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Fumigation, Gaseous Decontamination, and No-Touch Environmental Technologies in the Operating Theatre: A Narrative Review

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ABSTRACT

Background: Environmental decontamination is essential for infection prevention in operating theatres (OTs), yet terminology, evidence and implementation practices vary considerably. Objective: To review the efficacy, safety and implementation of traditional fumigation and contemporary no-touch decontamination technologies.

Methods: A structured narrative search of PubMed/MEDLINE, Scopus and Google Scholar prioritised systematic reviews and OT-specific studies. Formal risk-of-bias and GRADE assessments were not performed.

Results: Formaldehyde demonstrates broad-spectrum antimicrobial activity but presents substantial occupational health risks and prolonged environmental persistence. Vaporized hydrogen peroxide and aerosolized hydrogen peroxide are distinct technologies, with vaporized hydrogen peroxide having the strongest evidence base among gaseous approaches, although clinical findings remain variable. Ozone and chlorine dioxide demonstrate antimicrobial efficacy under laboratory conditions, but clinical evidence is limited and stringent safety measures are required. Ultraviolet-C has moderate supporting evidence as an adjunct to manual cleaning. Plasma air treatment and far-UVC require further evaluation, while photocatalytic coatings remain investigational. Clinical trials have not established a clear benefit for plasma air treatment.

Conclusion: No single technology suits all OT settings. Selection should consider efficacy, safety, cost and institutional capacity, with manual cleaning remaining fundamental and automated technologies serving as adjuncts.

Keywords: Fumigation, Operating Rooms, Communicable Disease Control, Hydrogen Peroxide, Decontamination, Ultraviolet Rays, Review

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INTRODUCTION

Surgical site infection (SSI) is a major cause of postoperative morbidity and environmental contamination plays a role in the overall surgical infection chain. Operating theatre hygiene is based on a coordinated system of environmental cleaning, ventilation, reprocessing of equipment, hand hygiene, aseptic technique, traffic control and other perioperative measures. Reduction of environmental bioburden does not necessarily lead to reduction of SSI.^{1,2} Environmental cleaning is important, but not necessarily a reduction in bioburden.

The use of fumigation in healthcare has a long history. With the evolution of the concept of airborne infection, early room-decontamination practices developed, particularly linked to formaldehyde use in the twentieth century. Since then, routine fumigation with formaldehyde has been replaced in many high-resource settings by standardised environmental cleaning and disinfection, and by safer and validated technologies for specific indications. In other settings, however, fumigation continues because of resource limitations, institutionalized procedures, equipment availability, and the lack of access to newer technologies.³

Terminology is important. The term “fumigation” is used in this review in a broad sense to refer to the intentional application of a gaseous, vaporized or aerosolized chemical to decontaminate a closed room. The deliberate application of a fog or mist of a liquid disinfectant is called “fogging”. Vaporized hydrogen peroxide (VHP) and aerosolized hydrogen peroxide are similar but use different delivery systems. Physical or material-based technologies (UV-C, far-UVC, plasma air treatment, photocatalytic coatings) are not fumigants but are mentioned as no-touch or emerging environmental technologies.

Surgical site infections are one of the most common healthcare-associated infections and contribute to patient morbidity, longer hospital stays, antimicrobial use, and healthcare costs. Low- and middle-income countries (LMICs) are disproportionately affected. The rates of SSI have been reported as higher in LMIC countries than in high income countries in various surveillance systems and systematic reviews, but the estimates have been variable depending on the surgical specialty, surveillance methods and income level of the country.^{4,5} This burden is also preventable, as evidenced by findings that targeted quality-improvement interventions can reduce SSI rates in LMICs.⁶

LITERATURE SEARCH AND EVIDENCE APPRAISAL

This narrative review was performed with a structured search strategy, but it is not a systematic review as the study was designed as a narrative review. A formal PRISMA screening flow was therefore not conducted, and record counts are not reported because these are not relevant to a narrative synthesis of heterogeneous technologies.

Search Strategy: PubMed/MEDLINE, Scopus and Google Scholar were used to search for literature. The search strategy included the following terms: clinical setting (operating theatre OR operating room), intervention (environmental cleaning OR environmental decontamination OR fumigation OR fogging OR room decontamination OR “environmental cleaning” OR “environmental decontamination” OR “fumigation” OR “fogging” OR “room decontamination”), specific technologies (hydrogen peroxide vapor OR vaporized hydrogen peroxide OR dry mist hydrogen peroxide OR aerosolized hydrogen peroxide OR ozone OR “chlorine dioxide” OR “UV-C” OR “far-UVC” OR “plasma air purifier” OR “photocatalytic coating”), and outcomes (surgical site infection OR healthcare-associated infection OR bioburden), which were combined using the Boolean operators AND and OR.

