

Review

Global Health Alert: Racing to Control Antimicrobial-Resistant *Candida auris* and Healthcare Waste Disinfection Using UVC LED Technology

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Abstract: Emerging antimicrobial-resistant (AMR) *Candida auris* presents a formidable global health challenge, causing severe healthcare-associated infections (HAIs) with high mortality rates. Its ability to colonize surfaces and resist standard disinfectants undermines traditional hygiene practices, prompting an urgent need for new strategies. Ultraviolet C (UVC) light offers a promising approach with rapid and broad-spectrum germicidal efficacy. This review examines current literature on UVC LED technology in combating *C. auris*, highlighting its effectiveness, limitations, and applications in healthcare hygiene. UVC light has potent activity against *C. auris*, with up to 99.9999% inactivation depending on certain conditions such as microbial load, type of organism, surface, environmental, equipment, and UVC radiation factors. UVC LEDs can effectively combat *C. auris*, driving down healthcare costs and reducing attributable global mortality. Here, we explore implementation strategies for the targeted disinfection of high-risk areas and equipment, air handling units (AHUs), and water treatment systems. Challenges associated with UVC LED disinfection devices in healthcare settings, current performance limitations, and radiation safety are discussed. This will help in optimizing application protocols for effective disinfection and radiation safety. To further strengthen healthcare facility hygiene practices and curb the global spread of *C. auris*, recommendations for integrating UVC LED disinfection into infection control programs are shared.

Keywords: antimicrobial resistance; *Candida auris*; global spread; high mortality rates; hospital infections; superbug; UVC light; healthcare waste management



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1. Introduction

1.1. Antimicrobial Resistance

Antimicrobial resistance (AMR) poses a significant threat to global health and economic development, with emerging pathogens like *Candida auris* (*C. auris*) sparking concern. AMR is characterized by microorganisms (bacteria, viruses, fungi, and parasites) resisting the effects of antimicrobial medications that they were once susceptible to, rendering them ineffective [1–4]. This phenomenon significantly threatens human health with rising attributable morbidity, mortality, and healthcare costs from healthcare-associated infections [5–7]. In recent years, the emergence of multidrug-resistant (MDR) pathogens, which

are resistant to multiple classes of drugs, has intensified the danger of microbial spread and infection [8]. In response to the global public health threat due to AMR, the World Health Organization (WHO) established a global tripartite partnership with the Food and Agriculture Organization of the United Nations (FAO) and the World Organization for Animal Health (WOAH) to monitor and evaluate global progress on AMR [9,10]. Other contributing challenges include the non-uniform surveillance and monitoring systems for AMR across geopolitical locations, cross-sector and multi-industry siloes, non-uniform policies, and resource disparities to build and maintain the infrastructure needed to sufficiently address AMR [9].

1.2. *Candida auris*

C. auris is a member of the *Candida* genus, which colonizes the skin more than other mucosal surfaces like the gastrointestinal system, leading to potential person-to-person transmission [11]. *C. auris* has been in the media spotlight due to frequent infections with poor prognosis among compromised hosts and its persistent antifungal resistance compared to other *Candida* species. While cases of *C. auris* have been on the rise since the first accurately identified case in Japan in 2009, there has been a rapid spike in global cases recently [12]. Media attention to the active outbreaks across the United States (Washington, Nevada, Illinois, and New York) in early 2024 has raised alarm bells for health officials, with social media calling this the “*C. auris* fungus 2024 pandemic” [13–19]. Scholarly work on *C. auris* has seen an annual publication and citation growth rate of nearly 38% [20]. *C. auris* is currently the only fungal pathogen identified by the Centers for Disease Control and Prevention (CDC) as an urgent threat by the Mycotic Diseases Branch [21,22].

While most reports suggest that *C. auris* infections are not a threat to healthy individuals, vulnerable populations in healthcare facilities are at high risk for adverse outcomes. Nosocomial infections, also called hospital-acquired infections or healthcare-associated infections (HAIs), are associated with the worst outcomes for *C. auris* clinical infection, with expert consensus advising that *Candida auris*-associated candidemia (*Candida*-related blood infections) and subsequent sepsis could contribute to crude mortality rates (reported as attributable deaths per 100,000 population) as high as 72% in hospitals and residential healthcare facilities [7,23]. Despite the remarkably high mortality rate, there are very few effective drugs against *C. auris* due to the growing AMR and (well-meaning) misuse of antibiotics and antifungals [24]. *C. auris* is also an opportunistic fungus, with frequent outbreaks overlapping with other pathogenic spreads such as COVID-19. A recent retrospective chart review at one of NYC’s largest hospitals found that *C. auris* incidence tripled during the COVID-19 pandemic [18].

Implementing robust prevention and disinfection practices to reduce the overall burden of *C. auris* presents substantial challenges [20]. Poor surveillance and non-uniform screening practices contribute to the continued spread [15,25]. However, once *C. auris* is colonized (presence of fungus on the skin, but without any clinical infection), there are no specific interventions that reduce or eliminate colonization [26]. While a few medications have an efficacious impact on *C. auris*, early detection and treatment are imperative for optimal outcomes.

1.3. Environmental Disinfection

Considering the challenges of identifying and treating *C. auris* colonization and infection, primary prevention through environmental disinfection may be the most promising method for reducing nosocomial spread despite implementation challenges [26]. Infection control strategies span from the environmental disinfection of contaminated areas (water, air, and surface) to appropriate waste management strategies. Current environmental infection control procedures focus almost entirely on manual cleaning and chemical disinfection [26]; however, this is not 100% effective against *C. auris* and leaves substantial room for nosocomial spread. Current waste management strategies emphasize segregation,

transport, and disposal procedures but often fail to properly disinfect and sanitize waste contaminated with highly pathogenic microbes such as *C. auris*.

1.4. UVC LED Technology for No-Touch Disinfection

No-touch disinfection is a critical disinfection modality for the management of *C. auris* outbreaks and the reduction in the global candidemia burden. No-touch disinfection includes ultraviolet C light-emitting diode (UVC LED) disinfection or the use of chemicals such as vaporized hydrogen peroxide systems used for terminal cleaning and disinfection procedures [27]. UVC lamp technology at 253.7 nm is a validated disinfection modality for water, air, and surface applications. The application of UVC LEDs over a broad spectrum (200–280 nm) offers germicidal disinfection when used individually or in conjunction with common chemical cleaning agents [28–35]. UVC LED technology can inactivate microbes and pathogens because the intracellular structures, like DNA/RNA and proteins, are susceptible to the specific density of UVC photons that are emitted in a controlled environment, causing critical genomic damage that mainly occurs through a disruption in the adenine-to-thymine bond, resulting in a pyrimidine dimer between the adenines. Damage to the cell structures prevents the microbes from replicating and limits survival times substantially [30,31,36–38]. UVC is considered safer for human cells and DNA/RNA up to a specific energy exposure (though shielding may be necessary for direct human exposure) [39–41]. Tailored UVC wavelengths, time, and other parameters of the disinfection mechanism vary by microbe or pathogen, environmental application (i.e., water, air, and surface), and specific conditions of the contaminated element.

1.5. Healthcare Waste Management

Implementing robust waste management practices alongside proper patient care protocols is crucial to protect healthcare workers and patients from this emerging fungal threat. Healthcare wastes are generated within healthcare facilities, research centers, and laboratories related to medical procedures, with considerable potential for microbial contamination and transmission. It is estimated that between 75% and 90% of all healthcare waste is generalized and non-hazardous, with the remaining 10% to 25% considered hazardous and potentially causing environmental or health risks [42]. Hazardous waste covers a wide range of materials, including pathological waste, sharps waste, chemical waste, pharmaceutical waste, cytotoxic waste, radioactive waste, and infectious waste [43]. Improper waste management practices can facilitate the spread of *C. auris* through contact with contaminated waste by healthcare workers and environmental contamination in healthcare facilities [44].

Infectious waste may contain pathogens (including fungi like *C. auris*) capable of causing disease in susceptible hosts and may include waste contaminated with blood or bodily fluids, cultures and stocks of infectious agents from laboratory work, and waste from infected patients in isolation wards [42]. Microorganisms in a reservoir (such as an inanimate object) may exit the reservoir via a suitable mode of transmission (such as through droplets or contact) and gain entry to infect a susceptible host [45]. This transmission pathway further explains how *C. auris* can easily spread throughout and beyond healthcare facilities. Despite the importance of safe and adequate healthcare waste management, 2019 data showed that one in three healthcare facilities globally does not safely manage healthcare waste [46].

While chemical disinfection and incineration are effective, they have drawbacks: chemicals can pose environmental and health risks, and incineration can contribute to air pollution [47]. UVC LEDs offer a promising alternative for waste management, providing a safe and environmentally friendly disinfection method made adaptable for various waste streams, including healthcare waste, food waste, and wastewater, offering a broader application than some traditional methods.

While UVC LEDs offer a compelling alternative for waste management, there are still challenges to overcome for widespread adoption:

- a. **Safety Concerns:** UVC light can cause damage to the skin and eyes upon direct exposure. Implementing proper safeguards like protective equipment, engineering controls (enclosed systems), and training for workers is essential.
- b. **Limited Penetration Depth:** UVC light has a limited ability to penetrate healthcare waste. This means that for effective disinfection, waste needs to be spread out in a thin layer or well mixed, or the UVC source needs to be strategically placed to ensure that all areas are exposed.
- c. **Efficacy for Complex Waste Streams:** The effectiveness of UVC LEDs may vary depending on the type of waste and the presence of organic matter that can shield microorganisms from the UVC light. Further research is needed to optimize UVC LED application for different waste compositions.
- d. **Long-Term Performance and Maintenance:** The long-term effectiveness of UVC LEDs can be impacted by factors like lifetime/aging and dust accumulation. The regular maintenance and monitoring of UVC LED systems are crucial to ensure consistent disinfection performance.
- e. **Regulatory Landscape:** Regulations governing the use of UVC LEDs for waste disinfection may vary by region. Staying updated on relevant regulations and obtaining necessary approvals is essential.

1.6. Enhanced Infection Prevention and Control

UVC LEDs may be a feasible and scalable method for environmental disinfection with technical applications in water, air, surface, and waste disinfection [41,48–56]. The primary objective of this review is to provide a comprehensive analysis and critical discussion of the relevant literature on the global public health impact and economic disruption relative to the rapid spread of *C. auris*. In addition, we explore the feasibility of applying UVC LED disinfection technology to environmental services and waste management strategies in healthcare facilities, including critical UVC LED device operating parameters. To meet our objectives, we provide a review of selected global case studies of UVC LED device applications in various healthcare applications that offer practical insight for adopting enhanced infection control procedures. The benefits and challenges of implementing robust infection control protocols using UVC LED devices across applications are also discussed. We offer clear recommendations for scalable and affordable UVC LED-enhanced disinfection protocols in global healthcare facilities and briefly discuss future research and development in the field.

2. Relevant Literature

Electronic databases (Google Scholar, Ovid MEDLINE® Epub, MED Pub, PubMed, Web of Science, and Dimensions) were systematically searched for articles published in the past ten years (2014–2024) from a broad range of fields, including the physical sciences (e.g., mycology, biochemistry, biology, engineering, and physics) and applied sciences (e.g., public health, healthcare management, medicine, and economics). Four authors (JR, TF, SA, and RM) searched for literature on the antimicrobial control of *C. auris* in healthcare facilities using UVC LED disinfection technology. Search terms included “*Candida auris*”, “antimicrobial resistance”, “nosocomial spread”, “*C. auris* surveillance”, “UVC LED disinfection”, “healthcare facility disinfection”, “healthcare waste management”, “UVC waste disinfection”, and other critical terms. Additional literature was identified by carefully reviewing appropriate articles’ citations and relevant conference presentations. The primary authors independently assessed study eligibility and performed data abstraction as it applied to this review. Our review critically examines the evidence base for the feasibility of UVC LED disinfection and waste management for *Candida auris*. As a cross-discipline review, the literature was limited to *C. auris* disinfection when possible; however, the available studies specifically examining *C. auris* were limited. In these instances, the disinfection of surrogate fungi, bacteria, and other pathogens was included.

