Review

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Global Health Alert: Racing to Control Antimicrobial Resistant *Candida auris* and Waste using UVC LED Technology

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Abstract: The emergence of antimicrobial resistance (AMR) *Candida auris* presents a formidable global health challenge, causing severe healthcare-associated infections with high mortality rates. Its ability to colonize surfaces and resist standard disinfectants undermines traditional hygiene practices, prompting an urgent need for novel strategies. Ultraviolet C (UVC) light offers a promising approach due to its rapid and broad-spectrum germicidal efficacy. This review comprehensively examines the current knowledge of UVC LED technology in combating *C. auris*, highlighting its effectiveness, limitations, and potential applications in healthcare hygiene. UVC light has potent activity against *C. auris*, including multidrug-resistant (MDR) strains. UVC can reduce *C. auris* on contaminated surfaces, aiding in transmission prevention. This review explores implementation strategies, including mobile UVC systems for targeted disinfection of high-risk areas and equipment, integration into air handling units (AHUs) to continuously disinfect recirculating air, and incorporation into water treatment systems. Current limitations in our understanding of UVC safety and effectiveness necessitate further research to optimize application protocols and ensure treatment safety while maintaining efficacy against *C. auris*. Integrating UVC disinfection technology into infection control programs holds promise for strengthening hygiene practices that will curb the global spread of *C. auris* and improve patient outcomes.

Keywords: *Antimicrobial resistance*; *Candida auris*; Global Spread; High Mortality Rates; Hospital Infections; Superbug; UVC Light; Hospital Waste Management

1. Introduction

Antimicrobial Resistance

Antimicrobial resistance (AMR) poses a significant threat to global health and economic development, with emerging pathogens like *Candida auris* (*C. auris*) sparking particular 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 [5,6]. 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

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[7]. In response to the global public health threat due to AMR, the World Health Organization (WHO) convened a global tripartite in 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 [8,9]. The spread of AMR and fungal diseases is further complicated by the rapid rise in healthcare-associated infections (HAIs), which now constitute the most common adverse patient events [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 [8].

Candida auris

Candida 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 healthcare and public health officials [13–18]. Some savvy social media users have even dubbed the emerging crisis the "*Candida auris* fungus 2024 pandemic" [19]. *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 [20,21].

While most reports suggest that *C. auris* infections are not a threat to healthy individuals, vulnerable populations and 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 *C. auris*-associated candidemia (*Candida*-related blood infections) and subsequent sepsis could contribute to crude mortality rates as high as 72% in hospitals and residential healthcare facilities [10,22]. 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 [23]. *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].

Despite recent attention, including media coverage, public health advisories, and even heightened scholarly work on *C. auris* (annual publication and citation growth rate of nearly 38%), implementing robust prevention and disinfection practices to reduce the overall burden of *C. auris* presents substantial challenges [24]. 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. Early treatment is often prohibitive without standardized and uniform screening and surveillance [23].

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. However, effective environmental disinfection also faces substantial challenges in implementation [26]. Infection control strategies span from 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*.

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UVC LED Technology

The resilient and antimicrobial-resistant nature of *C. auris* poses significant challenges to adequate disinfection protocols in healthcare settings. No-touch disinfection is a critical disinfection modality for the management of *C. auris* outbreaks and the reduction of the global candidemia burden. No-touch disinfection includes Ultraviolet C light emitting diodes (UVC LED) disinfection or vaporized hydrogen peroxide systems used for terminal cleaning and disinfection procedures [27]. UVC technology is a validated disinfection modality for water, air, and surface applications, and the UVC spectrum (200 – 280 nm) offers enhanced germicidal disinfection when used 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]. Despite genetic damage to pathogenic cells, UVC is considered safe 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. The most common UVC wavelength used for healthcare disinfection is 253.7 nm emitted by low-pressure mercury lamps, as this is absorbed by microbial cell structures, allowing for targeted DNA/RNA damage.

Waste Management

Effective waste management is a critical component of controlling the spread of *C. auris* in healthcare facilities. 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 may cause 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 body 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 the susceptible host [45]. This transmission pathway further explains how *C. auris* can easily spread throughout and beyond healthcare facilities. High-income countries, on average, generate 0.5 kg of hazardous waste per hospital bed per day, while low-income countries generate 0.2 kg per hospital bed per day [43]. 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].

Traditionally, waste management relies on methods like chemical disinfection or incineration. While effective, these methods 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. UVC LEDs can be adapted 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:

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a. **Safety Concerns:** UVC light can cause damage to 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 limited ability to penetrate through materials. This means that for effective disinfection, waste needs to be spread out in a thin layer or the UVC source needs to be strategically placed to ensure 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 aging and dust accumulation. 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.