MeSH terms and database subject headings were used where possible. The search was carried out until August 2026, with emphasis on publications from January 2000 onwards. Older publications were included if they gave background or historical information. The January 2000 cutoff was selected because it falls within the period when modern automated room-decontamination technologies have become available and when important WHO and CDC guidance documents have been published that guide current practice.

Inclusion and Exclusion Criteria: Studies were included if they focused on technologies for environmental decontamination in operating rooms or similar healthcare environments, antimicrobial efficacy, safety, or implementation, and were published in English. Studies were not included if they were conference abstracts with no full data, non-English publications with no translation, or proprietary manufacturer data that was the only source for conclusions.

Screening and Data Extraction: Because this is a narrative review, a formal PRISMA-style screening process with independent duplicate reviewers was not performed. Articles were selected by the authors on the basis of relevance to operating-theatre practice, technology-specific evidence, safety, implementation, and patient-centred outcomes; this selection is judgment-based and is a limitation of the review, as selection bias cannot be excluded. Relevant articles were checked against reference lists, and WHO and CDC guidance was reviewed directly. Where studies were cited, information was extracted narratively on study design, technology, setting, outcomes, and limitations.

Google Scholar Limitations: Google Scholar was used as a supplementary source to identify grey literature and additional references. However, Google Scholar lacks stable indexing and Boolean operators function inconsistently; therefore, searches in this database were not reproducible and were used only for supplementary identification of relevant publications.

Evidence Appraisal: Evidence was appraised using a narrative approach about study design, recency, clinical relevance and directness to OT practice. Systematic reviews and guidelines were accorded greater weight than individual laboratory studies, and operating-theatre-specific clinical evidence was given greater weight than evidence from general hospital rooms or laboratory models. Patient outcome studies (including healthcare-associated infection or SSI) were clearly distinguished from environmental microbial reduction studies. The narrative approach was not intended to provide a pooled effect estimate, but to compare heterogeneous technologies.⁷ Heterogeneity of technologies, doses and outcomes precluded meaningful quantitative synthesis and therefore formal risk-of-bias assessment, and GRADE evaluation were not conducted.

CURRENT INFECTION-CONTROL POSITION: CLEANING FIRST, DECONTAMINATION TECHNOLOGY AS AN ADJUNCT

The basic principle of healthcare environmental hygiene is routine environmental cleaning and disinfection as recommended by WHO and CDC. Environmental surfaces in the OT are normally non-critical surfaces and should be cleaned according to a schedule and disinfected as needed.

In 2003 and 2008, the CDC recommended against routine disinfectant fogging in patient-care areas. This historical recommendation should be taken with a grain of salt: it was a recommendation against routine disinfectant fogging using the technology available at the time and does not mean that all automated room-decontamination technologies are the same as fogging. VHP, aerosolized hydrogen peroxide, and UV-C systems were not available or widely used at the time the original fogging guidance was created and should be evaluated individually.^{7,8}

Some older guidance documents were created prior to the development of newer and more advanced systems like modern VHP, aerosolized hydrogen peroxide, and UV-C. These technologies should be evaluated on their own merits, safety profiles, and uses, and not just be labelled “fogging. These technologies should not be routinely used for all OTs at this time but should be considered for specific indications as part of an institutional infection-control program.^{9,10}

TECHNOLOGY CLASSIFICATION AND TERMINOLOGY

For consistency, this review uses a mechanism-based classification. Chemical gaseous decontamination refers to the use of a gas or vapor to reduce microbial load in an entire room (e.g., formaldehyde, VHP, ozone, chlorine dioxide). Aerosolized or dry-mist systems disperse liquid droplets or fine mist and do not necessarily represent true vapor-

phase systems. No-touch technologies is an operational term for technologies that treat environmental surfaces or air without manual wiping during the treatment cycle, including physical technologies like UV-C and selected automated chemical technologies. Emerging technologies include far-UVC, plasma air treatment, and photocatalytic coatings, which differ from established terminal-room technologies.

These distinctions are important because there are significant differences in dose delivery, room geometry, shadowing, containment, clearance, equipment compatibility, and validation requirements between categories. The term "technology" should not be used as an alternative term for "fumigation" or "fogging."

VENTILATION AND ENGINEERING CONTROLS

Room decontamination technologies operate within an engineering environment that includes supply and return air systems, pressure relationships, filtration, air-change rates, room sealing, and exhaust pathways. These controls do not replace cleaning and cannot substitute for terminal decontamination. Ventilation may affect the removal of airborne contaminants, distribution of treatment, humidity, and the time needed to remove a chemical after a cycle. The treatment protocol must therefore include the room's ventilation configuration as part of the validated treatment protocol, including isolation of the treated room, if necessary, control of leakage, and clearance documentation prior to re-entry. Room geometry and airflow can also impact dose distribution and shadowing in UV-C systems. Routine cleaning should be part of the environmental-control strategy, along with appropriate heating, ventilation, and air conditioning (HVAC) operation, filtration, pressure control, and preventive maintenance, and should not be limited to a single decontamination technology.