2.1. Global Disease Threat of *Candida auris*

Fungal diseases account for a significant global burden of morbidity and mortality. Fungal infections (including skin, nails, and hair) are estimated to impact approximately one billion people, with associated mortality rates accounting for over 1.5 million deaths annually [57]. Nearly all forms of yeast are from the *Candida* genus, though many are not responsible for infection or have only superficial infection capacity [58]. Ringworm, nail fungus, yeast infections (e.g., vaginal candidiasis), and thrush (e.g., oral *Candida* infections) are among the most common fungal infections [59]. Candidiasis is an infection caused specifically by a *Candida* species and can present in many infection sites; however, there are over 200 specific species [60]. The annual incidence of oral and esophageal candidiasis is estimated at about 3.3 million, with the global burden of recurrent vulvovaginal candidiasis being about 134 million each year. Invasive candidiasis is unlike oral and vaginal candidiasis because it infects the bloodstream, brain, heart, eyes, bones, and other internal parts of the body. The annual incidence of invasive candidiasis (from any form of *Candida* spp.) is estimated to be approximately 750,000 [57]. Candidemia, a common healthcare-associated infection, is a specific and dangerous blood infection caused by *Candida* isolates with adverse outcomes [61].

C. auris is a particularly resilient branch of the *Candida* species that rapidly develops multidrug resistance with morphisms specific to regional development or genetic clade [62–64]. To date, *C. auris* has been reported in over 47 countries worldwide, representing all continents except Antarctica [65]. *C. auris* has high genetic diversity, with strains categorized into different genomic clades: I (southern Asia), II (eastern Asia), III (Africa), IV (South America), and V (Iran), each with independent emergence, which is visualized in Figure 1 [66,67]. *C. auris* clades are revealed by genome analysis, PCR amplification of genetic loci, or mass spectrometry [67]. Despite the first isolation in 2009 (ear canal), retrospective sample testing revealed the presence of *C. auris* as far back as 1996 in South Korea [12]. More than 740 isolates of *C. auris* have now been identified [24,62,68–76]. *C. auris* is a particularly resilient branch of the *Candida* species that rapidly develops multidrug resistance with morphisms specific to geographical regions or genetic clade [62]. Multidrug-resistant and pan-drug-resistant *C. auris* isolates are increasingly detected worldwide [63,64].

The rising ambient air temperatures (i.e., emerging climate change), combined with changes in avian migration patterns, farm activities, and increased urban dwellers, have created an environment that supports thermotolerant fungi like *C. auris* [69,77]. Since first being identified in Japan, *C. auris* has become a globally transmitted pathogenic infection that often leads to invasive candidemia and invasive candidiasis of the heart and central nervous system [78,79]. In 2016, the Centers for Disease Control and Prevention (CDC) identified the first reported case of a patient in the United States with *Candida auris*, discovered via a misidentified isolate collected in 2013 [80]. *C. auris* has been identified in several infection sites and bodily fluids, including the blood, urine, bile, ear canal, nares, axilla, skin, and, in rare instances, the oral, esophageal, and gut mucosa [62]. While *C. auris* infections are particularly dangerous, several challenges in identification and control mean that many studies and facility reports fail to separate *C. auris* from other candidemias or conflate *C. auris* with other dangerous pathogens.

Many *C. auris* strains have a high minimum inhibitory concentration (MIC) toward antifungal drug classes and common disinfectants, contributing to the challenge of decolonization and the treatment of infections [51,62]. Its pathogenicity has been associated with virulent traits like the production of proteases, lipases, mannosyltransferases, oligopeptides, siderophore-based iron transporters, and biofilm formation. These virulent traits assist *C. auris* in invading, colonizing, and acquiring nutrients from the host [11]. Further, *C. auris* has the capability of transforming into a persistent yeast capable of surviving under unfavorable conditions [11,60,81,82].

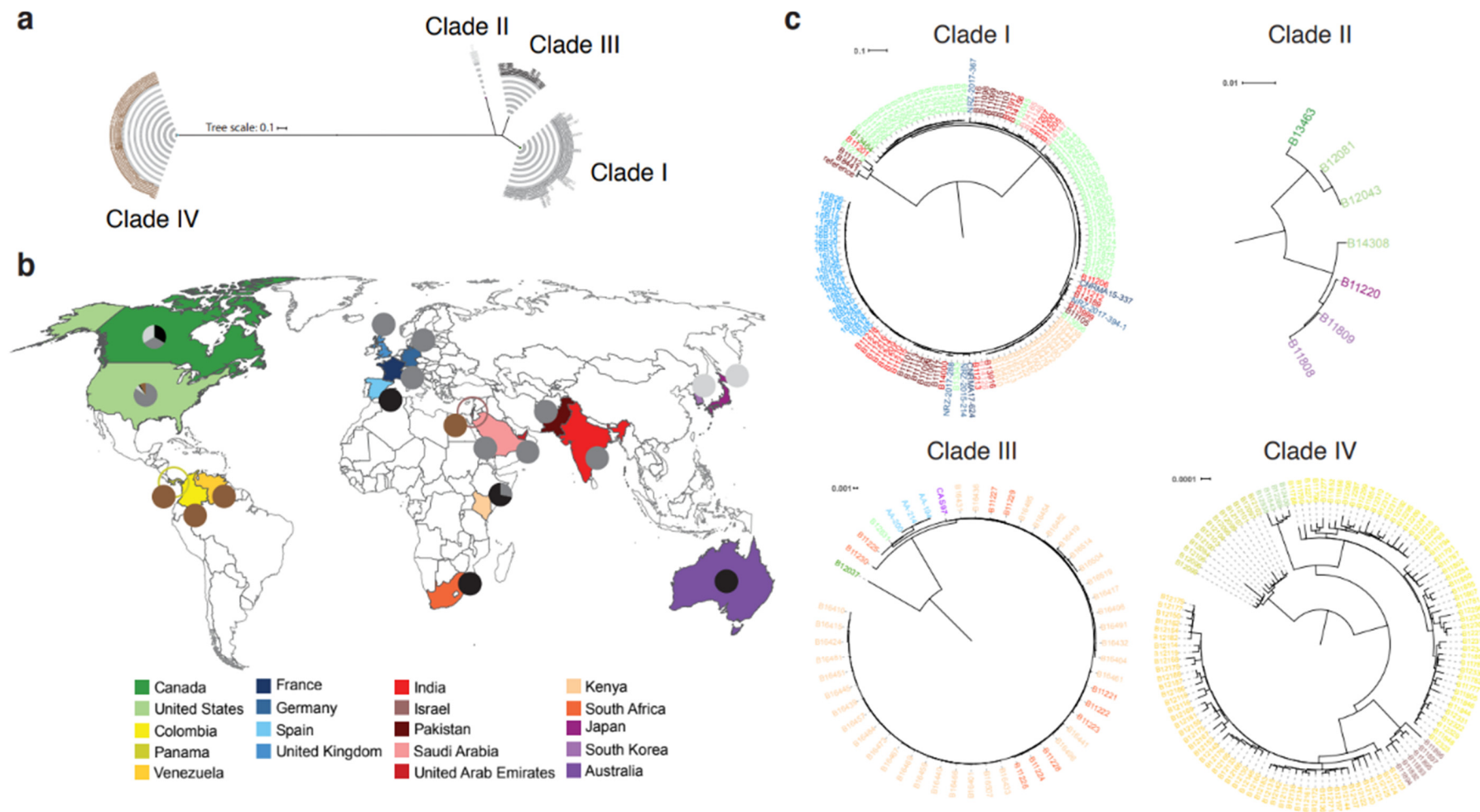


Figure 1. Global distribution of *C. auris* clades. (a) Phylogenetic tree of 304 *C. auris* whole-genome sequences clustered into four major clades. Maximum likelihood phylogeny using 222,619 SNPs based on 1000 bootstrap replicates. (b) Map detailing *C. auris* clade distribution by country ($n = 19$). (c) Phylogenetic tree of clades I to IV. The countries are indicated by color. Figure and caption reprinted with permission from Chow et al. 2020 [67].

Once *C. auris* colonizes and progresses to invasive candidiasis or candidemia, several molecular mechanisms can evade the action of antifungals, leading to resistance to agents like amphotericin B and the azole and echinocandin classes of drugs. Azole (e.g., fluconazole) resistance is associated with the overexpression of drug efflux pumps belonging to ATP binding cassette (ABC) and major facilitator superfamily (MFS) transporters and encoding alterations in the ergosterol synthesis pathway (overexpression of ERG11 and point mutations in ERG11, Y132F, or K143R). Echinocandin resistance in *C. auris* has been shown to be attributable to mutations in FKS1, a gene that encodes the enzyme responsible for the key fungal cell wall component β (1,3) D-glucan. Single nucleotide polymorphisms in genes related to the ergosterol synthesis pathway leading to altered sterol composition and potential amino acids substitution in the FUR1 gene (i.e., F211I) have been linked to *C. auris* resistance to polyenes (e.g., amphotericin B) and nucleoside analogs (e.g., flucytosine), respectively [60,83–88]. In addition to the multidrug resistance, *C. auris* can survive on surfaces, including human skin, for extended periods, contributing to high mortality rates (30–60%) in healthcare settings [62,65,89,90]. Difficulties in pathogen identification and disinfection have also led to increased transmission and delayed infection management [11,60,81,82].

The near-simultaneous emergence of multidrug-resistant *C. auris* on multiple continents, as well as the associated high mortality rate, make *C. auris* a significant global threat [91]. The changing climate trending toward warmer global temperatures is not enough to fully explain the rapid ability to develop resistance to antifungals [69]. More concerning is that many MDR *C. auris* outbreaks have no direct epidemiological links, indicating that they are developing new resistance in each cluster [92]. In 2022, the World Health Organization listed *C. auris* on the “WHO fungal priority pathogens list” in the critical priority group, urging global action in three priority areas: (1) surveillance; (2) research, development, and innovation; and (3) public health interventions [78]. In 2018, the CDC made *C. auris* a nationally notifiable infectious disease [93]. While antifungals may be used to treat invasive candidiasis due to *C. auris*, multidrug-resistant and pan-drug-resistant isolates are rapidly being identified across the globe [78]. The near-simultaneous emergence of multidrug-resistant *C. auris* on multiple continents, as well as the associated high mortality rate, make *C. auris* a significant global public health threat [91].

The global incidence rate of *C. auris* infections cannot currently be established due to a lack of uniform surveillance systems, few epidemiological outbreak studies, and limited diagnostic capability [78]. Conventional laboratories often misidentify *C. auris* as one of several similar isolates, such as other *Candida* species like *C. haemulonii*, *C. famata*, and *C. sake*, as well as *Rhodotorula glutinis*, *R. mucilaginosa*, and *Saccharomyces* species [25,94]. While accurate incidence rates are challenging to estimate, individual studies and health systems across the globe have evaluated incidence through outbreak investigations. Studies across Asia, Europe, the Middle East, Africa, Australia, and the Americas have examined colonization, progression to IC and candidemia, and specific AMR [12,79,91,95–101]. Du et al. (2020) estimate that there are over 400,000 candidemias (bloodstream infections) each year across all species, with a global mortality rate higher than 40%; however, other studies have estimated mortality rates up to 60% [102].

In the United States, the CDC reported 1747 confirmed clinical cases across 26 states and DC, with 95% of cases occurring in population-dense states (i.e., New York, Illinois, New Jersey, California, and Florida) by the end of 2020 [80]. This rapid escalation continued in the US, with over 3200 active cases accumulated between 2019 and 2021, which rose from a 45% case increase in 2019 to a 95% case increase in 2021, with a three-fold increase in AMR cases [103]. Following this trend, the CDC reported 2377 clinical cases and 5754 screening cases of *C. auris* in 2022 [21]. These rates are widely thought to be underreported due to a lack of robust surveillance systems and non-uniform screening protocols [15].

While incidence rates may be underreported or unreliable, disease burden has been tracked more frequently. The median length of hospital stays for adult patients identified with *C. auris* candidemia was 46–68 days (70–140 days for pediatric patients) [78]). Re-

searchers and hospital investigation teams more frequently report mortality rates; however, rates related to IC and candidemia vary significantly across the globe, as noted in Table 1. Since the emergence of *C. auris*, mortality rates reported for candidemia have been quite high, nearing 50% of diagnosed infections [62]. Further complicating accurate surveillance and monitoring is that the misidentification of *Candida* species also extends to mortality reporting errors. Mortality rates are often reported only for candidemia or IC, without species attribution [104].

Table 1. Global crude mortality rates attributable to candidemia. Mortality rate is expressed according to standard population health reporting as the annual death rate attributable to a specific cause (i.e., candidemia) per 100,000 people/population in a specific geographic region. In this case, mortality is attributable to candidemia or, specifically, *C. auris* when available (see below). Geographic regions and time periods are defined per column and row.