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 [48–57]. This review provides a comprehensive analysis and critical discussion of the relevant literature on the global public health threat and economic disruption relative to the rapid spread of *C. auris*, the feasibility of applying UVC LED disinfection technology to environmental services and waste management strategies in healthcare facilities, and the challenges to implementing robust infection prevention protocols and surveillance systems. We offer recommendations for scalable and affordable UVC LED-enhanced disinfection protocols and briefly discuss future research and development in the field.

2. Relevant Literature

Due to the cross-industry content, literature was obtained through reputable research databases (e.g., PubMed, Web of Science, and Dimensions) that index high-quality journals 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). Search terms included (but not limited to) "*Candida* a*uris*," "*C. auris*," "antimicrobial resistance," "nosocomial spread," "*C. auris* surveillance," "UVC disinfection," "healthcare facility disinfection," and "global fungal disease burden." Additional literature was identified by carefully reviewing appropriate articles' citations and relevant conference presentations. Our review critically examines the evidence base for the feasibility of UVC LED disinfection and waste management of *C. auris*.

2.1. Global disease Threat of C. 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 [58]. Nearly all forms of yeast are from the *Candida* genus, though many are not responsible for infection or have only superficial infection capacity [59]. Ringworm, nail fungus, yeast infections (e.g., vaginal candidiasis), and thrush (e.g., oral *Candida* infections) are among the most common fungal infections [60]. Candidiasis is an infection caused specifically by a *Candida* species and can present in many infection sites; however, there are over 200 specific species [61]. The annual incidence of oral and esophageal candidiasis is estimated to be approximately 3.3 million, with the global burden of recurrent vulvovaginal candidiasis being approximately 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 [58]. Candidemia, a common healthcare-associated

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infection, is a specific and dangerous blood infection caused by *Candida* isolates with adverse outcomes [62].

C. auris is a particularly resilient branch of the *Candida* species that rapidly develop multi-drug resistance with morphisms specific to regional development or genetic clade [63]. To date, *C. auris* has been reported in over 47 countries worldwide, representing all continents except Antarctica [64]. *C. auris* strains have been 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. *C. auris* clades are revealed by genome analysis, PCR amplification of genetic loci, or mass spectrometry [65]. 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 [23,63,66–74]. Multidrug-resistant and pan-drug-resistant *C. auris* isolates are increasingly detected worldwide [75,76].

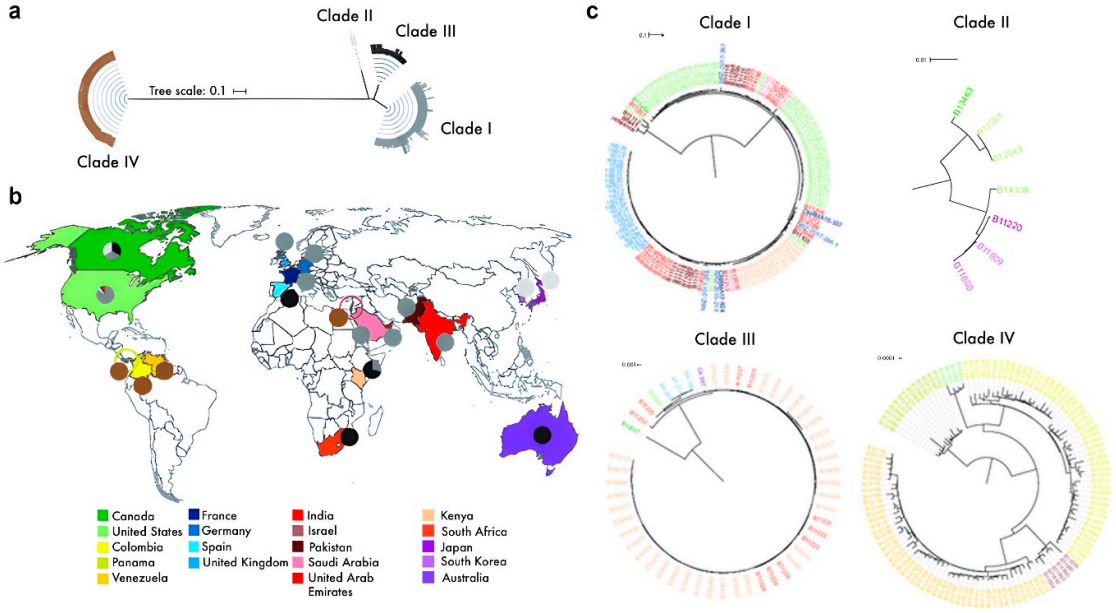

Figure 1. The global distribution of *Candida auris* is categorized into four clades based on phylogenetic analysis and geographic origin. Reprinted from [65].