CHEMICAL GASEOUS AND AEROSOLIZED TECHNOLOGIES

Formaldehyde

Formaldehyde has been employed for room decontamination for many years because of its wide antimicrobial activity and activity against bacterial spores under specific conditions. It has significant disadvantages, however, as it is an irritant, a Group 1 carcinogen (International Agency for Research on Cancer), a known human carcinogen (U.S. National Toxicology Program) and a carcinogen (OSHA), and must be contained, aerated and verified prior to room re-entry. These hazards make standard OT formaldehyde protocols impractical to continue as standard practice when safer validated alternatives are available^{11,12}

The formaldehyde fumigation protocols used in the past were based on formalin solutions with about 37-40% formaldehyde, and the reported room concentrations and exposure times were widely different. The efficacy was found to be dependent on relative humidity, temperature, exposure time and room sealing. Long aeration periods were usually required prior to re-entry. The room should not be released because of the passage of time, but by a validated method of measuring residual formaldehyde. Concentration ranges, exposure times and clearance thresholds should not be given as universal operating parameters as the historical protocols were very different. If formaldehyde is still used, it should be controlled by appropriate occupational-health regulations, institutional policy, and proven equipment, with monitored clearance prior to re-entry.

Hydrogen Peroxide Technologies: VHP, Aerosolized H₂O₂, and Dry Mist

Hydrogen peroxide technologies need to be further differentiated. VHP systems generate a vapor phase, whereas aerosolized or dry-mist systems generate aerosolized or dry mist of hydrogen peroxide. Laboratory testing has shown that these systems can be distributed, effective, cyclic, and safe. Thus, they should not be substituted for each other just because they both contain hydrogen peroxide.^{13,14}

VHP has a more solid evidence base than other automated chemical room-decontamination systems. A 2024 review compiled substantial evidence of antimicrobial activity and found that VHP is a valuable technology for decontamination in the hospital environment, although more mechanistic and comparative studies are needed. Reductions in environmental contamination and, in some studies, pathogen acquisition have been demonstrated in

clinical and quasi-experimental studies. Evidence is not consistent, however, and the best evidence for use is for specific indications for use at the end of life or outbreak-specific indications, rather than as a replacement for routine manual cleaning. Most VHP studies report reduction in environmental bioburden, not SSI reduction, and clinical evidence is limited by the heterogeneity of study designs and inconsistent reporting of outcomes.^{7,15,16}

Dry-mist or aerosolized hydrogen peroxide systems also have great potential for environmental decontamination. A head-to-head comparison of Bioquell VHP and aerosolized hydrogen peroxide showed that both products were effective in significantly reducing microbial levels in controlled environments, and other studies demonstrated that both products significantly reduced environmental *C. Difficile* levels. But in one dry-mist study, *Mycobacterium tuberculosis* was more resistant. The results indicate the need for biological validation of each technology and the need to be careful not to assume that all hydrogen peroxide systems are equally effective for all organisms.^{13,17-21} The length of the cycle varies from system to system. The quoted treatment time may not be the actual OT downtime because there are separate stages of room preparation, conditioning, exposure, aeration and clearance. The parameters of the cycles should be device-specific, validated and should not be extrapolated from one system to another.

Manual Hydrogen Peroxide-Silver Ion Surface Disinfectants

Hydrogen peroxide-silver ion formulations should not be considered gaseous room fumigation. A 2% hydrogen peroxide formulation with 10 ppm of silver ions was compared to 0.5% sodium hypochlorite for manual surface disinfection in a multicentre randomized study of 24 operating rooms and was found to have a longer residual antimicrobial activity. This study is applicable to manual surface disinfection, not to gaseous fumigation or automated room decontamination.²² To make it clear that this is a manual surface disinfection technology and not a room decontamination technology, the use of hydrogen peroxide/silver ion formulations is discussed here.

Ozone

Ozone is a strong oxidizing gas that has a wide range of antimicrobial properties. Experimental studies provide significant evidence of microbial inactivation, but much of this evidence is from laboratory or environmental models, not from controlled clinical trials. Sharma and Hudson found antibacterial activity in a laboratory study at 25 ppm, which is a concentration that would be used in a controlled experimental setting, not in clinical spaces.^{23,24} The context of the occupation is very important. The Occupational Safety and Health Administration (OSHA) has set a time-weighted average (TWA) permissible exposure limit of 0.1 ppm for 8 hours of exposure to ozone, and the National Institute for Occupational Safety and Health (NIOSH) has recommended a ceiling exposure limit of 0.1 ppm for 8 hours of exposure. Thus, experimental decontamination concentrations of 25 ppm are 250 times the 8-hour occupational exposure limit and must be contained, excluded from the area, and cleared before re-entry. Ozone is not a standard or “occupied space” disinfection technique and should not be depicted as such. There is still a lack of evidence correlating ozone use with lower SSI rates.^{25,26} Ozone is attractive because it is relatively short-lived after it is produced and can be produced at the point of use; however, it does not negate the need for controlled containment during the treatment cycle.

