of how these technologies fit into broader infection control goals, supporting adherence to standard precautions and other safety practices (Barratt & Gilbert, 2021).

### 6.4 Compatibility with Multi-Barrier Infection Prevention Strategies

Nano-silver and ozone technologies integrate well within multi-barrier infection prevention frameworks that include standard precautions, surface disinfection, and waste management practices. Nano-silver coatings enhance physical barriers by reducing surface microbial load and biofilm development without replacing routine cleaning and disinfection. Ozone’s rapid antimicrobial activity complements manual cleaning by reaching difficult-to-access areas and inactivating pathogens resistant to chemical disinfectants. Both technologies support layered infection control measures combining hand hygiene, environmental cleaning, PPE use, and equipment sterilization to reduce healthcare-associated infections (HAIs). Importantly, these emerging disinfectants are compatible with existing protocols and materials used in healthcare, though compatibility testing is recommended for specific devices and surfaces due to possible material degradation with ozone exposure. Incorporating them as adjuncts rather than substitutes ensures strengthened, comprehensive infection control that addresses multiple microbial threats effectively (Hu et al., 2022).

## 7. Role of the Radiologic Technician in Infection Control with Emerging Disinfection Technologies

Radiology technicians have a crucial role in infection control within medical imaging environments by ensuring the safety and cleanliness of imaging equipment and surroundings. They are responsible for implementing and adhering to infection prevention protocols to reduce healthcare-associated infections (HAIs) in radiology departments, where patient contact and equipment pose high contamination risks (Jimenez & Lewis, 2023).

Nano-silver disinfection technologies, which incorporate silver nanoparticles with antimicrobial properties, offer a promising method to control infections in radiology. These nanoparticles can be applied as coatings on radiologic devices and accessories that frequently contact patients and healthcare workers, effectively reducing bacterial contamination without compromising image quality. Radiologic technicians help apply and maintain these coatings as part of their infection control tasks (Ahn & Kim, 2022).

Ozone disinfection is another advanced technology employed to sterilize imaging rooms, surfaces, and air, reaching areas that manual cleaning may miss. Radiologic technicians operate ozone generators safely under protocols to minimize occupational exposure, while enhancing environmental hygiene by rapidly inactivating a wide range of pathogens, including bacteria and viruses relevant in healthcare settings (Westover et al., 2022).

To maximize the benefit of these emerging disinfection methods, radiologic technicians require comprehensive training in infection prevention principles, the technical application of nano-silver and ozone technologies, and adherence to safety measures. Their frontline role in daily imaging workflows underscores their critical contribution to patient safety, equipment integrity, and overall healthcare quality in radiology departments (Matsunaga et al., 2022).

## 8. Research Gaps and Future Perspectives

Despite promising advancements in the applications of nano-silver and ozone-based disinfection technologies for infection control, several critical research gaps remain that require focused attention to advance their clinical and environmental potential.

### 8.1 Need for Standardized Testing Protocols and Efficacy Benchmarks

Currently, a major limitation in the development and comparison of nano-silver and ozone-based disinfectants is the absence of universally accepted standardized testing protocols and efficacy benchmarks. Variations in nanoparticle synthesis methods, particle size, shape, and surface chemistry significantly influence antimicrobial potency, complicating the direct comparison across studies and product formulations. For nano-silver, diverse assays targeting different microbial species under varying conditions have been used, often without harmonized criteria for bactericidal effectiveness or cytotoxicity. Similar challenges exist for ozone-based disinfection, where the optimal ozone concentrations, exposure durations, and humidity levels vary widely across experimental setups and devices, making efficacy evaluations inconsistent. Establishing clear, regulatory-aligned protocols akin to standards used for chemical disinfectants (e.g., EN 14885) would facilitate more robust validation and safer clinical translation (Westover et al., 2022).

### 8.2 Development of Composite or Hybrid Systems

An encouraging future perspective centers on the design of composite or hybrid disinfection systems that combine the complementary benefits of nano-silver with ozone. Nano-silver provides potent broad-spectrum antimicrobial activity through mechanisms such as reactive oxygen species generation and membrane disruption, while ozone offers strong oxidizing capacity, capable of reaching difficult surfaces via gas phase diffusion. Integrating these modalities could enhance overall disinfection efficacy, reduce required doses, and mitigate microbial resistance development. Preliminary research and commercial examples of nano-silver combined with other agents like hydrogen peroxide suggest such synergies are feasible and can lead to sustained antimicrobial effects in healthcare environments (Knobling et al., 2021).