Country	Mortality Rate (Estimated)	Dates of Measurement	Citation
Pakistan	52%	2009	[105]
India	50% *	2009–2011	
	44%		[106]
South Africa	46%	2012	[107]
Panama	78% *	2017	[96]
Venezuela	28% *	2012–2013	[97]
Brazil	72%	2007–2010	[108]
Columbia	43%	2015–2016	[68]
England (three London hospitals)	14.5% *	2015–2018	[109]
India, US, UK (combined systematic review)	30% *	2017	[24]

* Rate estimate attributed specifically to *C. auris*, not all possible candidemias.

2.1.1. Vulnerable Populations

Invasive candidiasis and candidemia are nosocomial infections that can disproportionately impact the critically ill, immunocompromised, elderly, and patients with extensive comorbidities or a history of frequent antimicrobial therapy [12,24,62,78,110,111]. Patients with indwelling medical devices (e.g., central venous catheters), patients receiving parenteral nutrition, patients on mechanical ventilation, and patients with hospital admissions longer than 10–15 days are among the most at risk for adverse outcomes [78]. Underlying respiratory and/or cardiovascular illness, vascular surgery, prior antifungal exposures, and low APACHE II score (ICU-based severity-of-disease classification system) are considered significant risk factors associated with *C. auris* candidemia and poor prognosis [62,112]. Nosocomial outbreaks of invasive candidiasis (*Candida auris*-specific) in intensive care (ICU) settings are common, especially where colonization on non-human hosts has been previously identified [94]. In an analysis of 27 ICUs in India, where 1400 candidemia cases were reported, over 5% were attributed to *C. auris* [112]. Rudramurthy et al. also found that patients with *C. auris* candidemia had longer ICU admissions prior to diagnosis than those with other microbial infections, indicating that nosocomial spread contributed to fungal outbreaks in India [78]. It is estimated that unless substantial actions to address AMR infections are taken, nearly 10 million people will die annually by 2050 [113,114].

Annually, over 2 million children die globally before their first month of life [115,116], with infection as one of the top three most prevalent causes (along with prematurity-related complications and intrapartum-related complications) [116,117]. *Candida* species are responsible for the greatest number of neonatal invasive fungal infections [117]. The most common *Candida* species affecting pediatric populations are *C. albicans*, *C. parapsilosis*,

C. glabrata, and *C. krusei* [118]; however, *C. auris* is now impacting pediatric populations as well. In a prospective cohort study of hospitalized infants (<60 days postnatal age with sepsis) in low- and middle-income countries (LMICs) at 19 hospitals across 11 countries, researchers found *C. auris* to be the third most commonly reported pathogen [3,4,117–119]. In South Africa, *C. auris* was among the fifth most common *Candida* species responsible for candidemia [120]. In India, among 273 neonates from three hospitals with neonatal invasive candidiasis (NIC) cases, investigators isolated *C. auris* in 2.2% of the cases, highlighting the vulnerability and susceptibility of infants in LMICs [121].

The crude mortality rate associated with NIC varies significantly, unsurprisingly, with higher rates disproportionately impacting LMICs compared to high-income countries (HICs) (8.9–75% in LMICs and 12–37% in HICs) [117]. Risk factors for neonates developing NIC or candidemia include preterm birth, older infants and children with ICU stays, post-surgical stays, underlying malignancies, malnourishment or requiring parenteral nutrition, post-solid organ transplantation, an underlying renal disease requiring hemodialysis, central venous catheter placement, and requiring respiratory support [118,119]. A case study in Italy found that an extremely-low-birth-weight preterm neonate born via vaginal delivery from a *C. auris*-colonized mother was colonized within only a few hours of birth [122]. Though limited by the ability to clearly determine if the colonization route was the birth canal or the ICU environment, this case does highlight the heightened risk for already vulnerable infants to *C. auris* [122].

2.1.2. Economic Impact

Economic simulations run by the World Bank suggest that by 2050, with an optimistic (i.e., low) AMR impact, the annual global gross domestic product (GDP) could fall by approximately 1.1%, with GDP shortfalls exceeding \$1 trillion annually after 2030. Less optimistic simulations (i.e., high AMR impact) predicted a 3.8% decline in annual GDP by 2030, with an annual shortfall of \$3.4 trillion by 2030 [123]. The predicted impact of AMR is likely to disproportionately impact low-income countries and increase the rate of poverty [123]. The total economic burden of fungal diseases and AMR in the US is thought to be dramatically underestimated [58,124]. The financial burden can be estimated as a total burden or pared down to direct costs, loss of productivity costs, premature death costs, costs per patient, and costs per hospitalization. In the absence of a standard reporting mechanism, economic burden is not always consistent across reports. Table 2 provides an overview of the estimated global economic burden for all AMR diseases, fungal diseases, and candidiasis/candidemia specifically.

Table 2. Global economic burden of fungal disease and AMR.

Economic Burden	Cost Estimate (\$USD) *	Cost Type	Source	Citation
AMR Disease Burden				
Europe	\$9.77 billion	Total burden	CDC	[3]
United States	\$55 billion	Total burden		
	\$20 billion	Direct healthcare costs		[6]
	\$35 billion	Loss of productivity		
Fungal Disease Burden				
	\$11.5 billion	Total burden	CDC	[58,124,125]
	\$7.5 billion	Direct healthcare costs		
	\$870 million	Loss of productivity		
	\$3.2 billion	Premature death		

Table 2. Cont.

Economic Burden	Cost Estimate (\$USD) *	Cost Type	Source	Citation
Candidiasis and Candidemia Burden				
Noninvasive candidiasis	\$2.5 billion	Total cost burden	CDC	[124,125]
Invasive candidiasis	\$1.7 billion	Total cost burden		
	\$1.2 billion	Direct medical costs		
	\$75 million	Loss of productivity		
	\$450 million	Premature death		
Western developed countries	Range: \$48,487–\$157,574	Cost per patient	Systematic review	[126]
Western developed countries	Range: \$10,216–\$37,715	Cost per hospitalization	Systematic review	
London outbreak	\$1.2 million	At time of outbreak	Institutional report	[109]
	\$73,000 per month	Year to year post-outbreak		

* All economic estimates are indicated in US dollars. Any global economic impact reports have been converted to US dollars from the primary source for this review.

2.2. Public Health Pandemonium—AMR and Nosocomial Spread of *Candida auris*

Public Health Prevention

Global public health initiatives often fall into three categories: primary, secondary, and tertiary prevention methods. Tertiary (treating infections before spread) and secondary prevention (screening for colonization and early infection of common pathogens) are common protocols for addressing AMR; however, the most effective form of public health prevention is primary prevention (stopping the transmission of the pathogen before colonization). The WHO Tripartite Global Action Plan Objective Three (GAPO 3) is specifically aimed at primary prevention by reducing infection through adequate sanitation, hygiene, and infection prevention measures [9]. GAPO 3 urges participating countries to develop or implement robust action plans for infection prevention and control through enhanced waste management and improved WASH conditions (water, sanitation, and hygiene), among other priorities.

Multidrug-resistant *C. auris* is increasingly becoming a challenge for successful clinical intervention [127]. AMR is closely linked to misguided and clinically ineffective prescribing practices of antibiotics and the increased presence of antibiotics in food sources such as farm-raised meats [128]. Global estimates suggest that AMR and MDR infections are directly responsible for over 1.2 million deaths and are a contributory factor in nearly 5 million deaths each year, with a concerning annual upward trend [78]. Even more concerning is that the burden of AMR-related deaths falls heaviest on resource-limited settings. AMR and basic antifungal stewardship programs, often absent or insufficient in resource-limited regions, are critical in addressing this global health threat [78]. Guided by similar principles of standard antibiotic stewardship programs that suggest effective diagnostic tools and encourage empirical antibiotic use, antifungal stewardship aims to protect the effectiveness of antifungal therapy in the future [127]. Antifungal stewardship programs must be tailored to the specific resources and capacity of each healthcare institution and health system. Key elements common in all antifungal stewardship programs include guidelines for diagnostic tests to inform therapy initiation and withdrawal, specialist consultation, the identification of provider knowledge gaps and coinciding education, and the implementation of prescribing restrictions when specialized infectious disease support is available [129]. A lack of access to diagnostic tests, delayed results, and the unavailability of *C. auris* low-resistance antifungals (e.g., echinocandins, which have limited availability in many countries despite designation as a WHO essential medicine) make effective antifungal stewardship challenging in many resource-limited health systems [78,127].

The lack of accurate screening and non-uniform testing protocols significantly contribute to the rising spread of AMR pathogens. Detecting *C. auris* is particularly challenging due to the over 700 isolates and limited laboratory testing capabilities [24]. Labs often

misidentify *C. auris* as another *Candida* species due to common multiplex testing media that lack the sensitivity and accuracy to detect specific strains of *C. auris*. Hospitals, healthcare facilities, and clinical labs have no standard testing protocols or procedures, with tests ranging from differential to selective media, mass spectrometry, and real-time PCR (polymerase chain reaction) tests. Each test varies in sensitivity and accuracy, as well as the associated need for precision in implementation, sensitivity to tester variation, and cost for scaled testing [130]. Rapid and accurate testing for *C. auris* colonization on surfaces, in water, and in human hosts is critical. In addition to identifying *C. auris* colonization or infection, labs need the capacity and standardized protocol to complete pathogen genomic analysis and AMR testing to determine the best action for remediation. Enhanced screening protocols play a significant part in outbreak investigations and rapid remediation, particularly in reducing nosocomial spread [130].

Effective infection prevention control measures to prevent the transmission of *C. auris* must include strategies that consider demonstrated transmission pathways, including the isolation of patients and contacts, wearing personal protective equipment, the routine screening of patients, skin decontamination, environmental cleaning, and terminal decontamination [100,102,131]. Source control of *C. auris* should include the disinfection of commonly identified surfaces where *C. auris* is colonized (mattress, bed rail, bedside tables, ventilators), aseptic removal of intravascular catheters, and adequate drainage and disposal of biological material. Biswal et al. noted that *C. auris* could be reduced by the most common hospital chemical disinfectants when adhering to the proper concentrations and contact time; however, these protocols are challenging to meet in understaffed and under-resourced ICUs [132]. Terminal cleaning with UVC light to reduce infection by nosocomial pathogens may be effective at preventing the transmission of *C. auris* but may need to be a supplement to standard disinfection strategies [133,134].

2.3. Current Healthcare Environmental Infection Control Standard Procedures

The global spread of *C. auris* has been attributed to its easy transmission through direct or indirect contact on high-touch surfaces, air, and wastewater; its ability to survive outside of a human host; and its ability to sustain long periods of desiccation, biofilm formation, and high thermal tolerance [22,41,62,89,121,135–139]. Not only is *C. auris* highly resilient to hostile environments, but studies suggest that it is also adaptive to environmental stress, creating near-impossible parameters for disinfection [62]. In India, ICU patients who were not colonized with *C. auris* at the time of admission were later colonized during their stay [132]. After a *C. auris* outbreak at a London hospital, researchers found that *C. auris* was not isolated from any patient prior to their admission to the ICU [100]. Once the patient's skin is colonized, transmission can proceed via skin-to-skin contact with individuals beyond the healthcare setting [140]. Appropriate infection control protocols include identifying *C. auris* colonization and infections and performing genomic analysis to assess for AMR. However, a critical factor in infection management is adequate and scalable disinfection [104]. Given the broad range of colonization sites, disinfection and environmental health facility management are critical for water, air, and surfaces. Due to the cross-sector siloes, the protocols for point-of-service (e.g., patient- and bed-specific cleaning in rapid rooming flips) disinfection across applications, larger healthcare facility environmental health management, and waste management are often ineffective and inefficient.