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* [67,77]. 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 *C. auris*, discovered via a misidentified isolate collected in 2013 [80]. *C. auris* has been identified in several infection sites and bodily fluids, including blood, urine, bile, ear canal, nares, axilla, skin, and, in rare instances, the oral, esophageal, and gut mucosa [63].

C. auris has gained notoriety due to its increasing resistance to common antifungal agents and the possibility that it may be the first fungal disease related to emerging climate change [67,77]. Many *C. auris* strains have a high minimum inhibitory concentration (MIC) towards antifungal drug classes and common disinfectants, contributing to the challenge of decolonization and the treatment of infections [51,63]. 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 [11,61,81,82].

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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 Echinocandins 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 of the ergosterol synthesis pathway (overexpression of ERG11, and point mutations in ERG11, Y132F or K143R). The Echinocandin resistance in *C. auris* is shown to be attributable to mutations of FKS1, a gene that codes 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 [61,83–88]. 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 [63,64,89,90]. Difficulties in pathogen identification and disinfection have also led to increased transmission and delayed infection management [11,61,81,82].

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 multi-drug 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 towards warmer global temperatures is not enough to fully explain the rapid ability to develop resistance to antifungals [67]. More concerning is that many MDR *C. auris* outbreaks have no direct epidemiological links, indicating 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 on 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].

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 antimicrobial resistance [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 1,747 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 – 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 2,377 clinical cases and 5,754 screening cases of *C. auris* in 2022 [20]. These rates are widely thought to be under-reported 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 stay for adult patients identified with *C. auris* candidemia was 46-68 days (70-140 days for pediatric patients) (WHO, 2022). Researchers 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 [63]. Further complicating accurate surveillance and monitoring is that misidentification of *Candida*

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species also extends to mortality reporting errors. Mortality rates are often reported only for candidemia or IC, without species attribution [104].

Table 1. Global Mortality Estimates – Global Crude Mortality Rates Attributable to Candidemia .

Country	Mortality Rate (*estimated*)	Date	Citation
Pakistan	52%	2009	(Farooqi et al., 2013) [105]
India	50%*	2009-2011	(Chowdhary et al., 2013) [68]
	44%		(Pfaller & Diekema, 2007) [106]
South Africa	46%	2012	(Smidt et al., 2014) [107]
Panama	78%*	2017	(Araúz et al., 2018) [96]
Venezuela	28%*	2012 – 2013	(Calvo et al., 2016) [97]
Brazil	72%	2007 – 2010	(Doi et al., 2016) [108]
Columbia	43%	2015 – 2016	(Armstrong et al., 2019) [66]
England (3 London hospitals)	14.5%*	2015 – 2018	(Taori et al., 2019) [109]
India, US, UK (combined systematic review)	30%*	———	(Osei Sekyere, 2018) [23]

*Rate attributed specifically to *C. auris*.

2.1.1. Vulnerable Populations

While invasive candidiasis and other infections from *C. auris* are not thought to pose a significant threat to healthy people even if colonization occurs, vulnerable populations are often unprotected and unable to successfully clear the infection without intensive therapies [110]. 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 [12,23,63,78,111]. Patients with indwelling medical devices (e.g., central venous catheters), patients using parenteral nutrition, patients on mechanical ventilation, and 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 [63,112]. Nosocomial outbreaks of invasive candidiasis (*C. 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 1,400 candidemia cases were reported, over 5% were attributed to *C. auris* [112]. Rudramurthy et al. (2017) also found that patients with *C. auris* candidemia had longer ICU admissions prior to diagnosis than 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

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(<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 5th most common *Candida* species responsible for candidemia [120]. In India, of 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 (HIC) (8.9%-75% in LMIC and 12%-37% in HIC) [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 after 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

AMR is a significant and global threat to public health and the successful clinical management of microorganisms [2,6]. 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 2050, 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 [59,124]. 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 Antimicrobial Resistance.

Economic Burden	Cost Estimate ($USD)*	Cost Type	Source	Citation
AMR disease burden				
Europe	$9.77 billion	Total burden		(Prestinaci et al., 2015) [3]
United States	$55 billion	Total Burden	CDC	(Dadgostar, 2019) [6]
	$20 billion	Direct healthcare costs		
	$35 billion	Loss of productivity		
Fungal Disease Burden				
	$11.5 billion	Total burden	CDC	(Benedict et al., 2019, 2022; Kumar et al., 2022) [59,124,125]
	$7.5 billion	Direct healthcare costs		
	$870 million	Loss of productivity		

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	$3.2 billion	Premature death		
Candidiasis & Candidemia Burden				
Noninvasive Candidiasis	$2.5 billion	Total Cost Burden	CDC	(Benedict et al., 2019, 2022) [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	(Wan Ismail et al., 2020) [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	(Taori et al., 2019) [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 C. auris

