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Customising ecosystem to boost antimicrobial prophylaxis: Contemporary Review of UV-C rays and other modalities

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Abstract

Healthcare-associated infections (HAIs), and particularly those caused by multidrug-resistant organisms, remain a major source of morbidity, mortality and cost, and the contaminated hospital environment is an important reservoir driving their transmission. Because manual cleaning is inherently variable, there is growing interest in supplementary, "no-touch" and engineered strategies that shrink this reservoir. This review examines ultraviolet-C (UV-C) disinfection as the most extensively studied of these technologies, summarising how it works, how it is deployed and what the clinical and microbiological evidence shows: UV-C consistently reduces surface and air contamination, but its effect on actual infection rates is encouraging yet inconsistent and varies by pathogen. It then situates UV-C within a wider and rapidly evolving toolkit, spanning far-UV-C and upper-room ultraviolet systems, antimicrobial surfaces and coatings (including copper and silver), ventilation and filtration, wastewater-based environmental surveillance, and biological and ecological strategies such as bacteriophages, predatory bacteria, photodynamic therapy, engineered live bacteria and vector control. Traditional and complementary approaches, including Ayurvedic fumigation (Dhoopana) and camphor-containing essential oils, are also appraised. For every modality the available efficacy data are weighed against the relevant safety, ecological and ethical trade-offs, supporting the central conclusion that these interventions are best used as integrated adjuncts to, rather than replacements for, rigorous conventional cleaning.

Keywords: healthcare-associated infections; multidrug-resistant organisms; UV-C disinfection; environmental disinfection; no-touch decontamination; infection prevention

1. Introduction

Healthcare-associated infections (HAIs) remain among the most common adverse events in acute care. Point-prevalence data from the United States indicate that between roughly 648,000 and 1.7 million hospitalised patients are affected in a single year, with consequences that include prolonged length of stay, increased mortality, and substantial additional cost. A disproportionate share of this burden is driven by multidrug-resistant organisms (MDROs), methicillin-resistant *Staphylococcus aureus* (MRSA), vancomycin-resistant enterococci (VRE), *Clostridioides difficile*, and multidrug-resistant Gram-negative organisms such as *Acinetobacter baumannii*, whose limited treatment options make prevention especially important.

A substantial body of evidence implicates the hospital environment as a reservoir for these organisms. MDROs persist on high-touch surfaces, bed rails, tray tables, call buttons, and bathroom fixtures, and an estimated up to 20 percent of HAIs are attributable to environmental contamination. The clearest demonstration of this link is the “prior room occupant” effect: a patient admitted to a room whose previous occupant was colonised or infected with an MDRO is at measurably higher risk of acquiring the same organism, a relationship documented for C. difficile, VRE, and multidrug-resistant Gram-negative bacilli.

Manual cleaning is the foundation of environmental control, but it is inherently variable: it depends on staff reaching every surface with the correct product and contact time, and in practice contaminated sites are frequently missed. These limitations prompted interest in automated, “no-touch” decontamination technologies intended to supplement, not replace, manual cleaning. Ultraviolet-C (UV-C) light is among the most widely studied of these. This article reviews how UV-C works, how it is deployed in practice, what the clinical and microbiological evidence shows, and where its limitations lie. It then widens the lens to the broader and rapidly expanding toolkit for interrupting environmental transmission, from other ultraviolet modalities and antimicrobial surfaces to ventilation and filtration, environmental surveillance, biological strategies, and traditional approaches such as Ayurvedic fumigation and camphor-based essential oils, before appraising the safety, ecological and ethical trade-offs that accompany each.

2. UV-C Disinfection

This section examines UV-C as a no-touch surface-disinfection technology, how it inactivates microbes, how it is deployed in practice, what the clinical and microbiological evidence shows, how its benefit varies by pathogen, and where its practical limits lie.

1.1 How It Works

UV-C refers to the short-wavelength band of ultraviolet light, roughly 200 to 280 nanometres. At these wavelengths the energy is absorbed directly by the genetic material of microbes, damaging their DNA and RNA. The damage prevents the organisms from replicating, effectively rendering bacteria and viruses non-viable even if they are not physically removed from a surface. Because the effect is physical rather than chemical, UV-C acts on a broad range of pathogens without relying on a specific biocidal reaction.

2.2 How It Is Used

UV-C is applied as a final, automated layer of disinfection rather than a substitute for cleaning. After a room has been cleaned conventionally and the patient has been discharged, staff position a mobile UV-C-emitting device in the empty room and run it for a defined cycle, commonly around 30 minutes. The device emits UV-C throughout the room, reaching surfaces that are difficult to clean manually, and reduces residual contamination remaining after the manual pass. The room is then prepared for the next occupant.