Chlorine Dioxide

Chlorine dioxide is an antimicrobial, potent oxidizing gas. It is very concentration and application condition dependent. Evidence for clinical benefit in operating theatres is much less convincing than evidence for antimicrobial activity in controlled environments.²⁷

Gaseous chlorine dioxide is not to be confused with aqueous chlorine dioxide disinfectants. The gaseous approach is a whole room engineering solution that includes sealing, concentration monitoring, humidity control and controlled evacuation. Experimental hospital room studies have shown significant decreases in environmental organisms, even at high concentrations, but these studies have focused on environmental efficacy rather than reductions in SSI.

If gas evacuation is needed, a system for destruction of the gas, such as activated carbon or other validated destruction systems, can be integrated into the engineering design. This type of equipment reduces residual gas, but does not eliminate the need for leak testing, exposure monitoring, and documented clearance. The operational requirements, coupled with the absence of patient-outcome evidence, make chlorine dioxide a technology that is not routinely used in OTs.

Chlorine dioxide is also a common disinfectant in water treatment. This does not mean that gaseous chlorine dioxide is appropriate for routine OT decontamination, however, because the requirements for exposure, containment, concentration and clearance are different.

Chemical Fogging

Traditional disinfectant fogging is different from systems that use validated vapor generation. CDC does not recommend routine disinfectant fogging in patient-care areas because of concerns about effectiveness, patient exposure, and interference with routine environmental cleaning. Modern aerosolized hydrogen peroxide systems should not be grouped with traditional fogging but rather evaluated on a case-by-case basis, with validated parameters and evidence base.^{7,14}

UV-C AND NO-TOUCH PHYSICAL TECHNOLOGIES

Conventional UV-C (254 nm)

Conventional germicidal UV-C is not fumigation, it is a physical surface and air-treatment technology, usually at 254 nm. It is effective depending on the dose, distance, exposure time, surface orientation, and shadowing. Shadowing is a basic constraint: regions that are not directly in front of the UV-C source can be exposed to much lower or even no dose. The irradiance in shadowed areas has been quantified in test rooms and is significantly lower than that of directly exposed surfaces, but the amount depends on the device, room geometry, and object placement. This includes the back of monitors, shaded areas of complex equipment configurations, rear panels of equipment, and undersides of surgical tables. Thus, UV-C should only be used on well-exposed surfaces, and manual cleaning should be done on shadowed surfaces. Clinical studies and systematic reviews indicate that UV-C can help decrease environmental contamination and may have a beneficial effect on the acquisition of certain healthcare-associated pathogens when used in addition to routine terminal cleaning. Systematic reviews, however, have yielded mixed results, with some studies reporting benefits and others reporting no benefits, possibly because of variations in dose, room geometry, and baseline cleaning compliance.²⁸⁻³⁰

The BETR Disinfection trial is a good example of the importance of distinguishing between clinical outcomes and environmental efficacy. This cluster-randomized crossover trial demonstrated that better cleaning procedures in the terminal room led to a reduction in the acquisition of some multidrug-resistant organisms and *C. Difficile*, but not all pathogens and interventions. The main outcome was acquisition of multidrug-resistant organisms, not SSI, and the impact was not uniform for all pathogens. The results are not necessarily generalizable to operating rooms and other health systems. UV-C should not therefore be claimed to always reduce SSI. The evidence is in favor of using UV-C in conjunction with, rather than in place of, manual cleaning.^{31,32}

UV-C room-decontamination devices are not the same as upper room ultraviolet germicidal irradiation (UVGI). The main difference between upper-room UVGI and mobile or fixed UV-C room-decontamination systems is that the former is primarily an engineering control to reduce the concentration of airborne microbes in occupied rooms, while the latter is used to treat unoccupied rooms and is highly dependent on the line-of-sight dose. The two approaches are conducted under different conditions, safety requirements, and outcome measures.

UV-C systems must be equipped with controls to ensure that staff are not exposed during operation. With conventional germicidal UV-C devices, exposure levels can exceed the limits and cause acute photokeratitis and erythema, so terminal-room devices must be operated under controlled conditions with interlocks, exclusion zones, and manufacturer-validated safe operating procedures.