2.2.1. 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 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 [8]. 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 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 the 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, identification of provider knowledge gaps and coinciding education, and implementation of prescribing restrictions when

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specialized infectious disease support is available [129]. In many healthcare institutions, especially in developing countries, the resources, capacity, and specialized health workforce required to create and operationalize effective antifungal programs may be limited. Lack of access to diagnostic tests and delayed results, and unavailability of *C. auris* low-resistance antifungal (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 contributes to the rising spread of AMR pathogens. Detecting *C. auris* is particularly challenging due to the over 700 isolates and limited laboratory testing capabilities [23]. Labs often misidentify *C. auris* as another *Candida* species due to common multiplex testing mediums 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 or 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 the *C. auris* colonization or infection, labs need the capacity and standardized protocol to complete pathogen genomic analysis and antimicrobial resistance 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 isolation of patients and contacts, wearing personal protective equipment, routine screening of patients, skin decontamination, environmental cleaning, and terminal decontamination [100,102,131]. Source control of *C. auris* should include 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 if 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 UV-C light to reduce infection of nosocomial pathogens may be effective at preventing transmission of *Candida 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 the easy transmission through direct or indirect contact on high-touch surfaces, air, and wastewater, the ability to survive outside of a human host, and the ability to sustain long periods of desiccation, biofilm formation, and high thermal tolerance [21,41,63,89,121,135–139]. 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 [63]. 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 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 is critical for water, air, and surface. 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.

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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 control of *C. auris* in healthcare settings includes 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 [26,104,111]. These generic and nonspecific disinfection procedures all lack the specificity for *C. 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, 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, 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 patient care of colonized individuals is not a sustainable or widely effective method. Enhanced disinfection and waste management is necessary for a robust infection prevention and control policy.

2.3.1. Water

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]. 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 *C. auris*, public health could be compromised by transmission of the pathogen through daily WASH activities. The 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 decontamination 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 affected the organoleptic properties of water [143,144]. No specific healthcare setting infection prevention and control protocols were found, including an absence of water testing protocols for *C. auris* isolates as a function of outbreak surveillance.

2.3.2. Air

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 decontamination 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 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 renders 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 the aerosolized spread, particularly in healthcare

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settings; however, data from this ongoing study has 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. Surface

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 include mattresses, bedside tables, bed rails, chairs, windowsills, ventilators, thermometers, pulse oximeters, IV poles, and ECG leads [21,26,63,100,132,154]. *C. auris* colonization and survival can also spread to sinks, bathrooms, cleaning buckets, computers, phones, and doors with relative ease [67]. 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 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 were considered the most effective for superficial disinfection, strict cleaning protocols must be followed [26,39,51,104,133,157]. Even slight deviation from the established protocol diminishes 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, 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 [111]; 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 have limited human and resource capacity often use less than ideal infection control procedures, leading to *C. auris* outbreaks [67,158].

Further complicating surface colonization and resistance to disinfection is the proclivity 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 multi-drug 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 the overall nosocomial spread and pathogenicity, particularly among medical equipment, including those with direct internal mucosal exposures (e.g., urinary and intravenous catheter tubing) [41,63,161]. When biofilm

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formation is present, common hospital-grade disinfectants are even less effective. Ledwoch and Maillard (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 from 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 seconds [163]. Even using optimal conditions, chlorohexidine (0.5%-4.0%) and other common alcohol disinfectants often achieve less than a 3-$\log_{10}$ reduction. There are no efficacy studies that demonstrate inactivation of *C. auris* colonization on skin with only 15 seconds 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 the 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 multi-drug 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. Waste Management

Regulated medical waste (RMW) or healthcare waste is not governed by a single regulating body, and therefore, waste management protocols vary widely by facility and region. Over time, common medical waste management strategies have included incineration, steam, microwave irradiation, mechanical, chemical, and pyrolysis [165,166]; however, disinfection and sterilization of healthcare waste have now become more common [167]. 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]. Standard disinfection of medical waste using chemical disinfectants has serious challenges, including hazardous operating conditions and limited germicidal efficacy. Without 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 [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.