2.3 What the Evidence Shows

The strongest support comes from the Benefits of Enhanced Terminal Room (BETR) Disinfection study [1], a cluster-randomised, multicentre, crossover trial published in The Lancet in 2017. Across nine hospitals and more than 300,000 admissions, adding UV-C after routine terminal cleaning was associated with a measurable drop in the acquisition of targeted multidrug-resistant organisms, with the largest reductions seen during the UV-C intervention periods. Pooled analyses of enhanced strategies have pointed to reductions in transmission of major resistant organisms on the order of 30 percent overall.

Earlier mechanistic studies provided supporting data. Nerandzic and colleagues [2] reported that UV-C decontamination produced substantial reductions in MRSA, VRE, multidrug-resistant Acinetobacter, and C. difficile contamination on surfaces in patient rooms, direct evidence that the technology does what it claims at the level of the surface itself.

The picture is not uniformly positive, however. A randomised evaluation by Rock and colleagues [3] did not find significant reductions in new VRE or C. difficile infections despite the use of UV-C. Systematic reviews have reconciled these results into a consistent message: UV-C clearly reduces environmental contamination, but the evidence that it lowers actual hospital-acquired infection rates is mixed. That is the central reason it is positioned as an adjunct, not a replacement.

Pooled analyses reinforce this nuanced picture. An early meta-analysis of no-touch disinfection methods by Marra and colleagues [4] reported reductions in MDRO infection rates. A more recent meta-analysis by Sun and colleagues [5], restricted to nine US studies, found no statistically significant reduction in C. difficile (incidence rate ratio [IRR] 0.90, 95% CI 0.62–1.32) or VRE infection rates (IRR 0.72, 95% CI 0.38–1.37), although the risk of Gram-negative rod infection was significantly reduced (IRR 0.82, 95% CI 0.68–0.99). A separate meta-analysis of pulsed-xenon UV devices [6] found significant reductions in C. difficile (IRR 0.73) and MRSA (IRR 0.79) infection rates but not VRE, while cautioning that the results were statistically unstable and the overall quality of evidence low.

A 2025 systematic review in the Journal of Hospital Infection [7], covering 25 studies of UV-C, pulsed-xenon UV, and other ultraviolet systems, reached a consistent conclusion: ultraviolet disinfection can reduce HAIs, one facility-wide programme reported a 34.2 percent fall in overall HAI incidence, but the magnitude varies by device, clinical setting, and target pathogen, and the benefit is greatest when ultraviolet treatment is integrated into a comprehensive infection-prevention strategy rather than used in isolation.

2.4 Effects Vary by Pathogen

The benefit of UV-C is not the same for every organism. It appears particularly useful against the transmission of MRSA. For VRE, combining bleach with UV-C produced a further reduction in transmission beyond either measure alone. The benefit for C. difficile, a spore-forming organism resistant to many disinfection methods, was more modest and variable, consistent with the broader finding that infection outcomes for this pathogen are the least clear-cut.

2.5 Advantages and Limitations

UV-C offers several practical advantages. It is a non-contact method, so it does not depend on a staff member physically wiping each surface. It reaches hidden and hard-to-clean areas that manual cleaning routinely misses. By shrinking the environmental reservoir of antimicrobial-resistant organisms, it has the potential to lower hospital-acquired infection rates and the costs that come with them.

Those strengths come with real constraints. UV-C is harmful to skin and eyes, so rooms must be completely empty during a cycle. The added cycle time lengthens the turnaround between patients, which matters when beds are in demand. The equipment is expensive to purchase and maintain. And crucially, UV-C cannot remove dirt, dust, or organic matter, it only inactivates microbes on surfaces it can reach, which is why thorough conventional cleaning remains a non-negotiable first step.

3. Complementary and Emerging Approaches

UV-C surface disinfection is one element of a much larger and rapidly evolving toolkit for interrupting the transmission of pathogens through the environment. These approaches range from closely related ultraviolet modalities to surface engineering, air handling, environmental surveillance, and biological strategies that act on pathogens or their vectors directly. A brief survey of this landscape helps situate where UV-C fits and where its boundaries lie.