According to several pathogenic surveillance agencies (i.e., CDC, European Centre of Disease Prevention and Control, Pan American Health Organization, World Health Organization, Public Health England, and Centre for Opportunistic, Tropical and Hospital Infections in South Africa), infection prevention and the control of *C. auris* in healthcare settings include proper hand hygiene, transmission-based precautions (i.e., patient and room precautions to limit exposure), cleaning and disinfection, uniform screening and surveillance practices, and enhanced communication [26,104,110]. These generic and nonspecific disinfection procedures all lack specificity for *Candida auris*. This strategic gap in environmental *C. auris* mitigation to prevent nosocomial spread is apparent [39]. Each

component of the infection prevention protocol is critical; however, this review focuses specifically on disinfection as a primary prevention method. Environmental disinfection and cleaning (hand hygiene products are included here; however, policies and methods of hand washing are not) in patient care and high-traffic environments is challenging and covers patient and room turnover, daily cleaning practices, and mobile and high-touch equipment disinfection (e.g., blood pressure cuffs, glucometers, stethoscopes, crash carts, etc.) [26]. Standard protocols are limited by the required complex procedures to reach efficacy, the availability of disinfecting agents, and end-user education. Another significant limitation is the non-standardized use of “no-touch” disinfection, such as UVC LED technology. Reliance on standard contact and air precautions for the patient care of colonized individuals is not a sustainable or widely effective method. Enhanced disinfection and waste management are necessary for a robust infection prevention and control policy.

2.3.1. Current Infection Control Standard Procedures in Water Applications

C. auris can survive and spread through wastewater as well. A recent study in Nevada positively detected the dangerous fungus in nearly 80% of effluent samples, with over 90% positivity rates near healthcare facilities [141]. The testing and surveillance of wastewater, particularly in effluent sewer sheds near healthcare facilities, can help identify and track potential outbreaks and trigger early warning alarms for public health action. Lower-resourced regions and LMICs without proper water infrastructure may also reuse wastewater after only superficial disinfection. If water treatment and disinfection strategies in these areas do not fully inactivate *Candida auris*, public health could be compromised by the transmission of the pathogen through daily WASH activities. Its documented capability to produce biofilms can complicate wastewater system testing and surveillance and require more nuanced disinfection of water supplies [41,141]. The most common methods of water disinfection are chemicals (i.e., chlorination and ozonation). However, these methods generate persistent residual carcinogenic by-products (such as chlorine or bromate) [142–144]. Furthermore, these methods have led to new resistant microorganisms and affect the organoleptic properties of water. No specific healthcare setting infection control protocols for water or wastewater were found.

2.3.2. Current Infection Control Standard Procedures in Air Applications

Airborne transmitted pathogenic infections, which occur via droplets or aerosol, are also a common concern [145–147]. Coughing, sneezing, and even talking may lead to pathogen transmission, which became a critical concern during the COVID-19 pandemic. Researchers have also found a positive relationship between disinfection effectiveness and airflow conditions [148]. In poorly ventilated environments, indoor air has lower convection, leading to the environmental accumulation of pathogens and increasing the likelihood of infection [149]. *C. auris* can spread through the contamination of air handling units (AHUs) [150]. Fungal colonies can be transmitted via aerosolized particulates with both active and passive air samples. In Tehran, air samples tested positive for the presence of fungi (*C. auris* was not included in the testing protocol), indicating low air quality and the need for enhanced filtration and air purification [151]. However, the lack of discriminant air particulate testing and non-uniform air sampling render the rate of aerosolized *C. auris* transmission unknown. Public Health England’s efforts to address *C. auris* include a targeted effort to understand the transmission pathways via aerosolized spread, particularly in healthcare settings; however, data from this ongoing study have yet to be reported [152]. No standard air purification protocols or procedures for monitoring and disinfecting air handling systems for *C. auris* were found.

2.3.3. Current Infection Control Standard Procedures on Surfaces Applications

C. auris can survive on surfaces for more than three weeks (wet or dry surfaces), with colony growth (up to 1 log increase) possible on wet wood surfaces [41,104,153]. Among the surfaces from which *C. auris* has been isolated in healthcare facilities are sinks,

bathrooms, cleaning buckets, computers, phones, mattresses, bedside tables, bed rails, chairs, windowsills, doors, ventilators, thermometers, pulse oximeters, IV poles, and ECG leads [22,26,62,69,100,132,154]. In fact, an outbreak in Brazil during the height of the COVID-19 pandemic (March 2020) and increased infection prevention and control awareness was traced back to colonized axillary thermometers reused across patients without sufficient disinfection [154].

In surface applications, the current chemical disinfection protocols range widely by site and sector and are impacted by the MICs associated with *C. auris* isolates. Common disinfection wipes containing quaternary ammonium compounds (QACs) used for high-touch surfaces or in floor detergent mixtures are ineffective on the fungal strain, allowing for the transfer and spread of *C. auris* colonies to other areas [104,155]. Only a few hospital-grade disinfectants are certified by the Environmental Protection Agency (EPA) to kill *C. auris* (List P), and no registered products have been developed specifically for *C. auris* [104,156]. Three of the most common hospital disinfectants (QACs, iodine based, and chlorine based) have only minimal effectiveness unless strict protocols are followed, including follow-up with ethanol-based gel sanitizers after wet-to-dry cleaning. Disinfectants without sporicidal claims were not able to inactivate *C. auris* [155].

While chlorine-based products are considered the most effective for superficial disinfection, strict cleaning protocols must be followed [26,39,51,104,133,157]. Even slight deviations from the established protocol diminish effectiveness tremendously and use in patient care areas is limited due to the caustic chemical properties and respiratory irritation [104,157]. All high-touch items and multi-use equipment, personal protective equipment, and employee items require disinfection after every use; however, when these standards are not followed, nosocomial spread increases [158]. Chemical-based cleaning agents also require accurate concentrations tailored to the specific surface for cleaning and cannot be used across varying surfaces with efficacy [12]. In environments where strict adherence to complex cleaning protocols requires nuanced chemical concentrations and specific wet and dry times before effectiveness, the window for error widens. Despite adherence to standard infection prevention and control procedures, a significant, high-mortality *C. auris* outbreak was identified in a European tertiary care hospital [159]. Healthcare facilities facing growing patient boarding challenges, the rapid turnover of fatigued and burned-out staff, and continual cost cuts can lead to seemingly innocuous shortcuts in environmental disinfection procedures. However, even small deviations amplify the nosocomial spread of *C. auris* and contribute to AMR in patients who become colonized in healthcare facilities. Switching to single-patient-use materials is recommended where feasible [110]; however, this is costly and not always practical in lower-resourced facilities where the reuse of even single-use equipment is common. Healthcare facilities overburdened with patients and having limited human and resource capacity often use less-than-ideal infection control procedures, leading to *C. auris* outbreaks [69,158].

Further complicating surface colonization and resistance to disinfection is the propensity for biofilm formation. Biofilms can form around the exterior of fungal (and other microbial) colonies on plastics, steel, poly-cotton, and other high-touch surfaces, including on dampness-prone skin niches (e.g., sweat in axillary regions) [41,160]. Biofilms may promote multidrug resistance, as the film protects *C. auris* from hostile environments, including dehydration and common germicides [41,98,104]. In healthcare settings, biofilm development contributes to overall nosocomial spread and pathogenicity, particularly among medical equipment, including instruments with direct internal mucosal exposures (e.g., urinary and intravenous catheter tubing) [41,62,161]. When biofilm formation is present, common hospital-grade disinfectants are even less effective. Ledwoch and Mailard (2018) tested 12 commercial wipes and hypochlorite disinfectants on *C. auris* biofilms on stainless steel. They found that over 50% failed to decrease survival or transferability, and up to 75% failed even to delay regrowth [162].

For skin colonization, common chlorhexidine-based soaps are not widely effective through standard hand washing procedures, which may be due to biofilm

formation [104,134]. Additional steps using alcohol-based sanitizers are needed to reach maximal disinfection of the skin [104]. When using alcohol-based sanitizers, at least one minute of wet contact time is necessary to achieve disinfection; however, the standard hand sanitation time for healthcare professionals is often under 15 s [163]. Even using optimal conditions, chlorohexidine (0.5–4.0%) and other common alcohol disinfectants often achieve less than a 3 log₁₀ reduction. There are no efficacy studies that demonstrate the inactivation of *C. auris* colonization on skin with only 15 s of contact time [163]. No matter what chemical agent is used for disinfection, terminal cleaning should be completed at least twice daily in addition to per-patient disinfection practices [12], which adds another layer of time and capacity complexity to infection prevention protocols.

Other less common disinfecting agents have been used with varying effectiveness. Farnesol, which is a quorum-sensing molecule, has been used to inhibit biofilm formation, similar to its properties in *C. albicans*, and has the capacity to reduce the expression of multidrug resistance genes [164]. Ozone disinfection units have also been used for beds and linens with some success; however, they require long exposure times [51].

2.3.4. Current Infection Control Standard Procedures in Healthcare Waste Management

Waste management protocols vary widely by facility and region, with common strategies including incineration, steam, microwave irradiation, mechanical, chemical, and pyrolysis methods [165,166]; however, the disinfection and sterilization of healthcare waste have now become more common [167]. The disinfection of surgical waste is paramount for disrupting and preventing the spread of infectious diseases, such as pathogenic MDR microbes. Disease outbreaks across several countries and facilities have been traced back to an organizational failure to comply with established guidelines for medical waste [167]. The standard disinfection of medical waste using chemical disinfectants has serious challenges, including hazardous operating conditions and limited germicidal efficacy. Without the proper disinfection of infectious waste, transmission across healthcare facilities and among waste workers and communities is likely [168]. Another notable challenge in LMICs is that increased diagnostic testing has generated a rise in healthcare waste that was not accounted for during implementation planning. Many of the facilities and even governments of LMICs were not prepared to be held accountable for adequate waste management strategies, strongly calling for strategies that required lower resources, costs, and technical expertise [169].

Fundamental principles for the appropriate management of hazardous waste to safeguard public health and environmental protection have been established through several international agreements, including the following [170]:

- The Basel Convention on the Control of Transboundary Movements of Hazardous Waste and Their Disposal minimizes the generation of hazardous wastes, the treatment of waste close to where it was generated, and the transboundary movement of hazardous waste.
- The Bamako Convention is a treaty with well over a dozen signatories that bans the importation of hazardous wastes into Africa.
- Polluter Pays Principle—the producer of waste is legally and financially liable for disposing of waste in a manner safe for people and the environment.
- Precautionary Principle—when risk is uncertain, it must be regarded as significant.
- Proximity Principle—hazardous waste must be treated and disposed of as close as possible to where it was produced.

As improved healthcare access and technological advancements have grown exponentially, the need for enhanced waste management has also risen. Infectious disease outbreaks have driven the need for the field testing of medical waste to identify and disrupt pathogen spread. Field indicators have been used in West African nations (Liberia and Guinea) to improve the efficacy of chlorine-based disinfection against Ebola, while modern technology (e.g., genome sequencing of contaminants for targeted disinfection) continues to be applied for contemporary standards [171]. Some facilities in Uganda and India have

even designed smart waste bins to assist in the proper segregation and disinfection of infectious waste [172,173].

Incomplete disinfection and variation in medical waste management procedures can significantly contribute to the spread of infectious diseases. Within the context of national healthcare systems, active governmental intervention can help establish and operationalize a successful and sustainable healthcare waste management system [42]. Components of the development of effective and safe healthcare waste management systems must include (1) healthcare waste management planning at the national level and at healthcare facilities; (2) waste minimization, reuse, and recycling protocols; (3) waste segregation; (4) safe storage and transport; and (5) treatment and the effective disposal of waste [42]. While these strategies are not specific to the disinfection of *Candida auris*, a broad application of microbial disinfection to healthcare waste should employed in multi-layered protection procedures.

2.4. UVC LED Disinfection of *C. auris* in Healthcare Settings

UVC technology is rapidly advancing, as are the many use cases, with many potential opportunities in healthcare settings. The evidence confirms that UVC can inactivate up to 99.9999% of microbial pathogens, including highly resilient *Candida auris*, depending on UV dose. The recent emergence of UVC light-emitting diodes (LEDs) as an alternative to mercury lamps is a significant advancement. UVC LEDs can potentially provide as good or better disinfection as traditional mercury lamps but have other advantages beyond efficacy ratings [174]. Conventional mercury lamps (254 nm peak wavelength) can have high energy demands, short lifespans, cumbersome sizes, and pose potential human exposure hazards [31,175]. UVC LEDs can emit light at multiple wavelengths between 250 and 280 nm and have lower energy and voltage requirements. UVC LED devices are also smaller in size, have a simplified electrical engineering system, offer resistance to mechanical and thermal shocks, and feature optics that can be tailored to specific microbial disinfection [31,176,177].