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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 field testing of medical waste to identify and disrupt pathogen spread. Field indicators have been used in West African nations (Liberia & 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 effective disposal of waste [42]. While these strategies are not specific to the disinfection of *C. auris*, a broad application of microbial disinfection of healthcare waste should be applied to serve 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 99.99% of microbial pathogens, including highly resilient *C. auris*. Conventional UVC disinfection uses low-pressure mercury lamps emitting light at the wavelength of 253.7 nm; however, the energy dose required to kill or inactivate resilient pathogens (e.g., *C. auris*) often rises quickly beyond the safe exposure levels for humans [40]. 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 – 280 nm and have lower energy and voltage requirements, smaller sizes, and optics that can be tailored to 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* k-values 0.108 to 0.176 cm^2/mJ vs. *C. albicans* k-values 0.239 and 0.292 cm^2/mJ). In general, lower k-values were found for isolates expressing AMR properties, indicating a higher dose of UVC is necessary for the inactivation of AMR *C. auris* [53]. Studies have determined the optimal wavelength dose for inactivating *C. auris*. As shown in Table 3, Mariita et al. (2022) found that a peak wavelength sensitivity of 267–270 nm offered higher disinfection performance against multidrug-resistant *C. auris*. Giese and Darby (2000) 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 $LRV/mJ^{-1}/cm^2$. 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 [54].

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Table 3. UVC efficacy in inactivating *C. auris* is found with 267 and 270 nm peak wavelengths, and 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 10 20 40	5 10 20 40	8.60E + 05 8.60E + 05 8.60E + 05 8.60E + 05	3.67E + 05 2.43E + 05 7.67E + 04 9.33E + 02	0.37 0.55 1.05 2.96	57.336 71.744 91.081 99.892	0.0691	(Mariita et al., 2022) [54]
261	5 10 20 40	5 10 20 40	8.60E + 05 8.60E + 05 8.60E + 05 8.60E + 05	5.47E + 05 2.03E + 05 5.50E + 04 5.21E + 03	0.20 0.63 1.20 2.22	36.617 76.477 93.627 99.396	0.0565	(Giese & Darby, 2000) [178]
267	5 10 20 40	5 10 20 40	6.40E + 05 6.40E + 05 6.40E + 05 6.40E + 05	2.50E + 05 4.33E + 04 2.33E + 02 1.00E + 01	0.41 1.17 3.44 4.81	60.938 93.234 99.964 99.998	0.1294	(Mariita et al., 2022) [54]
270	5 10 20 40	5 10 20 40	9.53E + 05 9.53E + 05 9.53E + 05 9.53E + 05	3.33E + 05 6.33E + 04 3.33E + 02 2.33E + 01	0.46 1.18 3.46 4.61	65.058 93.358 99.965 99.998	0.126	(Giese & Darby, 2000) [178]
273	5 10 20 40	5 10 20 40	8.00E + 05 8.00E + 05 8.00E + 05 8.00E + 05	3.27E + 05 1.07E + 05 2.03E + 03 3.67E + 01	0.39 0.88 2.59 4.34	59.125 86.625 99.746 99.995	0.111	(Mariita et al., 2022) [54]
280	5 10 20 40	5 10 20 40	4.07E + 05 4.07E + 05 4.07E + 05 4.07E + 05	2.07E + 05 1.70E + 05 2.87E + 04 4.00E + 01	0.29 0.38 1.16 4.01	49.140 58.537 93.000 99.990	0.0889	(Mariita et al., 2022) [54]

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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 *C. 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 deposited on surfaces where skin contact can escalate. 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 application, 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. Water

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 at inactivating microbial pathogens in water and wastewater, though few studies have specifically evaluated *C. auris* due to its rapid transmission via surface contact first [35,141,144,180–188].

Research has discovered that UVC technology has applications in disinfecting drinking water [181,182,189], rainwater disinfection [190], and food processing water management [191]. UVC LED technology in water reactors can inactivate biofilm-bound *Pseudomonas aeruginosa* (265nm at UV dose 8 mJ/cm^2) to a 1.3 ± 0.2 log inactivation or LRV [180], pathogenic bacteria *Aeromonas salmonicida* and *Escherichia coli* (265nm at UV dose 24 mJ/cm^2 and 28 mJ/cm^2) to a 4.5 log reduction [35], *Giardia sp.* and *Cryptosporidium sp*. [183], and a wide range of other pathogenic microbes [33,34,143,192]. 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 [193].

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 that wastewater treatment plant's sewer shed in Southern Nevada, further highlighting the importance of scalable and sustainable pathogen disinfection [194]. Researchers have specifically found effective UVC disinfection for wastewater reuse [142,195,196] and sewage decontamination [197]. While chlorine-based disinfection has traditionally been used to disinfect wastewater, concerns about the impact have resulted in UVC disinfection as an alternative [42]. UVC LED water reactors are effective at eliminating microorganisms in water and wastewater using peak wavelengths between 260-270 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 treatment facilities, which can integrate UVC LED Driven Advanced Oxidation Processes (AOP) to decontaminate and disinfect wastewater simultaneously [184,185]. Combined UVC LED and AOP disinfection of wastewater has also been effective at reducing medical contaminants. The combined UVC LED + H_2O_2 wastewater treatment system showed efficacy and efficiency for smaller-scale water treatment facilities [198].