Far-UVC (222 nm)

Far-UVC at 222 nm is a newer technology with a different safety and biological profile than traditional germicidal UV-C at 254 nm. It has been tested and reviewed for potential inactivation of airborne and surface pathogens and has a reduced potential for mammalian DNA damage under tested conditions. Safety, however, is dependent on source characteristics, dose, exposure limits, and regulatory requirements, and the clinical evidence base is still evolving.^{33,34}

A systematic review and meta-analysis of 222 nm and 254 nm UV-C was conducted in 2025, and preliminary evidence suggests that disinfection efficacy may be similar or superior with 222 nm in some experimental settings, but there was high heterogeneity and no clinical outcome data. Far-UVC should thus be viewed as a new addition to the existing OT cleaning or traditional UV-C, rather than a replacement.³⁵

The typical doses applied to microbial inactivation in far-UVC studies range from tens of mJ/cm², but there is no universal dose that can be readily translated from the lab to the OT. All of these factors must be considered: device spectrum, exposure geometry, irradiance, occupancy, skin/eye exposure limits, and regulatory requirements. There is insufficient evidence to support the routine use of far-UVC as a substitute for proven environmental cleaning products. The regulatory status of far-UVC devices is jurisdiction- and device-dependent, and new devices should not be assumed to be approved for use in occupied rooms just because the underlying wavelength has been studied experimentally. Use, exposure limits and regulatory clearance or authorization should be checked before implementation.

Cold Plasma and Plasma Air Treatment

Plasma-based technologies are heterogeneous technologies like air purifiers generating reactive species and plasma sterilization technologies for instruments. They should not be considered a component of room fumigation. Evidence for the effectiveness of OT air-treatment systems is mixed. In a large, double-blind, cluster-randomized crossover study of more than 40,000 patients undergoing orthopedic surgery, no difference was observed between the composite measure of postoperative infection with wall-mounted plasma air purifiers and inactive devices. The primary outcome was a composite postsurgery infection marker (PSIM) based on registry data on antibiotic prescriptions and diagnostic/procedural codes for postoperative infection within 12 weeks of surgery, not a directly adjudicated SSI diagnosis.³⁶

This negative clinical finding is important because it shows a gap between what is plausible as an antimicrobial mechanism and what is proven to benefit patients. Plasma technologies might be used in some engineering or air-treatment applications, but their use in OTs should be delayed until there is more evidence of clinical effectiveness, cost-effectiveness, and workflow benefit. Plasma air-treatment systems are not to be confused with plasma instrument and surface sterilization. In the OT literature, the goal of an air-purifier system is to change the concentration of airborne particles or microbes, typically through electrical discharge, filtration, and/or reactive species. Although this is biologically plausible, it is not a proof of clinical benefit; the postoperative infection trial discussed above illustrates the need to distinguish air-quality endpoints from patient outcomes.

The lack of clinical benefit seen with plasma air purification could be due to insufficient dose delivered, insufficient air exchange or capture efficiency, airflow patterns, or the fact that the airborne burden targeted was not the most significant contributor to postoperative infection. These explanations are provisional until they are directly tested.

Photocatalytic and Long-Lasting Surface Coatings

The potential of photocatalytic coatings, such as titanium dioxide-based materials, as long-lasting antimicrobial surface treatments is being explored. Advances have been made in coatings for visible-light activated TiO₂ for surfaces that are touched often. Most of the evidence, however, is laboratory- or materials-science based, and there are important questions about durability, contamination in the real world, compatibility with cleaning, environmental conditions, and clinical outcomes. A 2023 review of TiO₂ coatings revealed that most studies were performed in controlled laboratory settings with limited real-world validation, and no clinical trials have shown a reduction in SSI. These coatings are not meant to replace the need for routine OT cleaning and disinfection, but rather as new technologies.³⁷

Careful classification of photocatalytic coatings is also necessary. The UV-activated titanium dioxide systems need sufficient light intensity and wavelength, and the visible-light-activated systems need modified catalysts that can work under a broader spectrum of light. Laboratory antimicrobial activity does not guarantee long-term performance in cleaning, abrasion, soiling or routine OT use. At this time, these coatings should be used as investigational aids, not

as a replacement for standard cleaning and disinfection. Practical uncertainties for photocatalytic coatings include cleaning compatibility and durability. Claims of long-lasting antimicrobial activity may diminish over time due to repeated wiping, abrasion, chemical exposure, surface soiling, and changes in illumination. Durability testing under realistic OT cleaning conditions should support claims of long-lasting antimicrobial activity.

COMPARATIVE EVIDENCE AND PRACTICAL CONSIDERATIONS

The relative evidence and operational considerations for each technology are summarized in Table 1. There are no generic cost or downtime figures as cycle times and costs depend on the device, room size, organism to be validated, local labour costs and regulatory requirements.

Table 1. Comparative evidence and practical considerations for environmental decontamination technologies.