C. auris is susceptible to UVC inactivation; however, longer exposure times and higher doses of UVC energy are required when compared to other common *Candida* species (*C. auris* inactivation rate k-values from 0.108 to 0.176 cm²/mJ vs. *C. albicans* k-values from 0.239 to 0.292 cm²/mJ) [40]. In general, lower k-values were found for isolates expressing AMR properties, indicating that a higher dose of UVC is necessary for the inactivation of AMR *C. auris* [53]. Studies have determined the optimal wavelength dose for inactivating *Candida auris*. As shown in Table 3, Mariita et al. found that a peak wavelength sensitivity of 267–270 nm offered higher disinfection performance against multidrug-resistant *Candida auris* [41]. Giese and Darby also noted that wavelength sensitivities of 267 and 270 nm showed a similar effect, with the fastest inactivation rate at the average log reduction value (LRV) of 0.13 LRV/mJ^{−1}/cm² [178]. A linear regression analysis revealed a significant association between all arrays and their disinfection efficacy at 5, 10, 20, and 40 mJ/cm^{−2} while emphasizing the effectiveness of UVC emission wavelengths of 267–270 nm [41].

Table 3. UVC efficacy in inactivating *C. auris* is found with 267 and 270 nm peak wavelengths, and a log reduction value (LRV) 3 (99.9% reduction) is obtained.

Peak Wavelength (nm)	Time (s)	Dose (mJ/cm ^{−2})	Controls (CFU mL ^{−1})	UVC Treated (CFU mL ^{−1})	Log Reduction Value (LRV)	% Reduction	Susceptibility Constant (k) (cm ² mJ)	References
252	5	5	8.60 × 10 ⁵	3.67 × 10 ⁵	0.37	57.336	0.0691	[41]
	10	10	8.60 × 10 ⁵	2.43 × 10 ⁵	0.55	71.744		
	20	20	8.60 × 10 ⁵	7.67 × 10 ⁴	1.05	91.081		
	40	40	8.60 × 10 ⁵	9.33 × 10 ²	2.96	99.892		
261	5	5	8.60 × 10 ⁵	5.47 × 10 ⁵	0.20	36.617	0.0565	[178]
	10	10	8.60 × 10 ⁵	2.03 × 10 ⁵	0.63	76.477		
	20	20	8.60 × 10 ⁵	5.50 × 10 ⁴	1.20	93.627		
	40	40	8.60 × 10 ⁵	5.21 × 10 ³	2.22	99.396		

Table 3. Cont.

Peak Wavelength (nm)	Time (s)	Dose (mJ/cm ⁻²)	Controls (CFU mL ⁻¹)	UVC Treated (CFU mL ⁻¹)	Log Reduction Value (LRV)	% Reduction	Susceptibility Constant (k) (cm ² mJ)	References
267	5	5	6.40×10^5	2.50×10^5	0.41	60.938	0.1294	[41]
	10	10	6.40×10^5	4.33×10^5	1.17	93.234		
	20	20	6.40×10^5	2.33×10^5	3.44	99.964		
	40	40	6.40×10^5	1.00×10	4.81	99.998		
270	5	5	9.53×10^5	3.33×10^5	0.46	65.058	0.126	[178]
	10	10	9.53×10^5	6.33×10^4	1.18	93.358		
	20	20	9.53×10^5	3.33×10^2	3.46	99.965		
	40	40	9.53×10^5	2.33×10	4.61	99.998		
273	5	5	8.00×10^5	3.27×10^5	0.39	59.125	0.111	[41]
	10	10	8.00×10^5	1.07×10^5	0.88	86.625		
	20	20	8.00×10^5	2.03×10^3	2.59	99.746		
	40	40	8.00×10^5	3.67×10	4.34	99.995		
280	5	5	4.07×10^5	2.07×10^5	0.29	49.140	0.0889	[41]
	10	10	4.07×10^5	1.70×10^5	0.38	58.537		
	20	20	4.07×10^5	2.87×10^4	1.16	93.000		
	40	40	4.07×10^5	4.00×10	4.01	99.990		

The applications for UVC disinfection in healthcare settings are broad. UVC LED technology can be effectively and easily integrated into protocols for water, air, surface, and waste disinfection. In fact, a systematic review of UVC germicidal inactivation found that UVC had a potent effect on microorganisms, including those with AMR, when used as an adjunct to manual chemical cleaning procedures [179]. UVC disinfection in water and water distribution systems at healthcare sites can ensure that pathogens, like *Candida auris*, are not recycled within closed systems and can prevent transmission to water treatment facilities where wide distribution would be possible. UVC LED water reactors at treatment facilities can prevent the transmission of pathogens to community and household water sources. In air applications, UVC LED technology can be applied to air handling units and circulated air systems to enhance the purification of recirculated air. Pathogens can colonize inside air ducts, become dislodged, and then spread through circulated air and be deposited on surfaces where skin contact can escalate. The UVC disinfection of in-duct systems will purify and disinfect forced air, while in-room units will disinfect the circulating air between two UV sources. In surface applications, mobile UVC units may provide terminal cleaning enhancements for all surfaces (particularly high-touch surfaces). Mobile units may be autonomous robots or personnel-monitored units but can disinfect manually pre-cleaned areas with a high degree of efficacy.

2.4.1. UVC LED Disinfection Potential for Infection Control in Water Applications

UVC LED technology is a proven method for disinfecting water and wastewater, which are primary transmission sources of many gastrointestinal pathogens. Several studies have demonstrated the efficacy of UVC LED technology for inactivating microbial pathogens in water and wastewater, though few studies have specifically evaluated *C. auris* due to its rapid transmission via surface contact first [35,141,142,144,180–187].

Research has discovered that UVC technology has applications in drinking water disinfection [181,182,188], rainwater disinfection [189], and food processing water management [190]. UVC LED technology in water reactors can inactivate biofilm-bound *Pseudomonas aeruginosa* (265 nm at UV dose 8 mJ/cm²) to a 1.3 ± 0.2 log inactivation or LRV [180], pathogenic bacteria *Aeromonas salmonicida* and *Escherichia coli* (265 nm at UVC dose 24 mJ/cm² and 28 mJ/cm²) to a 4.5 log reduction [35], *Giardia* sp. and *Cryptosporidium* sp. [183], and a wide range of other pathogenic microbes. UVC LED disinfection also reduces the use of harmful chemicals and any associated risks while demonstrating efficacy at eliminating microorganisms, pharmaceuticals, and personal care product residue [191].

In addition to the disinfection of water for consumption or daily use and solid waste management, UVC may also effectively disinfect wastewater, particularly in and around healthcare facilities. Researchers isolated *C. auris* from wastewater, demonstrating an

epidemiologic link to healthcare facilities within a wastewater treatment plant's sewer shed in southern Nevada, further highlighting the importance of scalable and sustainable pathogen disinfection [192]. Researchers have specifically reported effective UVC disinfection for wastewater reuse [33,142,193] and sewage decontamination [194]. UVC LED water reactors are effective at eliminating microorganisms in water and wastewater using peak wavelengths between 260 and 270 nm, with synergistic inactivation at 260–280 nm for *E. coli* [28,48]. Human norovirus can be effectively inactivated in wastewater by UVC LED water reactors and scaled tertiary wastewater simultaneously [142,184]. The combined UVC LED and AOP disinfection of wastewater has also been effective at reducing medical contaminants. The combined UVC LED + H₂O₂ wastewater treatment system showed efficacy and efficiency for smaller-scale water treatment facilities [195].

The effectiveness of UVC-based water disinfection depends on several important operating parameters. More opaque liquids reduce UV treatment effectiveness at different levels [182,196], whereas water circulation and exposure time improve water disinfection effectiveness [197]. Interestingly, water volume causes a dubious effect on UVC treatment, with insignificant to slightly better performance in lower volumes [188,197]. Continuous or pulsed UVC light application provides comparable results [143]. Depending on the intended final use of the treated water, the protocols must reach different disinfection targets. For drinking water, the treatment should disinfect the surface with at least a 4 log reduction [182]. The reuse of wastewater, excreta, and greywater, on the other hand, requires at least a 3 log reduction for water disinfection [182]. Combining UV wavelengths or combining UV treatments with other methods may also have additive effects. Several studies have demonstrated that combined UV wavelengths and multi-method treatment applications [142,193,198] have demonstrated synergistic effects that have improved the disinfection or decontamination process. Combining UVA and UVC, UVB and UVC [185], UVC with other light sources such as excimer lamps [198], or UVC with chemical oxidants [193] all lead to synergistic effects.

A systematic review of the literature found that all examined studies achieved some level of disinfection. Most studies achieved biological reductions of less than 3 log [34,144,180,181,185,186,199], and three studies achieved up to 5–6 log reductions [182,190,196]. These results give users confidence in applying UVC for its disinfection capabilities in the water. While UVC light can inactivate microbial pathogens, some pathogens can recover from the UVC decontamination effect. These microorganisms use dark repair and photoreactivation processes to recover from the UVC impact [33,146,185,200]. To avoid repair or photoreactivation, UVC does require a lethal dose to effectively inactivate microorganisms.

2.4.2. UVC LED Disinfection Potential for Infection Control in Air Applications

UVC LED disinfection is effective at inactivating aerosolized viruses, bacteria, and fungi [145–147]. There is variation in how UVC technology is used to purify air from microbial contaminants, ranging from sanitizing the air circulating between UVC sources to disinfecting the surfaces of air handling units, filters, and fans to prevent the recirculation of spores [40,201–203]. Some studies of UVC LED air treatment have demonstrated the disinfection of biological indicators [145–148].

Forced-air handling systems can incorporate UVC disinfection technology into traditional filters and interior surfaces of the fans and system (in-duct systems) to further purify the air that is dispersed into the environment. While *C. auris* is not part of the standard air pathogen testing array, adding UV disinfection to filters increases the log reduction in many harmful pathogens, including *C. albicans* [203]. The log reduction in airborne pathogens is dependent on the highly variable UV dose and standard operating parameters of each in-duct UV disinfection product [204]. Air purification systems with combined HEPA + UV disinfection technology have been found effective at sanitizing rooms up to 12 m² in area [201]. Stand-alone UV recirculation units (or unitary UV systems) are another common application of UV air disinfection that work similarly to in-duct systems but

are more compact and operate at variable air flows. These units draw air from the floor or near other high-concentration areas and then redistribute the cleaned air at breathing height [203]. A 2 log reduction in *Candida* spores was achieved in a two-point circulating air sanitation cycle; however, when combining surface and air UVC disinfection in a single room, the required dose is unknown [40]. Mobile air disinfection units have shown effectiveness at eliminating *C. auris* from recycled air in healthcare settings using combination systems that disperse ozone into a room before sanitizing the recombinant air with UVC light [40]. The Khan–Mariita equivalent ventilation model (KM model) supplements standard mechanical ventilation with UVC air treatment, accounting for many of the previously noted variables (e.g., room size, occupancy, existing ventilation, and targeted air changes per hour) [202]. In healthcare settings (as with many other environments), it is challenging to circulate only fresh air. Therefore, the recirculation of potentially contaminated air is necessary. The utilization of the enhanced KM model that integrates UVC disinfection into standard mechanical ventilation allows for increased energy efficiency, carbon net-zero requirements, and decreased dependency on outside air injection. The broad application of the principle of UVC disinfection of *C. auris* on surface and circulated air shines a spotlight on the potential for building systems to integrate the KM model as a standard ventilation system in addition to other disinfection protocols [202].

Muramoto et al. developed an air purifier that combines UVA/UVC LEDs, a HEPA filter, a honeycomb ceramic filter, and a pre-filter. In this system, the LEDs are responsible for treating the surface of the HEPA filter to decontaminate any microorganisms trapped in it, leading to the faster elimination of floating influenza viruses [205]. Researchers are also particularly interested in demonstrating how compact systems that are easy to implement in different settings are applicable for UVC LED disinfection [146–148,174]. Nicolau et al. found that UVC possessed higher decontamination efficacy than ozone and could achieve synergistic effects when combined with other methods [174].

2.4.3. UVC LED Disinfection Potential for Infection Control on Surface Applications

Researchers have also determined UVC disinfection effectiveness on different materials, including various hard surfaces (e.g., carpet or laminate) [206], food contact surfaces [207], and recreational ball types [208]. In addition to the decontamination effectiveness, Wood et al. evaluated the relative humidity impact on the effectiveness of UVC LEDs in disinfection and its impact on materials [206]. Trivellin et al. found that UVC light did not cause any visual changes or material degradation following disinfection [208]. A synergistic effect from the combination of UVC treatment with mild temperatures (60 °C) was also found [145].