The effectiveness of UVC-based water disinfection depends on several important operating parameters. More opaque liquids reduce UV treatment effectiveness at different levels [182,199]. Whereas water circulation and exposure time improve water decontamination effectiveness [200]. Interestingly, water volume causes a dubious effect on UVC treatment, with insignificant to slightly better performance in lower volumes [189,200]. Continuous or pulsed UVC light application provides

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comparable results [143]. Depending on the intended final use of the treated water, the protocols must reach different decontamination 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]. Combined UV wavelengths or combining UV treatments with other methods may also have additive effects. Several studies have demonstrated that combining UV wavelengths [144,187,195,201,202] and multi-method treatment applications [142,196,203] have demonstrated synergistic effects that have improved the disinfection or decontamination process. Combining UVA and UVC [144,187,202] or UVB and UVC [186], UVC with other light sources such as excimer lamps [203], or UVC with chemical oxidants [196] all lead to synergistic effects.

A systematic review of the literature found that all examined studies achieved some level of decontamination or disinfection. Most studies achieved biological reductions of less than 3 log [144,181,186,187,201,202,204], and three studies achieved sterilization levels up to 5-6 log reduction [182,191,199]. These results give users confidence in applying UVC for its decontamination 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 [146,186,195,205].

2.4.2. Air

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 of microbial contaminants, ranging from sanitizing the air circulating between UVC sources to disinfecting the surfaces of air handling units, filters, and fans to prevent re-circulation of spores [40,206–208]. Some studies of UVC LED air treatment have demonstrated disinfection of some, but not all, biological indicators [145–147], and one study achieved sterilization in part of its biological targets [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 of many harmful pathogens, including *C. albicans* [208]. The log reduction of airborne pathogens is dependent on the highly variable UV dose and standard operating parameters of each in-duct UV disinfection product [209]. Air purification systems with combined HEPA + UV disinfection technology have been found effective at sanitizing rooms up to 12 m^2 in area [206]. Stand-alone UV recirculation units (or unitary UV systems) are another common application of UV air disinfection that works 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 [208]. A 2-log reduction of *Candida* spores was achieved in a 2-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) [207]. In healthcare settings (as with many other environments), it is challenging to circulate only fresh air. Therefore, recirculation of potentially contaminated air is necessary. Utilization of the enhanced KM model that integrates UVC disinfection into standard mechanical ventilation allows for increased energy efficiency, net carbon-zero requirements, and decreased dependency on outside air injection. 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 [207].

Muramoto et al. (2021) developed an air purifier that combines UVA/UVC LEDs, a HEPA filter, a honeycomb ceramics filter, and a pre-filter. In this system, the LEDs are responsible for treating the

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surface of the HEPA filter to decontaminate any microorganisms trapped in it, leading to the faster elimination of floating influenza viruses [210]. Researchers are also particularly interested in demonstrating how compact systems that are easy to implement in different settings are applicable to UVC LED disinfection [146–148,211]. Nicolau et al. (2022b) found that UVC possessed higher decontamination efficacy than ozone and was capable of achieving synergistic effects when combined with other methods.

2.4.3. Surface

Researchers have also determined UVC decontamination effectiveness on different materials, including various hard surfaces (e.g., carpet or laminate) [212], food contact surfaces [213], and recreational ball types [214]. In addition to the decontamination effectiveness, Wood et al. (2021) evaluated the relative humidity impact on the decontamination effectiveness and compared conventional UVC sources with LEDs. Trivellin et al. (2021) found that UVC light did not cause any visual changes or material degradation following disinfection. 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 is common in healthcare settings [49,51–53,55–57,215]. 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 *C. auris*, at least a 3-$\log_{10}$ reduction (99.9% reduction) is suggested to most likely be clinically effective [57]. A review of several UVC exposure parameters and devices found that UVC was clinically effective against *C. auris* when using proper conditions [56]. In lab testing, a mobile UVC tower equipped with high-performance bulbs at the 254 nm wavelength used for a continuous 7-minute 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 [49–51,55]. Maslo et al. (2019) saw a 99.6% reduction after a 10-minute pulsed-xenon UV light exposure cycle at a 2-meter distance from their mobile UV device and 100% elimination after more than 15 minutes of exposure. Chatterjee et al. (2020) reported a 0.8 to 1.19 log reduction of *C. auris* when exposed for 30 minutes. 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 of *C. auris* after 15 minutes of exposure to a novel UVC chip [50]. In a modification of the American Society for Testing and Materials (ASTM), six relatively low-cost (<$15,000 per unit) UVC devices (3 room decontamination devices and 3 UVC box devices) were tested against the suggested clinically effective 3-$\log_{10}$ reduction of *C. auris*. Three of the tested units (one room decontamination and two enclosed boxes) met all criteria for effective decontamination [216]. 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 [54]. The field studies branch of the Respiratory Health Division at NIOSH) found UV disinfection of *C. auris* was 99.9% effective but required significantly higher UV energy dose than other *Candida* species (*C. auris* 103–192 mJ/cm^2 vs. *C. albicans* 78-80 mJ/cm^2) [217].