### 8.3 Advances in Controlled-Release Nanomaterials and Smart Disinfection Devices

Emerging research is focused on engineering controlled-release nanomaterials that can provide sustained, targeted delivery of silver ions or ozone, optimizing antimicrobial activity while minimizing toxic environmental release. Controlled-release formulations such as encapsulated silver nanoparticles within hydrogels, membranes, or films are being developed to extend shelf-life and allow programmable disinfection cycles in clinical and environmental settings. Additionally, the integration of smart sensing and automation technologies into disinfection devices enables real-time monitoring of microbial load and adaptive dosing strategies, reducing human error and resource waste. Such smart disinfection platforms could revolutionize infection control by ensuring consistent, effective decontamination with minimal ecological footprint (Dixit & Singh, 2025).

### 8.4 Clinical Trials Evaluating Real-World Impact on Healthcare-Associated Infection Reduction

While in vitro and pilot studies demonstrate strong antimicrobial efficacy of nano-silver and ozone-based disinfection, there is a critical need for well-designed clinical trials that assess their effectiveness in reducing healthcare-associated infection (HAI) rates under real-world conditions. A handful of clinical studies have reported positive impacts of nano-silver sprays and rinses in reducing microbial colonization and infection incidences in intensive care and surgical wards, yet larger multi-center trials with standardized endpoints are lacking. Similarly, ozone disinfection devices have shown promising bacterial reduction on surfaces but require further clinical validation to quantify actual HAI prevention benefits. Such trials will be essential to justify widespread adoption and inform guidelines for integrating these emerging technologies into infection control protocols (Wu & Wu, 2025).

### 8.5 Sustainable and Eco-Design Considerations for Green Nanotechnology

The sustainability and environmental impact of nanomaterial-based disinfection technologies represent a vital future research domain. Although nano-silver offers potent antimicrobial action, concerns remain regarding its long-term ecological toxicity, bioaccumulation, and the fate of silver ions released into wastewater systems. Efforts are ongoing to develop green synthesis approaches using plant-based reducing agents and to design biodegradable or recyclable nanomaterials that align with principles of green chemistry and circular economy. Similarly, ozone-based devices benefit from being chemical-free and generating ozone that decays to oxygen, but manufacturing and energy consumption must be optimized for environmental friendliness. Integrating eco-design principles will be crucial to ensuring that these advanced technologies contribute to sustainable infection control solutions without unintended environmental harm (Alabdallah & Hasan, 2021).

## Conclusion

Nano-silver and ozone-based disinfection technologies represent significant advancements in the evolution of infection control strategies, offering effective alternatives to conventional chemical and physical methods. Both demonstrate broad-spectrum antimicrobial activity and address critical gaps associated with healthcare-associated infections (HAIs) and antimicrobial resistance (AMR). Nano-silver's sustained ion release and surface activity enable long-term antimicrobial protection in medical devices and coatings, while ozone's gaseous and aqueous applications provide rapid, residue-free disinfection of air, water, and surfaces. Together, they offer complementary benefits that enhance the resilience of infection prevention systems.

However, the transition from laboratory efficacy to routine clinical adoption demands careful attention to safety, standardization, and sustainability. Nano-silver's potential cytotoxicity and environmental persistence necessitate the development of safer, green synthesis methods and controlled-release systems. Ozone's strong oxidative power requires strict occupational safety measures and operational controls to prevent overexposure. Standardized efficacy testing, regulatory frameworks, and clinical trials are essential to validate their performance and ensure consistent outcomes across healthcare settings.

The integration of these emerging technologies should be viewed as a supplement, not a replacement for established disinfection protocols, fitting within multi-barrier infection prevention frameworks. Education and training of healthcare staff, including radiologic technicians, remain vital to their safe and effective implementation. Looking forward, innovations such as hybrid nano-silver/ozone systems, smart disinfection devices, and eco-designed nanomaterials hold promises for achieving sustainable, high-performance infection control. By bridging technological innovation with responsible application, these advanced disinfection approaches can play a transformative role in safeguarding global health and reducing the burden of HAIs in the era of antimicrobial resistance.

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