UVC disinfection is also specifically effective at inactivating *C. auris* on hard surfaces, which are common in healthcare settings [49,51–56,209]. The use of UVC technology as an adjuvant disinfection modality for *C. auris* may be an advantageous environmental mitigation strategy [26]. While there is no standard log reduction requirement for *Candida auris*, at least a 3 log₁₀ reduction (99.9% reduction) is suggested to most likely be clinically effective [56]. A review of several UVC exposure parameters and devices found that UVC was clinically effective against *C. auris* when using proper conditions [55]. In lab testing, a mobile UVC tower equipped with high-performance bulbs at a 254 nm wavelength used for a continuous 7 min exposure period in a patient-room-sized test chamber demonstrated 99.97% inactivation of *C. auris* [52]. Other lab settings have found UVC technology to be an effective approach to inactivating *C. auris* as well [49–51,54]. Maslo et al. saw a 99.6% reduction after a 10 min pulsed-xenon UV light exposure cycle at a 2 m distance from their mobile UV device and 100% elimination after more than 15 min of exposure [54]. Chatterjee et al. reported a 0.8 to 1.19 log reduction in *C. auris* when exposed for 30 min [49]. However, despite the increased exposure time, isolates from clade III were not susceptible to inactivation in their lab testing [49]. In 2020, an experimental test at the University of Siena found a 4.43 log reduction in *C. auris* after 15 min of exposure to a novel UVC chip [50]. In a modification of the American Society for Testing and Materials (ASTM),

six relatively low-cost (<\$15,000 per unit) UVC devices (three room decontamination devices and three UVC box devices) were tested against the suggested clinically effective 3 log₁₀ reduction in *Candida auris*. Three of the tested units (one room decontamination and two enclosed boxes) met all criteria for effective decontamination [210]. In a lab test, UVC exposure (267–270 nm) prevented *C. auris* biofilm growth on stainless steel and plastic and significantly reduced formation on poly-cotton fabrics [41]. The Field Studies Branch of the Respiratory Health Division at NIOSH found that the UV disinfection of *C. auris* was 99.9% effective but required significantly higher UV energy doses than for other *Candida* species (*C. auris* 103–192 mJ/cm² vs. *C. albicans* 78–80 mJ/cm²) [211]. In addition to whole-room surface disinfection, small portable units and automated disinfection robots are also becoming more readily available for commercial uses. In particular, UVDI-GO™: UV LED Surface Sanitizer (Ultraviolet Devices, Inc. [UVDI] Valencia, CA, USA) claims a 99.99% inactivation of *C. auris* in 20 s at 4 inches. This is a portable, handheld device with disinfection applications for high-touch areas that are more efficient to reach “by hand” [212].

Some studies have reported that *C. auris* is resistant to UVC treatment [213]; however, this seems to be a misnomer. More recent research has determined specific UVC parameters necessary for inactivation, aligning with the fungus’ propensity to respond differently to other common disinfectants and antimicrobial therapies due in part to its higher MIC and rapidly developing AMR [214]. While UVC inactivation efficacy is reduced when used outside of the recommended parameters, proper use as an adjuvant to other disinfection protocols is advantageous [51]. Time and exposure parameters, such as irradiance and fluence rate, in addition to clade- and strain-specific parameters are critical variables when determining the most efficacious disinfection protocol. Findings seem to suggest that efficacy is inversely proportional to the distance from the UVC source [214]; however, some studies achieved inactivation at shorter distances, although they later experienced regrowth [39]. The UVDI-360 Room Sanitizer™ (UVDI), using four vertical UV lamps (254 nm) in a 360-degree motion sensor cycle, produced maximal inactivation after 30 min exposure cycles; however, the authors noted that Japanese/Korean strains were most susceptible compared to Venezuelan, Spanish, and Indian strains [214]. Whole-room decontamination devices are capable of a 4.57 log reduction in *C. auris* when in the direct line of sight but had slightly reduced efficacy (3.96) when only achieving indirect exposure [56].

2.4.4. UVC LED Disinfection Potential for Infection Control in Healthcare Waste Management

The disinfection of or reduction in disease-causing microorganisms in medical waste to minimize disease transmission is imperative [42]. Since completely destroying all microorganisms is challenging, “sterilizing” medical and surgical instruments is generally expressed as a 6 log₁₀ reduction (a 99.9999% reduction) or greater in a specified microorganism [42]. In addition to thermal, chemical, biological, and mechanical waste-treatment technologies already discussed, UV has also been identified as an effective synergistic waste-treatment modality. Smart waste bins may include UV lights for additive disinfection of the interior walls and air circulating inside closed waste units, rendering waste safer to transport within and outside of healthcare facilities [172]. Other UV waste management strategies include the disinfection of waste prior to disposal, such as with mobile boxes designed to disinfect used N-95 masks during the COVID-19 pandemic [215]. Novel applications for small, mobile waste bins with integrated UVC LED disinfection are also emerging to address contamination before large-scale storage [216]. UV has been used to destroy airborne and surface pathogens as a supplement to other technologies; however, it may be limited in its ability to penetrate closed waste bags.

While there are many potential applications for UVC LED disinfection in waste management, the emerging literature base in this area is limited. UVC LED disinfection efficacy in waste management should mimic that of surface or water applications (i.e., solid waste and wastewater) with similar operational limitations. The effectiveness of UVC is likely to

depend on the processes and protocols in place, allowing for a direct line of sight to the discarded waste in either application [42]. In addition to the operating conditions required for UVC LED disinfection on surfaces or in water, there are added complications for waste management, such as the non-uniform size, composition, and porosity of materials found in waste and the reinfection of items only partially disinfected. Continued research and development are needed in this area; however, potential solutions may include multiple LED locations or reflective surfaces inside waste bins.

2.4.5. UVC LED Disinfection Critical Factors

The effective UVC LED disinfection of *C. auris* and other AMR pathogens relies on several critical factors across applications. Pathogen inactivation in water applications is highly dependent on the turbidity of the water and UV transmittance (or wavelength). Air temperature and humidity are critical factors in the UV disinfection of AHUs. Air velocity inside units is also an important factor, as higher velocities result in cooled air. Many critical factors impact surface UV disinfection, including the material, topography, and reflectiveness of the material to be treated. The critical factors associated with surface disinfection are also important considerations in air applications, as the interior surfaces of AHUs are necessary. UVC disinfection in waste management is subject to many of these critical factors depending on the specific waste and container to be treated; however, surface and air application parameters apply to solid waste management and water parameters apply to wastewater.

2.5. Case Studies of UVC in Reducing *Candida auris*

Several lab studies have demonstrated the technical capacity of the UVC LED inactivation of *C. auris*, establishing the theoretical best practices, critical factors needed for optimal disinfection, and the resulting log reduction in *C. auris*. While these studies are promising, the next step is to evaluate UVC LED disinfection efficacy and efficiency in real-world contexts, specifically in healthcare settings. The following is a critical discussion of the UVC LED disinfection case studies from around the globe, with a specific focus on *C. auris* disinfection.

2.5.1. Case Studies of UVC LED Disinfection for Infection Control in Water Applications

No clinical case studies were available that examined the specific efficacy of UVC LED disinfection of *C. auris* in healthcare facilities' water or wastewater. However, despite this lack of specific attention, several case studies demonstrate pan-microorganism reduction efficacy in water treatment facilities worldwide. The implementation of several point-of-use UVC LED water reactors (alongside chlorination systems) in the United States has demonstrated viral and bacterial inactivation efficacy using peak wavelengths ranging from 272 to 285 nm, depending on the unit and additive methods [217,218]. Due to the small size of UVC LED water reactors and affordable implementation, smaller villages in LMICs can also implement water disinfection infrastructure. There have been reportable success stories from across India and Thailand [189,219,220]. Sundar and Kanmani implemented a portable UVC water reactor at handpumps in a small village in South India, achieving a 2 log reduction in bacterial contaminants. Other portable UVC LED water reactors with multi-pass geometry were implemented throughout India with the effective elimination of test-selected *E. coli* [220]. Both of these implementations were considered cost-effective and efficient due to the relatively affordable price, small size, low-to-zero energy requirements, and practical operation guides [189,220]. In Thailand, a UVC LED wastewater reactor was implemented in conjunction with pre-treatment sand and settler filters. The UVC LED disinfection was effective at inactivating coliforms found in the wastewater [219]. When combined with adsorbent additives (e.g., agricultural waste), solar-powered UVC LED water reactors are effective at reducing microbial load in community wastewater, proving advantageous for public health protection [221]. In addition, two commercial-grade UVC LED water treatment systems have produced high-grade water purification

in their large-scale implementations. In Singapore, the NEWater Initiative utilizes UVC LED to disinfect the entire country's water system. The Orange County Water District's Groundwater Replenishment System uses the UVC LED disinfection of wastewater to prevent runoff into the Pacific Ocean [191].

2.5.2. Case Studies of UVC LED Disinfection for Infection Control in Air Applications

The mobile (remote, smart app-controlled) OZY AIR+Light combination air purification system disperses 60 g/h of ozone into a room for a preset time. Then, UVC sanitizers provide a flux of 80 m³/h, and the air is exposed to UVC LEDs before it is cycled back to the room [40]. In a clinical trial across Italian hospitals, the OZY AIR+Light system achieved a greater than 99% reduction in *C. auris* spores in each of three cycles of disinfection in medium- to high-risk patient areas. In the United States, UVC air purification units (15 W of high output UVC energy at 253.7 nm wavelength with a MERV 5 filter prior to UV light treatment) were installed in 16 special care unit rooms, hallways, and biohazard rooms of a long-term acute-care hospital. After installation and continuous run time (81 days), there was a 42% reduction in airborne bacteria and a significant reduction in clinical HAIs, including common pathogens with contact spread. While the air sampling did not test for *C. auris* specifically in this study, efficacy against other AMR fungal spores showed promise for the extension of UVC air disinfection to *C. auris* [222]. In a similar study (not tailored to *Candida auris*), HAIs were dramatically reduced after the clinical installation of in-room VidaShield (American Green Technology, Chatsworth, CA, USA) continuous air purification units in the long-term ventilation unit of a hospital [223].

2.5.3. Case Studies of UVC LED Disinfection for Infection Control on Surface Applications

Clinical pilot testing designed to mimic common surfaces in a hospital setting (i.e., steel, plastic, glass) also found UVC technology to be effective at disinfecting after 10 min of exposure; however, effectiveness was statistically different across all three surfaces. While this pilot study was conducted in a clinical environment, only four patient rooms with random swab testing were used in the experiment at a time without any known outbreaks [32]. The Tru-D (Lumalier, Memphis, TN, USA) UVC room disinfection device was clinically tested in an acute-care tertiary hospital in Chapel Hill, North Carolina. Room decontamination achieved a 4.45 log₁₀ reduction (direct line of sight) in *C. auris* after a 17–19 min cycle on the bacterial setting [56]. After standard chemical cleaning agents were applied, a larger academic medical center pilot tested a UVC disinfection robot (UVD robot, Clean Room Solutions) in two hospital outpatient clinics. The autonomous robot substantially reduced *C. auris* growth on surfaces compared to standard cleaning and disinfection practices. The clinical study confirmed previous in vitro tests that suggested that longer exposure times are needed as the resiliency of the microbe increases [224]. Clinical studies of ICU terminal disinfection have demonstrated that UVC is considerably more effective (96.75% reduction) than aerosolized hydrogen peroxide (50.71% reduction) at achieving a no-touch reduction in *C. auris* on surfaces already manually cleaned [225]. A large systematic review evaluated the efficacy of 12 commercial UVC applications in adjunct disinfection across the United States, Canada, and South Africa. Among the 12 clinical studies, each found UVC surface disinfection to be effective at substantially reducing microbial load. In addition, several studies noted that the UVC disinfection protocol was easy to implement and recommended its adoption for future adjuvant cleaning procedures [179].

2.5.4. Case Studies of UVC LED Disinfection for Infection Control in Healthcare Waste Management

No clinical case studies were identified that specifically examined the efficacy of the UVC LED disinfection of healthcare or medical waste. While the limited studies discussed demonstrated lab-tested effectiveness, additional research is needed to fully understand and

evaluate the potential efficacy of the real-world implementation of UVC LED disinfection in waste management.