Some studies have reported that *C. auris* is resistant to UVC treatment [218]; 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 the higher MIC and rapidly developing AMR [219]. 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 [219]; however, some studies achieved inactivation at shorter distances, although later experienced regrowth [39]. The UV-360 Room Sanitiser (UltraViolet Devices, Inc. Valencia, CA), using four vertical UV lamps (254 nm) in a 360-degree motion sensor cycle, produced maximal inactivation after 30-minute exposure cycles; however, they noted that Japan/Korean strains were most susceptible

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compared to Venezuela, Spain, and India strains [219]. 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 [57].

2.4.4. Waste Management

Disinfection or reduction of disease-causing microorganisms in medical waste to minimize disease transmission is imperative (WHO, 2014). Since completely destroying all microorganisms is challenging, sterilizing medical and surgical instruments is generally expressed as a 6 $\log_{10}$ reduction (a 99.9999% reduction) or greater of 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 light 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 disinfection of waste prior to disposal, such as with mobile boxes designed to disinfect used N-95 masks during the COVID-19 pandemic [220]. Novel applications for small, mobile waste bins with integrated UVC LED disinfection are also emerging to address contamination before large-scale storage [221]. While UV has been used to destroy airborne and surface pathogens as a supplement to other technologies, it may be limited in its ability to penetrate closed waste bags. The effectiveness of UVC is likely to depend on the processes and protocols in place, allowing a direct line of sight to the discarded waste [42].

2.4.5. UVC LED Disinfection Critical Factors

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 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 beholden to many of these critical factors depending on the specific waste and container to be treated

2.5. Case Studies of UV-C in Reducing C. auris

2.5.1. Water

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 [222,223]. 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 [224–226]. Sundar & Kanmani implemented a portable UVC water reactor at handpumps in a small village in South India, achieving a 2-log reduction of 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* [225]. 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 [225,226]. In Thailand, the 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 [224]. When combined with adsorbent additives (e.g., agricultural

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waste), solar-powered UVC LED water reactors are effective at reducing microbial load in community wastewater, proving advantageous for public health protection [227]. 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 UVC LED disinfection of wastewater to prevent runoff into the Pacific Ocean [193].

2.5.2. Air

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 shows promise for the extension of UVC air disinfection to *C. auris* [228]. In a similar study (not tailored to *C. auris*), HAIs were dramatically reduced after the clinical installation of in-room VidaShield (American Green Technology) continuous air purification units in the long-term ventilation unit of a hospital [229].

2.5.3. Surface

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 minutes 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) 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) of *C. auris* after a 17-19 minute cycle on the bacterial setting [57]. After standard chemical cleaning agents were completed, 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 longer exposure times are needed as the resiliency of the microbe increases [230]. 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 no-touch reduction of *C. auris* on surfaces already manually cleaned [231]. 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 adoption for future adjuvant cleaning procedures [179].

2.5.3. Waste Management

No clinical case studies were identified examining the efficacy of UVC LED disinfection of healthcare and medical waste. While many studies previously discussed demonstrated lab-tested effectiveness, additional research is needed to report on the real-world implementation of this strategy.

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3. Discussion

3.1. Benefits, Feasibility, & 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. Given the need for continued research on the standardization of disinfection conditions for *C. auris*, UVC LED disinfection across water, air, and surface can be used in a combination protocol and as an adjuvant sanitation procedure.

3.1.1. Challenges

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* [30,39,52,54,163,206]. Another notable challenge is that 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 [30,52,232]. Operating limitations resulting in diminished efficacy are also possible, including shadows, changes in topography and surface, barriers to direct line of sight, physical contamination, and lack of standardization [233]. Specialized units (e.g., mobile disinfection devices and robots) also required 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 [52,230,233]. Additionally, while UVC is considered safer than UVA and UVB, there are still risks for human exposure. There are unknown health and safety risks associated with frequent UVC disinfection exposure, and the standard shielding parameters are not yet fully understood [54,233].

While UVC LED devices are relatively low-cost or cost-effective, upfront purchase prices may be a barrier to low-resourced facilities [206]. 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]. 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 [235]. It is estimated that 1 in 4 health facilities in sub-Saharan Africa have no electricity and that 2 in 3 healthcare facilities in LMICs lack access to reliable energy [236]. 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 full disinfection of a desired area [234].