Technology	Mechanism/Cat egory	Evidence Level	Typical Operational Issue	Main Limitation	Current Role
Formaldehy de	Chemical gas	Historical/limited modern clinical evidence	Long containment and aeration; clearance required	Carcinogeni city (IARC Group 1, NTP, OSHA); irritation	Generally, not preferred for routine OT use
VHP	Vapor-phase H ₂ O ₂	Moderate-to- strong environmental evidence; clinical evidence variable and limited by heterogeneity	Room sealing, cycle validation, aeration/clea rance	Equipment cost; room downtime; system- specific parameters	Adjunct for selected terminal/out break indications
Aerosolized /dry-mist H₂O₂	Hydrogen peroxide aerosol	Moderate	Aerosol distribution and validated cycle required	Performanc e varies by system; some organisms may be resistant	Selected terminal decontamina tion settings
Hydrogen peroxide- silver ion	Manual surface disinfectant	Moderate (randomized trial)	Manual application	Not a room decontamin ation technology	Manual surface disinfection
Ozone	Oxidizing gas	Mostly laboratory/envirom mental evidence	Strict containment and clearance	Toxicity at effective concentratio ns (250× OEL); material compatibilit y	Emerging/sel ected controlled applications; limited clinical evidence

Chlorine dioxide	Oxidizing gas	Laboratory and limited room evidence	High-level containment and monitoring	Toxicity and material compatibility	Selected controlled applications; limited clinical evidence
UV-C 254 nm	Physical no-touch	Moderate clinical/environmental evidence; heterogeneous results	Line-of-sight, shadowing, dose verification	Cannot reliably reach shaded surfaces	Adjunctive terminal disinfection
Far-UVC 222 nm	Physical no-touch	Emerging; growing experimental evidence	Dose, source safety, and regulatory compliance	Limited clinical outcome data	Emerging adjunct
Plasma air treatment	Physical/chemical air treatment	RCT evidence shows no clinical benefit for postoperative infection	Continuous operation and maintenance	Clinical benefit uncertain	Research/selected engineering applications
TiO₂ photocatalytic coatings	Photoactivated oxidative surface coating	Early/mostly laboratory	Surface preparation, durability, and maintenance	Uncertain real-world clinical benefit; no clinical trials	Investigational

Note: The "Evidence level" is a qualitative synthesis of the literature and is not a formal GRADE assessment.

Practical Implementation Considerations

Implementation should be considered a systems intervention, not merely the purchase of equipment. A scoping review of the literature in the operating room in 2024 revealed that there was no consistency in the effectiveness of cleaning and that there was a need for work-system factors like tools, tasks, organization, monitoring, and training. A 2025 national survey of automated room disinfection systems also found uncertainty over effectiveness, operational issues, and maintenance costs to be barriers to adoption.^{38,39}

The purchase price is not the only cost to consider; it is the total cost of ownership. Generally, formaldehyde can be low in chemical cost and high in operational cost because of long downtime, containment and clearance times. VHP and aerosolized hydrogen peroxide can be expensive in terms of capital and consumables but can save some manual labor. UV-C can be moderately expensive with relatively low consumables but requires staff time for positioning, room preparation and monitoring. These are relative categories and depend on the context. Institutions should get quotes from several vendors and work out the total cost model over 3-5 years, including training, maintenance, consumables and opportunity cost of downtime of the room.

Downtime is system dependent. In general, formaldehyde needs longer aeration times, hydrogen peroxide and UV-C can offer shorter aeration times under certain conditions. Total OT downtime is not a nominal treatment time: preparation, sealing, cycle start, clearance verification, and documentation are all part of total OT downtime. Institutions should record the entire timeframe of the room closure when evaluating the impact on workflow until the room is released.

Validation should be done using documented acceptance criteria, based on technology. These can include chemical indicators, biological indicators, concentration sensors, environmental monitoring, cycle logs and/or verification of the room endpoint as defined by the manufacturer. Staff should be trained on room preparation, equipment operation, exposure prevention, emergency procedures, and release criteria. Each step should be documented in a written SOP and have clear responsibility.

Cost and Total Cost of Ownership

The capital cost range is too broad to give a general idea of the cost, as it depends on the manufacturer, country, room size, and service contract. A repeatable method is to compare total cost of ownership (TCO) over a specified time frame, such as 3–5 years. Table 2 lists the components that should be included in this analysis: capital acquisition, consumables, maintenance, calibration, staff training, biological or chemical indicators, room preparation, treatment time, clearance verification, modifications to room ventilation or sealing, and opportunity cost from room downtime. Cost-effectiveness should also be assessed against the clinical or infection control goal; a technology that decreases bioburden but does not affect a meaningful clinical or infection control goal may not warrant a large capital investment.

Cost scale: Low = relatively low capital/operating cost; Moderate = intermediate capital, containment, validation, monitoring, or downtime cost; High = significant capital, containment, validation, monitoring, or downtime cost; Context-dependent = cost dependent on local infrastructure and procurement.

Table 2. Components to consider when comparing total cost of ownership.

Cost Component	Formaldehyde	VHP / Aerosolized H ₂ O ₂	UV-C / Physical Systems
Capital equipment	Low–moderate / system-dependent	Moderate–high / system-dependent	Moderate / system-dependent
Consumables	Chemical and monitoring	Peroxide and indicators	Low; lamp/fixture replacement
Maintenance and calibration	Required	Required	Required
Room preparation	High; containment/sealing	Moderate–high; sealing/validation	Moderate; positioning
Clearance / release	Critical; prolonged aeration may occur	Critical; measured clearance	Dose/position verification
Downtime opportunity cost	Potentially high	System-dependent	System-dependent

Note: Relative categories are deliberately qualitative, as prices differ across devices and jurisdictions.