3. Discussion

This comprehensive review of UVC LED disinfection across water, air, surface, and waste management applications in healthcare settings has provided insight into the current management of *C. auris*. Our critical analysis of the widely used infection prevention and control procedures revealed that current procedures are insufficient for preventing or managing the dangerous spread of AMR *C. auris*. Current procedures focus largely on surface disinfection using standard healthcare-grade chemical cleaners developed for other common AMR pathogens. Most healthcare facilities also have general cleaning or disinfection procedures for air handling units, water, and waste management that address basic pathogen spread. However, few, if any, healthcare facilities have developed a disinfection protocol specifically for *C. auris*, and many fail to even monitor for colony spread. Due to the high AMR and resilient nature of *C. auris*, standard cleaning and disinfection protocols are insufficient. The efficacy of the current disinfection procedures across high-touch surfaces, air, water, and waste management is further challenged by the lack of comprehensive surveillance for *C. auris* in healthcare facilities. Because of these challenges, supplementing the current disinfection procedure with the tailored UVC LED disinfection of *C. auris* emerges as a promising option.

Examining the efficacy of the UVC LED disinfection of *C. auris* in healthcare facilities across water, air, surface, and waste management applications also proved challenging. Previous reviews have noted that the available research on UVC disinfection devices in healthcare settings is lacking, limited, or of low quality due to small sample sizes, researcher bias, and conflicts of interest (e.g., manufacturer relationships with the researchers). UVC LED disinfection studies vary in how they are reported, including UV dose and exposure times, other critical operating parameters, level of log reduction achieved, and environmental conditions. These variances are magnified when comparing across applications (i.e., water, air, surface, and waste management). The variation is partially attributable to industry differences in standard reporting and device research; however, a systematic and cross-industry review to standardize reporting is not likely to provide results that justify the costs. In addition to industry differences across UVC device applications, there is also a substantial variation in reporting standards and research priorities across scientific disciplines (e.g., materials sciences and engineering, microbiology and medicine, public health, and healthcare management). Further complicating this review is the inability to draw definite conclusions due to the large heterogeneity across studies, making cross-comparison and systematic evaluation impossible [226,227]. The case study analysis of UVC LED efficacy in disinfecting *C. auris* was also complicated by the transition from a lab setting to real-world use. In lab settings, devices are tested specifically against *C. auris* as the only method of disinfection. In practical applications, UVC LED disinfection technology is used as an adjunct to standard cleaning and disinfection procedures. Residual *C. auris* following traditional cleaning methods is variable, and there were few studies that measured the remaining colony levels prior to implementing the UVC LED disinfection device. Many of the testing limitations for both traditional cleaning methods and UVC LED disinfection are also closely tied to the time and human capacity constraints common in all healthcare facilities. As rooms take longer to turn over for the next patient, facilities face a direct loss in revenue. This can lead to inferior adherence to the necessary wet-to-dry times and UVC LED exposure times, as well as failure to address all high-touch surfaces. The disinfection of air, water, and waste also relies on a regular disinfection schedule that is often only loosely monitored.

While these concerns are evident across the studies included here, practice-based implementation priorities empower communities. The available studies provide considerable evidence supporting the implementation of UVC LED disinfection for *C. auris* infection control in healthcare settings despite the limitations in reporting rigor. By current healthcare

facility standards, dangerous AMR infections continue to increase with many negative health, quality of life, and economic outcomes. Using a community benefits approach, the current infection prevention and control protocols can be augmented with UVC LED disinfection across applications in healthcare facilities. Specifically, a reduction in *C. auris* infections is possible with supplemental UVC LED disinfection. Given this potential for successful implementation, it is critical to understand the benefits and challenges associated with UVC LED disinfection device implementation.

3.1. Benefits, Feasibility, and Challenges of Implementing UVC Disinfection in Healthcare Settings

Based on substantial lab testing and clinical case studies, UVC LED technology is a feasible and beneficial disinfection modality for healthcare environments. While this technology is promising, implementation and clinical efficacy measures present important challenges.

3.1.1. Challenges

The implementation of UVC LED disinfection is not without challenges. Across surface applications, the most predominant challenge is the requirement for specific conditions and parameters to reach the required clinical log reduction unique to *C. auris* [30,39,41,52,163,201]. Different isolates and clades have varying susceptibility to UVC light and require specific parameters tailored to the unique strain present [163]. The operational time required within an empty room for disinfection may be unachievable in busy healthcare facilities [30,52,228]. Operating limitations resulting in diminished efficacy are also possible, including shadows, changes in topography and surface, barriers to the direct line of sight, physical contamination, and a lack of standardization [229]. UVC light needs a direct path to the fungi for effective disinfection. Shadowing (disinfection of only one side of an object) can increase the risk of microorganisms remaining active in shadowed areas. Surface dirt or debris can be removed using water-based pre-clearing solutions; however, it is possible that the UVC light could be obstructed by other non-removable objects. A surface topography with rough finishes or irregularities can also cause shadowing, increasing the surface area and requiring higher energy to maintain the intensity (energy per effective area) [230]. The UV dose and exposure time would need to be increased to achieve the same desired level of inactivation. Reflective chambers or surfaces placed around the room that need disinfection may reduce shadowing and increase disinfection efficacy, though UV intensity is also diminished [231]. Another option is combining UVC disinfection with ozone disinfection that is able to move through shadows to ensure disinfection [226]. Compared to other disinfection techniques, UVC disinfection has a low penetration depth. It is speculated that this depth increases when using pulsed light [232]. However, there is still no consensus in the literature regarding the preference for pulsed or continuous light.

UVC LEDs have successfully been implemented in small and mobile systems (which are discussed above). While UVC LEDs have a lower wall plug efficiency when compared to traditional low-pressure mercury lamps (approximately 30% efficiency), UVC LED reactor design, optimal materials, and peak wavelength output more than overcome this limitation, as can be seen in Figure 2. Point-of-entry UVC LEDs currently offer a 4:1 benefit over lamps, with the rapidly emerging UVC LED technology for applications in industrial contexts on track to quickly outpace any apparent convenience that low-pressure lamps offer [233]. This is particularly important in light of the imminent restrictions on mercury lamps.

In air applications, air purification units equipped with HEPA filters + UVC LEDs (along with all other types of air purification with and without UVC) have been noted to sanitize a smaller-than-declared space, making it challenging for healthcare administrators to purchase and implement air purification units adequately sized for the full disinfection of a desired area [234].

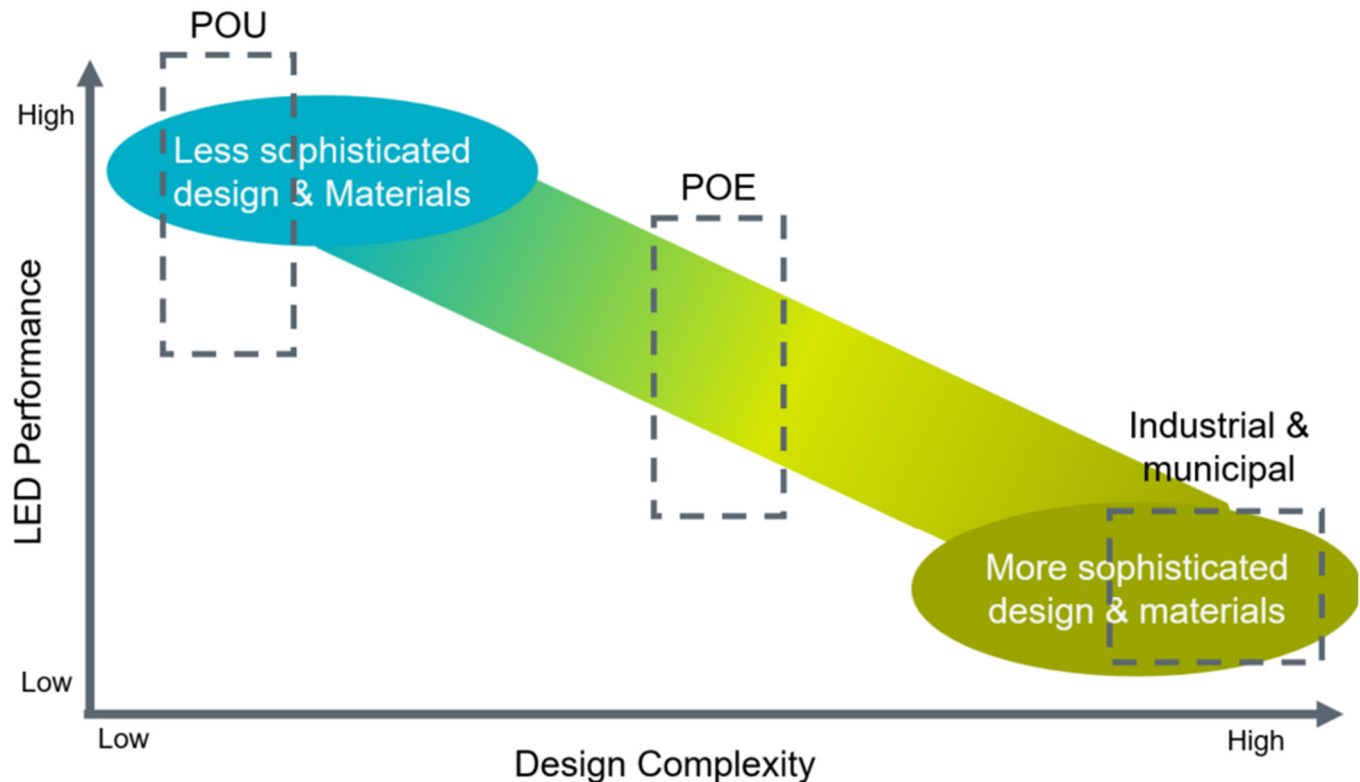


Figure 2. Illustration of UVC LED efficiency. LED performance is highest with smaller size units, such as with point-of-use (POU), with decreasing efficiency along the continuum toward industrial or municipal applications (image courtesy of Crystal IS) [233].

Another disadvantage of UVC disinfection technology is the non-uniform standards applied across commercially available devices. Each manufacturer and device advertises a different delivered dose, which makes comparison across the industry challenging. Specialized units (e.g., mobile disinfection devices and robots) also require trained personnel (e.g., microbiologists and technical engineers) to operate and troubleshoot errors in real-time and test the device's sensitivity to the identified isolates [52,224,229].

Patient and operator safety is another significant concern. While UVC light meets global requirements to phase out mercury lamps due to known harmful health and environmental impacts, there are still safety risks that need to be mitigated [185]. When used outside of the intended purpose or straying from the suggested parameters for use, DNA damage, skin damage, and other adverse bodily effects on the beneficial skin microbiome are possible [185]. Studies have found no significant DNA damage or cell toxicity associated with UVC exposure; however, these results may be dose-dependent [235–237]. UVB light (315–280 nm) can penetrate the epithelial tissue, reaching the inner epidermis layers, while UVA light (400–315 nm) penetrates even deeper, reaching the dermis layer [238]. UVC light has not been found to have the same level of skin penetration, which limits its potential carcinogenic effect [236]. However, direct exposure to higher UVC wavelengths may still cause photocarcinogenic, mutagenic, or cytotoxic damage to human cells. There are unknown health and safety risks associated with frequent UVC disinfection exposure, and the standard shielding parameters are not yet fully understood [41,179,229]. Shielding is likely necessary for any direct UVC source; however, the wavelength, energy threshold, and other baseline parameters are not yet known [41].

While UVC LED devices are relatively low cost or cost effective, upfront purchase prices may be a barrier to low-resourced facilities [201]. Cost is particularly prohibitive if multiple units are required to meet protocol standards and efficient disinfection across a larger facility [52]. Compared to alternative disinfection, UVC devices are more costly than current standard procedures (e.g., air purification without UVC and manual cleaning-only

protocols) [234]. The successful implementation of UVC disinfection is predicated on the availability of electricity, which can be a challenge in LMICs. A multiagency report found that close to 1 billion people in LMICs are served by healthcare facilities without a reliable electricity supply or no electricity at all [239]. It is estimated that one in four health facilities in sub-Saharan Africa have no electricity and that two in three healthcare facilities in LMICs lack access to reliable energy [240]. Despite this, the United Nations Development Programme's "Solar for Health" initiative, which has equipped over 1000 health centers with solar photovoltaic (PV) systems across 15 countries, including 11 in sub-Saharan Africa, provides strong infrastructure support that could assist LMICs in integrating UVC LED disinfection across water, air, surface, and waste applications [240].

3.1.2. Benefits

Despite these challenges, the benefits of enhanced no-touch UVC disinfection procedures are substantial. Given the limited efficacy of chemical agents in reducing colonization, the tremendous barriers to implementing strict disinfection procedures in overburdened healthcare settings, and the rapidly rising AMR and vast spread of *C. auris*, there is a significant need for supplementary disinfection modalities. UVC LED has favorable features for disinfection, including automatic device activation and environmentally friendly operating conditions that leave no dangerous residuals often found with other disinfection modalities [231,241].