3.1 Other Ultraviolet Modalities

Far-UV-C light at 222 nm is a notable extension of the technology. Welch and colleagues [8] proposed far-UV-C as a tool to control airborne-mediated microbial disease, and Buonanno and colleagues [9] showed that it efficiently inactivates airborne human coronaviruses. Crucially, because 222 nm light penetrates only the outermost, non-living layers of the skin and the tear film of the eye, it appears not to cause the tissue damage associated with conventional 254 nm UV-C, raising the prospect of safe, continuous air disinfection in occupied spaces, although long-term human safety data are still being assembled.

Upper-room germicidal UV takes a different approach, directing 254 nm light into the upper portion of a room to disinfect air circulating above the occupants while shielding people below. In a landmark trial on a tuberculosis ward in Lima, Escombe and colleagues [10] found that upper-room UV combined with negative air ionisation markedly reduced tuberculosis transmission to guinea pigs breathing the ward's exhaust air, strong evidence that engineering the air, and not only surfaces, can interrupt airborne spread.

3.2 Antimicrobial Surfaces

Self-disinfecting surfaces aim to suppress contamination continuously between cleanings. Salgado and colleagues [11] reported that replacing high-touch surfaces with antimicrobial copper alloys in intensive-care rooms significantly lowered the rate of healthcare-associated infections, attributing the effect to copper's intrinsic contact-killing activity against bacteria. Page, Wilson and Parkin [12] reviewed a broader class of engineered antimicrobial coatings, including photocatalytic, silver-based, and light-activated materials, as a means of diminishing the role of the inanimate environment in HAIs. Such coatings remain an active research area, with real-world durability and clinical benefit still to be firmly established.

3.3 Air Handling: Ventilation and Filtration

Attention to the air itself intensified during the COVID-19 pandemic. Morawska and Milton [13] argued that airborne transmission of SARS-CoV-2 was being underappreciated, and Allen and Ibrahim [14] highlighted air changes per hour and filtration as modifiable determinants of indoor transmission risk. Together they helped reframe ventilation and high-efficiency filtration as core, if long-neglected, infection-control measures that operate alongside surface disinfection rather than competing with it.

3.4 Environmental Surveillance

Monitoring the environment can also serve as an early-warning system. Medema and colleagues [15] detected SARS-CoV-2 RNA in municipal sewage and showed that the signal correlated with reported COVID-19 prevalence, helping to establish wastewater-based epidemiology as a non-invasive, population-level surveillance tool now applied to a range of pathogens.

3.5 Biological and Emerging Strategies

A further group of approaches acts on pathogens or their ecology directly, rather than through physical or chemical disinfection. Bacteriophages, viruses that infect bacteria, have been explored both as targeted therapeutics and as agents for reducing bacterial reservoirs on surfaces. Abedon [16] set out the methodological rigour that phage-therapy research should report, and Nale and Clokie [17] summarised the preclinical data and safety considerations for use in humans, reflecting renewed interest in phages against drug-resistant bacteria.

Predatory bacteria offer a related biological strategy. Sockett and Lambert [18] described *Bdellovibrio* and similar organisms, which invade and kill other Gram-negative bacteria, as a possible “living antibiotic”, an early articulation of using one organism to control another in clinical and environmental settings.

Photodynamic antimicrobial therapy takes yet another route. Hamblin and Hasan [19] reviewed an approach in which a photosensitising dye is activated by visible light to generate reactive oxygen species that kill nearby microbes. Because it does not rely on conventional antibiotic mechanisms, it is attractive against resistant organisms, particularly for localised infections and surface decontamination.

Synthetic biology has begun to yield engineered live bacteria designed to perform defined functions in the body. Isabella and colleagues [20] developed a synthetic bacterial therapeutic for the metabolic disease phenylketonuria, a proof of concept for a platform that could, in principle, be adapted to outcompete or neutralise pathogens.

3.6 Vector and Reservoir Control

At the broadest scale, controlling the vectors and reservoirs of infection extends the same logic well beyond the hospital. Utarini and colleagues [21] demonstrated in a randomised trial that releasing *Aedes aegypti* mosquitoes carrying the *Wolbachia* bacterium substantially reduced the incidence of dengue. Kyrou and colleagues [22] showed that a CRISPR-Cas9 gene drive targeting the doublesex gene could completely suppress caged *Anopheles gambiae* populations, a potential tool against malaria. The sterile insect technique, the classic area-wide method reviewed by Dyck, Hendrichs and Robinson [23], achieves comparable population suppression by releasing sterilised males. These ecological interventions sit far from surface disinfection, yet share its underlying aim: shrinking the environmental and biological reservoirs from which infection arises.