Regulatory Considerations

There are different regulatory pathways for different jurisdictions, uses and claims. In general, FDA 510(k) clearance implies that the cleared indications are deemed to be substantially equivalent to those of an existing, legally marketed predicate (Table 3). Some new moderate-risk devices that do not have an appropriate predicate are classified de novo. The CE marking of the device under relevant EU legislation does not automatically mean that the device is clinically effective for all indications of SSI prevention. There are other countries with their own authorisation procedures. Prior to procurement, regulatory status should be verified for the specific device, indication, setting, and country.

Table 3. Illustrative regulatory considerations.

Technology	Illustrative Regulatory Pathway	What Authorization Does Not Establish	Implementation Implication
VHP / H ₂ O ₂ systems	Device- and jurisdiction-specific	Does not by itself prove SSI reduction	Verify intended use, cycle validation, and clearance
UV-C room systems	Device- and jurisdiction-specific	Does not establish adequate dose in every room or SSI reduction	Validate dose distribution and safety controls
Ozone systems	Device- and jurisdiction-specific	Does not establish safe occupational exposure or clinical benefit	Verify containment, monitoring, and clearance
Chlorine dioxide systems	Device- and jurisdiction-specific	Does not establish safe occupational exposure or clinical benefit	Verify containment, monitoring, and clearance
Far-UVC devices	Device- and jurisdiction-specific	Does not establish safety for occupied rooms or clinical benefit	Verify intended use, exposure limits, and regulatory clearance
Plasma air treatment	Device- and jurisdiction-specific	Does not establish clinical benefit	Verify clinical evidence and intended use
Photocatalytic coatings	Device- and jurisdiction-specific	Does not establish durable antimicrobial activity or clinical benefit	Verify durability testing and intended use

Note: Regulatory status of the device, indication, and jurisdiction must be confirmed.

Decision Framework for Operating-Theatre Environmental Decontamination

The overall decision-making pathway from ensuring prerequisites to outcome monitoring is summarized in Figure 1.

Decision-Making Framework for Environmental Decontamination

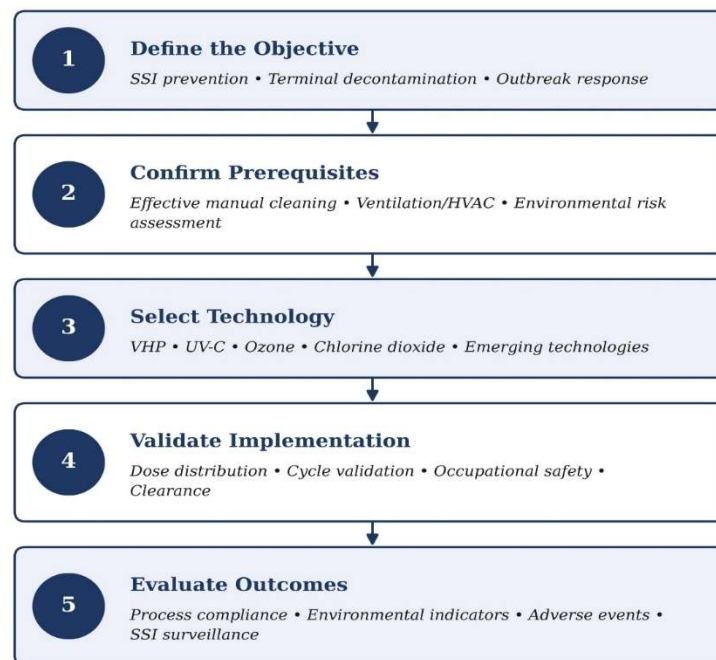


Figure 1. Decision-making process for selecting and applying operating-theatre environmental decontamination technologies. Source: Authors' original creation.

Selection should be based on desired outcome, room parameters, safety requirements, strength of evidence, validation, and clinically relevant outcome surveillance and should be based on effective manual cleaning and engineering controls.

Outcome Measures: Process vs. Patient-Centred Outcomes

Typical environmental decontamination studies report reductions in surface or air bioburden. These are process outcomes that are useful but not the same as patient-centred outcomes.

The BETR trial showed that for some pathogens, better terminal disinfection procedures can help reduce the acquisition of the pathogen, depending on the pathogen and the terminal disinfection procedure. Importantly, the trial was not intended to demonstrate the ability of UV-C or any single room-decontamination technology to prevent SSI.^{31,32}

Likewise, the 2025 plasma air-purifier trial did not demonstrate that plasma air purifiers lowered postoperative infection markers, although there was a biological plausibility that plasma air purifiers could control airborne pathogens. These results are consistent with a prudent hierarchy of evidence: validated process performance is required, reduction of environmental microbial levels is beneficial, and reduction of healthcare-associated infection and SSI is more compelling for clinical adoption.³⁶

RESOURCE-LIMITED AND REGIONAL CONSIDERATIONS

Fumigation may be continued in settings where there are no formalized environmental-cleaning programs, or where traditional fumigation is still in use due to the low cost of chemicals, or where access to validated automated systems is limited, or where staff are used to traditional fumigation. In these environments, switching to an unfamiliar technology without reinforcing the cleaning system may not enhance infection prevention.