Many emerging commercial systems offer rapid disinfection as compared to traditional procedures. UVC LED arrays intended to disrupt and eliminate biofilm formation can achieve >99.99% microbial reduction without any optimization in under 40 s, compared to the traditional 60 s wet contact time required for various chemical disinfectants [41]. Many other commercial units report effective a pathogen reduction in under 10 min [242]. While rapid disinfection is advantageous, it should be noted that the time to disinfect is dependent on target size (e.g., room, AHU, or water body), UV dose administered, and environmental conditions (e.g., topography, turbidity, etc.).

Implementing adjunct UVC LED disinfection across water, air, surface, and waste applications provides multi-layer protection against dangerous and costly *C. auris* spread. The cost of UVC disinfection systems depends on myriad factors, including the manufacturer, system parameters, and capacity, while operating costs also factor in power consumption, system maintenance, technical infrastructures, and human capital requirements. However, the associated costs of any UVC device (air, surface, or water) are comparable to or lower than the accrued costs of disease outbreaks (direct and indirect costs). Raggi et al. found that hospital-acquired infections were 19.2% lower after UVC terminal disinfection installation, which generated a direct cost savings of over \$1.2 million over a 12-month period [243]. With improvements in mobile UVC disinfection technology, cost-effective UVC disinfection robots are now more readily available for healthcare settings outside developed nations as well [244]. As technology improves, the costs to implement UVC disinfection systems will likely continue to decrease [245].

The addition of UVC disinfection to healthcare settings can substantially reduce the global incidence and mortality rates related to *C. auris*, disrupting the current escalation of AMR candidemia and IC. As international resource mobilization for LMICs progresses, the implementation of UV-C disinfection as a supplemental disinfection modality is likely to become feasible despite current challenges.

Quality of life benefits for patients who contract *C. auris* while admitted for other primary conditions are tremendous, but the costs associated with HAIs are skyrocketing. It is also important to note that the Medicare non-payment policy holds healthcare facilities responsible for all HAI-associated costs due to a failure to prevent infections [246]; however, this is not consistent across all payers [247]. Facing rising healthcare costs and dwindling payer reimbursements, healthcare facilities should prioritize patient safety and infection prevention. UVC LED water, air, and surface disinfection is a simple, cost-effective method with proven efficacy at reducing *C. auris* and decreasing clinical candidemia.

3.2. Recommendations for Use of UVC Disinfection in Healthcare Settings to Reduce Transmission of *Candida auris*

The current limitations of disinfection protocols highlight the need for strengthening and reinforcing a global concerted effort to standardize diagnostic capabilities, surveillance systems, and reporting standards for *C. auris*. Since no specific chemical cleaning agents or germicides are designed to target *C. auris*, supplemental disinfection procedures are critical in reducing the transmission of *C. auris*. UVC LED disinfection across water, air, and surfaces can be used in a combination method as an adjuvant disinfection procedure. Even with the challenges critically evaluated, the considerable benefits highlight the need to move forward with supplemental UVC LED disinfection in healthcare settings to more effectively and efficiently control the spread of the superbug *C. auris*.

The relatively low cost of UVC LED technology and broad use applications position it as an option for immediate adoption in healthcare settings globally. While developing nations may require significant technical assistance and capacity building to meet global standards, the necessary support will allow facilities to better control the spread of *C. auris* and other dangerous pathogens.

It is our recommendation to implement a multi-layered, enhanced UVC LED disinfection protocol, as illustrated in Figure 3, as an adjunct to any current infection prevention and control procedures. UVC LED water reactors for the disinfection of water and wastewater have the highest impact, while air and surface applications follow close behind. UVC water disinfection has the potential to impact the greatest population with the fewest units and associated costs. UVC air disinfection for air handling systems has a similar impact ratio, reaching many people with only one unit; however, circulating air disinfection systems would need to be placed in discrete areas and would require additional units and cost. UVC LED surface disinfection is the most challenging to implement and is limited to single-room use. While disinfection is highly effective, it offers the lowest impact ratio when used only during terminal cleaning. The UVC LED disinfection of waste has a more limited direct impact on healthcare facilities; however, the trickle-down effect may be substantial. The effective disinfection of healthcare waste can prevent the community transmission of HAIs and limit the pathogenic spread of fungi like *C. auris*. If patient safety and infection control budgets allow for implementing UVC LED disinfection measures in each application, this would be considered the gold standard for infection prevention and control.

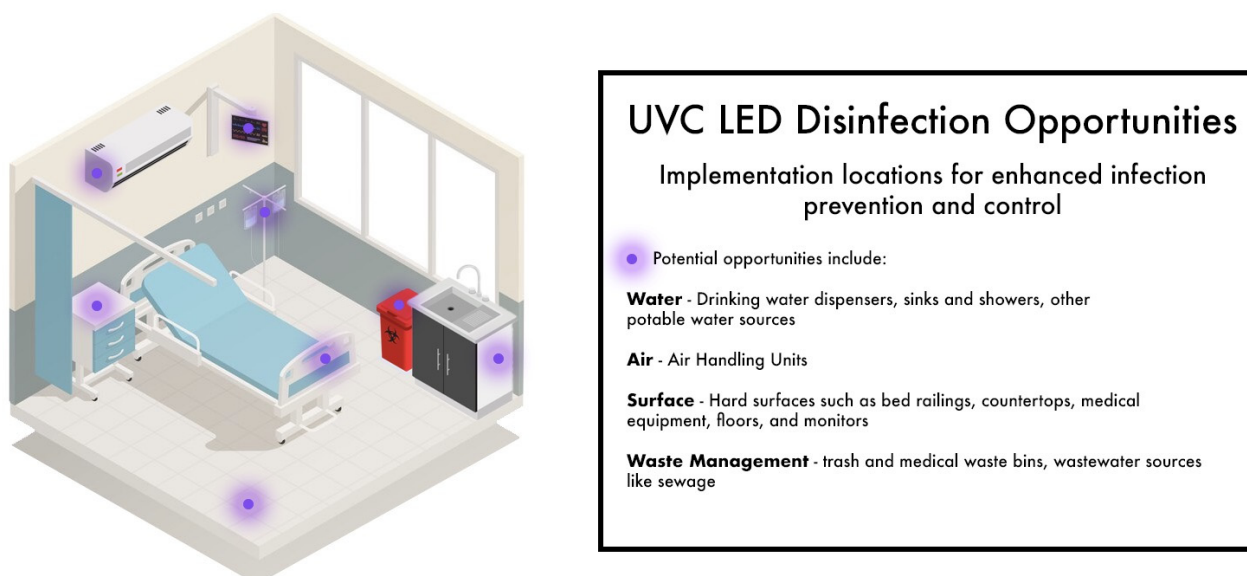


Figure 3. Illustration of potential multi-layered UVC LED protocol for enhanced infection prevention and control in healthcare environments. *UVC LED disinfection is not suggested to replace standard or regulated infection prevention protocols.* (Image created using icons designed by Freepik).

Using UVC LED disinfection in all relevant areas, in addition to standard cleaning methods and when used correctly within the parameters of all critical factors (e.g., UVC dose, surface type, and exposure time), can be considered a viable approach to infection prevention. The following recommendations outline considerations for scaled implementation, standard operating procedures, and policy revisions for any UVC disinfection applications in healthcare facilities.

Scaled Implementation Recommendations for Supplemental UVC LED Disinfection in Healthcare Settings

1. Determine the UVC application (i.e., water, air, surface, and/or waste) needed and how it will be integrated into the current infection prevention and control infrastructure.
 - a. Include a thorough evaluation of the current environmental services infection prevention and control protocols.
2. Research all available devices with a cross-tabulated list of specific needs. Then, find the device that most closely aligns with the facility's size and disinfection challenges.
 - a. Consider the necessary UVC LED device operating parameters and associated critical factors across application areas that are necessary for effective disinfection.
 - b. Determine if the current infrastructure limits the implementation of certain devices.
 - i. Evaluate if solar-powered PV systems can support UVC devices in electricity-limited settings.
 - ii. Determine the available time window for disinfection in the context of daily operating quotas.
 - c. Assess the time and space requirements for effective disinfection in contrast to the available time and space for implementation.
 - d. If the budget allows, layer UVC LED disinfection technology across applications (e.g., water, air, surface, and waste); however, given *C. auris*' primary transmission route, a minimum of surface disinfection devices is strongly suggested.
3. Consider the human capacity and technical expertise required to implement and operate each type of device.
 - a. Determine if the current infection prevention team will be sufficiently trained to augment disinfection with UVC LED or if new training or staff will be required.
 - i. Any new training or personnel requirement should be factored into the budget assessment for the device.
4. Ensure the UVC LED device meets all applicable regional, national, and international disinfection standards.
 - a. Ensure regulations put forth by the CDC or other regulating bodies are followed. We suggest using UVC LED disinfection as an adjunct to currently accepted chemical disinfection until nationally and internationally recognized regulations are amended to consider UVC LED technology a first-line defense for the disinfection of *C. auris*.
5. Ensure the UVC LED technology adopted meets all required industry disinfection standards specific to the application.
 - a. Surface—International Sanitary Supply Association (ISSA) standards for clean times [248,249].
 - b. Air—ASHRAE Standard 185.1 and 241 [250]; ISO 15858:2016 [251].
 - c. Water—NSF/ANSI 55 Class A certification [252].
6. Establish robust evaluation protocols.
 - a. Accurate data collection and disease surveillance are necessary to determine the efficacy of *C. auris* inactivation and reduce colony spread.
7. Develop and implement routine maintenance schedules for all UVC LED systems to ensure their proper function and efficacy in disinfection.

8. Educate all healthcare system staff and administrators on the new infection prevention and control protocols, device safety, and disinfection procedures.
9. Write all policies and procedures in a language the entire staff can understand and operationalize.
10. Establish a routine schedule for the evaluation of emerging UVC LED technology applications and device updates or upgrades.

4. Future Directions

Emerging UVC LED technology development for *C. auris* disinfection has been rapid and critical to advancing human health and well-being, though several gaps in research remain. Across applications, standardizing how efficacy and device operating parameter research is completed and reported would improve cross-discipline comparisons and enhance the rigor needed to support standardized implementation in healthcare facilities as an adjuvant modality or as a first-line prevention and control mechanism. Studies should also focus on establishing industry best practices for *C. auris* disinfection parameters and conditions, including UVC wavelength, energy requirements, time of exposure, distance from the UVC source, direct vs. indirect exposures, manual disinfection requirements, and frequency of use. The health and safety risks associated with frequent UVC exposure should also be explored to determine the safest operating procedures for shielding and repeated use. Beyond the further evaluation of clinical and operational efficacy and efficiency, additional research is needed on UVC LED systems' power, lifetime, reliability, optimal substrate material, and the size of LEDs inside devices [253]. Device requirements are an important consideration for healthcare facility management, and simplifying operating procedures and standardizing commercial reporting would aid administrators in decision-making and supply stakeholders with confidence. The industry-wide certification of operational parameters by a centralized regulating body should be a future goal for researchers and policymakers. The adoption of standard UVC LED disinfection procedures as part of a certified infection prevention and control program should also be addressed at the health system or facility level. Additional implementation studies across applications in healthcare are also needed to fully understand how healthcare facilities can most effectively use UVC LED to enhance infection control procedures. Specifically, case studies of UVC LED disinfection in healthcare waste management are needed to understand the potential for use in these contexts.

5. Conclusions

This article emphasizes the urgent need for surveillance, infection control, and global collaboration to combat the formidable fungal superbug, *C. auris*. Traditional cleaning and disinfection methods are inefficient and often ineffective, particularly when not performed in optimal conditions. UVC LED technology has demonstrated efficacy in inactivating *C. auris* and other healthcare-associated pathogens across many applications, including water, air, surface, and wastewater. UVC LED disinfection may also be more efficient and cost-effective than certain traditional methods. It is important to consider UVC disinfection operating parameters and other critical factors necessary for effective treatment across each application. Despite the critical factors that must be met, UVC disinfection can also be used synergistically with current cleaning and infection control standards to increase efficacy in reducing the transmission of AMR superbugs. We have provided clear recommendations for implementing UVC LED disinfection as a supplement to current infection control procedures using a multi-layered approach that is scalable for various healthcare settings and scenarios.

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