3.7 Studies Supporting Silver's Antimicrobial Activity

Silver has a long history as an antimicrobial agent, and a growing body of work supports its activity against bacteria. Rai, Yadav and Gade [24] reviewed silver nanoparticles as a new generation of antimicrobials, and Morones and colleagues [25] characterised the bactericidal effect of silver nanoparticles against a range of Gram-negative organisms.

Silver ions (Ag^+) can exert their effect through several complementary mechanisms. They can:

- Damage bacterial cell membranes
- Bind bacterial proteins
- Interfere with enzymes
- Generate reactive oxygen species
- Damage DNA

3.8 Ayurvedic Fumigation (Dhoopana)

A traditional counterpart to engineered air disinfection comes from Ayurveda in the form of Dhoopana, the fumigation of an enclosed space with the smoke of medicinal plant materials. Classically prescribed to purify wards such as the Sutikagara (post-natal unit) and Kumaragara (paediatric unit), the practice has attracted renewed scientific interest as a low-cost, locally available alternative to chemical fumigants such as formaldehyde.

A small but growing experimental literature supports its antimicrobial effect. Bhatwalkar and colleagues [26] showed that fumigation with common plant products, garlic peel, turmeric, carom seeds and loban, reduced airborne bacterial counts and disinfected surfaces contaminated with methicillin-resistant *Staphylococcus aureus*. Balkrishna and colleagues [27] characterised the smoke particles of a Vishaghn Dhoop formulation at the nanoscale and demonstrated activity against Gram-positive and Gram-negative bacteria, mycobacteria and *Candida*. Hospital-based studies have reported similar effects in occupied clinical settings: Sourabh and Pant [28] found reduced bacterial and fungal bioaerosols in a paediatric OPD and IPD, and Harishchandra and colleagues [29] reported statistically significant reductions in bacterial and fungal counts that persisted for several days after a single fumigation. In vitro, Naikwadi and Panchaxarimath [30] tested herbal Dhoopa against nosocomial isolates including *Pseudomonas aeruginosa*, *Staphylococcus aureus* and *Salmonella typhi*, with several organisms failing to regrow after exposure.

The evidence base, however, carries important caveats. Almost all of these studies are small, single-centre experiments published in specialty Ayurvedic or pharmacy journals, frequently without blinding or independent replication, and they measure surrogate endpoints, reductions in environmental colony counts, rather than any reduction in hospital-acquired infection. Formulations, doses and exposure times are not standardised, which makes results difficult to compare or reproduce. Crucially, the active agent is smoke: the same combustion that delivers antimicrobial compounds also generates respirable particulate matter and other products of incomplete combustion, so any benefit must be weighed against the indoor-air-quality and occupant-exposure concerns that fumigation by burning inevitably raises. As with the other emerging approaches surveyed here, Dhoopana is best regarded as a promising but not yet rigorously validated adjunct, requiring controlled trials with clinical endpoints before it can be recommended for routine use.

3.9 Camphor and Essential Oils

Volatile plant compounds offer another route to environmental antimicrobial activity. Camphor, a bicyclic monoterpene found in the essential oils of *Cinnamomum camphora*, *Salvia* and related aromatic plants, has attracted interest for its activity against enteric pathogens, including *Salmonella*. Broad screens of plant essential oils against foodborne organisms established the field: Burt and Reinders [31] quantified the bactericidal activity of oregano, thyme, bay and clove oils against *Escherichia coli* O157:H7, and subsequent reviews have catalogued camphor-containing oils such as those of *Salvia officinalis* among agents that inhibit *Salmonella typhimurium* and other enteric bacteria in vitro [32].

The mechanism is largely physical. As lipophilic terpenoids, camphor and its relatives partition into the bacterial cell membrane, disrupting its structure, increasing permeability and dissipating the pH gradient, which leads to leakage of ions and intracellular contents and interferes with membrane-bound enzymes and metabolism [33]. Because this action targets the membrane rather than a specific molecular pathway, it is relevant across a broad range of organisms, including Gram-negative bacteria such as *Salmonella*, although camphor is generally a weaker antibacterial than phenolic essential-oil constituents such as carvacrol and thymol; when isolated from the oil, camphor itself can show little activity of its own [34].

These findings come with an important caveat. The evidence for camphor against *Salmonella* is almost entirely in vitro, typically using essential-oil vapours or relatively high concentrations against isolated laboratory strains rather than contamination in real-world settings. Inhibitory concentrations are usually far above those achieved by, and the activity rarely matches, a registered clinical disinfectant. Camphor-based fumigation and surface treatments are therefore best viewed as supplementary measures of modest, adjunctive value rather than as substitutes for established disinfection.