The transition strategy should start with an assessment and improvement of the routine cleaning, staff training, procurement of appropriate cleaning products and equipment, and pragmatic monitoring of compliance. If a non-routine decontamination technology is then determined to be necessary, the institution should consider using the technology in a controlled manner, validate the technology, assess the impact on the work process and occupational

safety, and compare the total cost of the new technology to the existing technology. The reduction of historical formaldehyde use should be accompanied by practical alternatives, rather than just the removal of formaldehyde. A gradual transition may be implemented starting with direct observation of cleaning quality to establish current practices, then increasing the frequency of routine cleaning by staff training and providing a consistent supply of detergent/disinfectant with supervision. With these bases established, one validated automated technology could be deployed in one OT, with performance and cost tracking documented, and then slowly rolled out to other OTs, while continuing to clean regularly. This way, you don't have to replace an imperfect cleaning system with an expensive technology that might not address the issues.

LIMITATIONS

In this narrative review, no PRISMA screening, record counts, risk-of-bias or GRADE assessment or meta-analysis were performed, which means that selection bias cannot be ruled out. The evidence for ozone, chlorine dioxide, far-UVC, plasma air treatment, and photocatalytic coatings is primarily from laboratory studies and cost, and regulatory status vary by device and jurisdiction. Most of the evidence is from high resource environments, which reduces generalizability and makes it impossible to rank technologies.

FUTURE DIRECTIONS AND RESEARCH PRIORITIES

Comparative effectiveness studies in actual operating rooms should follow laboratory log-reduction studies. Future studies should include standardized environmental endpoints in addition to patient-centred outcomes like healthcare-associated infection and SSI, and should include treatment cycle time, room downtime, staff workload, adverse events, and device maintenance. Economic evaluations of automated decontamination technologies versus improved manual cleaning, ventilation and other infection control measures are required, as well as the ability to integrate with routine surveillance using electronic cycle logs, environmental monitoring, and electronic infection-control dashboards to enhance auditability and early detection of performance failures.

In addition to trained infection-prevention staff, the use of artificial intelligence for image-based cleaning verification and prediction of high-contamination-risk rooms should also be explored, as validated in future studies. Comparative cost-effectiveness ratios of VHP, UV-C, and enhanced manual cleaning for reducing clinically meaningful infection outcomes; safety and efficacy of far-UVC devices for use in occupied OTs without exceeding eye and skin exposure limits; and frequency of automated decontamination for various OT utilization patterns and contamination risks.

CONCLUSION

The fundamentals of operating-theatre infection prevention are still environmental cleaning and disinfection. The CDC's guidance on not routinely disinfecting with fogging should be taken in the context of the fogging methods outlined in the guidance and should not be used to classify all modern automated technologies as the same. Newer VHP, aerosolized hydrogen peroxide and no-touch physical systems should be evaluated individually for their evidence of effectiveness, safety and intended use.^{7,14}

Clinical-outcome evidence is less developed than environmental efficacy evidence, but the evidence for VHP is the most developed of the gaseous technologies reviewed here. Ozone and chlorine dioxide have been shown to be highly antimicrobial in laboratory studies, but there is limited evidence of reduction of SSI, and strict occupational containment requirements. There is a larger clinical body of evidence for UV-C as an adjunctive no-touch technology. Emerging or investigational in OT infection prevention are plasma air treatment and photocatalytic coatings. Hydrogen peroxide-silver ion formulations should not be considered gaseous fumigants.

If a new technology is being considered, the process of implementation should start with a baseline environmental assessment and a clear indication. A pilot evaluation with site-specific validation should be performed prior to regular

use, staff training, documentation of standard operating procedures, monitoring of performance, and re-evaluation periodically. Cost-effectiveness analyses are required to guide resource allocation and to identify technologies that are effective in the lab and will fit into the existing OT workflow. Finally, the most effective protection is not one “best” decontamination technology, but an effective, evidence-based environmental cleaning system that uses validated adjunctive technologies.

DECLARATIONS

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AUTHORS' CONTRIBUTION

Anas Jahangir: Conceptualization, literature search, evidence synthesis, critical analysis, manuscript drafting, review and editing.

Prof. Atia Ur Rehman: Project supervision, conceptualization and critical review of the manuscript.

Hira Khan: Conceptualization, manuscript revision, editing and preparation of the final draft.

Fatima Ashraf: Project administration, manuscript review, editing and preparation of the final draft.

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