4. Adverse Effects and Safety Considerations

Every intervention that acts on the environment or on living systems carries its own risks, and a balanced appraisal must weigh these against the benefits. The harms span a wide range, from direct tissue injury and by-product toxicity to ecological disruption and ethical concern, and they broadly scale with how far an intervention reaches beyond the empty room.

Table 1. Safety considerations

Approach	Key Adverse Effects and Safety Considerations
Ultraviolet technologies	254 nm UV-C causes photokeratitis, conjunctivitis and skin erythema, so units run only in vacated, interlocked rooms [35]; mercury-vapour lamps risk contamination if broken and can generate ozone, and repeated exposure degrades plastics and elastomers. Far-UV-C (222 nm) spares tissue but has limited long-term human data [36] and drives indoor ozone, VOC and secondary-aerosol photochemistry [37,38]. Upper-room fixtures can overexpose occupants if poorly aligned or shielded.
Antimicrobial surfaces and coatings	Copper tarnishes and corrodes, reducing efficacy; sustained metal-ion exposure selects for heavy-metal tolerance co-located with antibiotic-resistance genes [39]. Silver-releasing materials add silver to wastewater (ecotoxicity, resistance selection), and the safety of nano-silver and titanium dioxide (IARC Group 2B by inhalation) depends on release of respirable particles [40]. Real-world durability remains poorly characterised.

Air handling: ventilation and filtration	High air-change rates and HEPA filtration carry energy, carbon, noise and maintenance penalties, and spent filters are biohazards [41]. Poorly balanced systems can redistribute rather than remove contaminated air, and aggressive ventilation can compromise thermal comfort and humidity control.
Environmental surveillance	Essentially no physical risk, but wastewater surveillance raises ethical and privacy concerns, such as stigmatising communities or de-anonymising small populations as sampling narrows to single buildings, and signals can be misread without epidemiological context [42]. Governance and transparent data use are the main safeguards.
Biological therapeutics	Phages can provoke immune responses, release endotoxin on lysis, transfer virulence or resistance genes, and select for phage resistance [43]. Predatory bacteria remain experimental with limited human data [44]. Photodynamic therapy is local, causing phototoxicity and pain and unsuitable for systemic infection. Engineered live bacteria raise biocontainment, gene-transfer, colonisation and reversibility concerns, requiring kill-switches [45].
Vector and reservoir control	*Wolbachia mosquito programmes are well tolerated but effectively irreversible once established and need community consent. Gene drives risk irreversible, cross-border ecological spread and drive resistance, with governance still maturing [46]. The sterile insect technique is benign and species-specific but not self-sustaining, needing repeated mass releases.*
Silver-based antimicrobials	Chronic exposure can cause argyria (an irreversible blue-grey skin discolouration); silver nanoparticles induce oxidative stress and cytotoxicity, with respirable particles released by wear. Silver in wastewater is toxic to aquatic life, and sustained exposure selects for silver resistance (e.g. the sil operon) co-selected with antibiotic resistance [39]. Long-term safety remains incompletely characterised.
Camphor and essential oils	Camphor is a lipophilic terpene readily absorbed by ingestion, skin and inhalation; in excess it is neurotoxic, with generalised tonic-clonic seizures often the first sign, alongside vomiting, agitation and, in severe cases, respiratory depression and coma [47]. Children are especially vulnerable (ingestion above roughly 30 mg/kg can be lethal), and regulators cap camphor content in consumer products. Antimicrobial use relies on essential-oil vapours at relatively high concentrations, which raises respiratory-irritation and flammability concerns.

5. Conclusion

UV-C disinfection functions as an enhancement to hospital cleaning, not a substitute for it. The evidence that it reduces surface contamination is strong; the evidence that it reduces infections is encouraging but mixed, and varies by organism. For hospitals fighting drug-resistant pathogens that survive routine cleaning, UV-C offers a meaningful additional layer of defence, provided it is deployed on top of, and never instead of, rigorous manual disinfection. More broadly, UV-C is best seen as one component of an expanding toolkit, spanning other ultraviolet modalities, antimicrobial surfaces, ventilation and filtration, environmental surveillance, and biological and ecological strategies, whose shared aim is to shrink the environmental and biological reservoirs from which infection arises. The strength of evidence across this toolkit is uneven, ranging from randomised trials of UV-C and engineering controls to small, largely in vitro studies of antimicrobial metals, traditional fumigation and essential oils, so claims of benefit must be matched to the quality of the data behind them. Each, however, carries its own safety, ecological, or ethical trade-offs, and none is free of cost; the right choice depends on matching an intervention's reach and risks to the setting in which it is used.

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