Patient and operator safety is another significant concern. While UVC is safer than other subtypes of UV light (i.e., UVA and UVB are more highly carcinogenic) and meets global requirements to phase out mercury lamps due to the harmful health and environmental impact, there are still safety risks that are not fully understood. When used outside of the intended purpose or straying from the suggested parameters for use, DNA damage, skin damage, and other adverse bodily effects are possible. Direct exposure to higher UVC wavelengths may also cause photocarcinogenic, mutagenic, or cytotoxic damage to human cells. While the adverse effect of direct UVC light exposure is not well researched, caution is needed when operating these devices [179]. Shielding is likely necessary for any direct UVC source; however, the wavelength, energy threshold, and other baseline parameters are not yet known [54].

3.1.2. Benefits

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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. While time to disinfect is noted as a challenge, 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 seconds, compared to the traditional 60-second wet contact time required for various chemical disinfectants [54]. Many other commercial units report effective pathogen reduction in under 10 minutes [237].

Implementation of adjunct UVC LED disinfection across water, air, surface, and waste applications provides multi-layer protection against dangerous and costly *C. auris* spread. While there are costs associated with any UVC device (air, surface, or water), the upfront price is considerably less than the accrued costs of outbreaks (direct and indirect costs). The addition of UVC disinfection in 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, implementation of UV-C disinfection as a supplement disinfection modality is likely to become feasible despite current challenges. The United Nations Development Programme's 'Solar for Health' initiative, which has equipped over 1,000 health centers with solar PV systems across 15 countries, including 11 in sub-Saharan Africa, provides strong infrastructure support that could equip LMICs in integrating UVC LED disinfection across water, air, surface, and waste applications. [236].

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 the healthcare facilities responsible for all HAI-associated costs due to a failure to prevent infections [238]; however, this is not consistent across all payers [239]. 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 the use of UVC Disinfection in Healthcare Settings to Reduce Transmission of C. auris

Since no specific chemical cleaning agents or germicides are designed to target *C. auris*, supplemental disinfection protocols are critical in reducing the transmission of *C. auris*. UVC LED technology across water, air, and surface applications and enhanced waste management protocols can bolster insufficient infection control procedures. The relatively low cost of UVC LED technology and broad use applications position it as an option for immediate adoption in healthcare settings. It is our recommendation to implement a multi-layered, enhanced UVC LED disinfection protocol, as illustrated in Figure 2, as an adjunct to any current infection prevention and control procedures. UVC LED water reactors for 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. UVC LED disinfection of waste has a more limited direct impact in healthcare facilities; however, the trickle-down effect may be substantial. Effective disinfection of healthcare waste can prevent community transmission of HAIs and limit the pathogenic spread of fungi like *C. auris*. If patient safety and infection control budgets allow for the implementation of

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UVC LED disinfection measures in each application, this would be considered the gold standard for infection prevention and control.

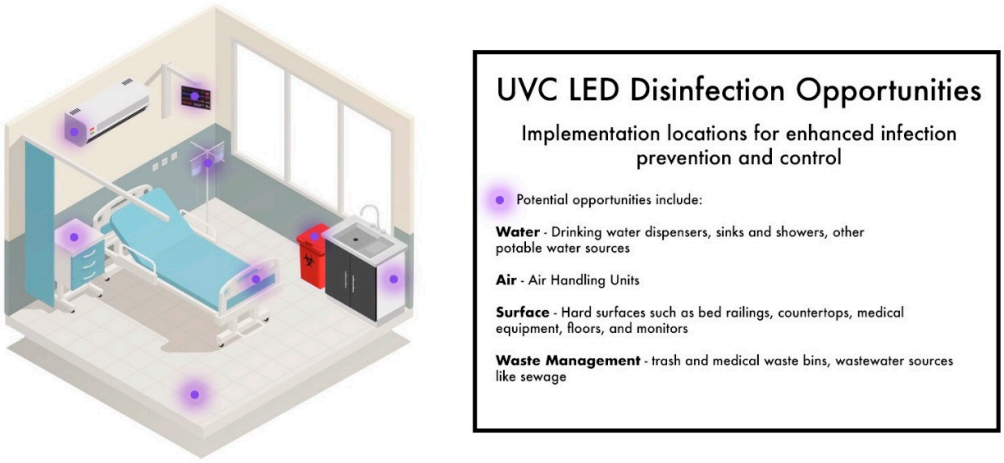

Figure 2. Illustration of potential multi-layered UVC LED protocol for enhanced infection prevention and control in a healthcare environment. *UVC LED disinfection is not suggested to replace standard or regulated infection prevention protocols.* (Image created using icons designed by Freepik).

In the absence of an unlimited budget, careful consideration of the healthcare facility's specific needs, the existing infrastructure, and the institutional capacity for implementation should be considered. The following recommendations outline considerations for scaled implementation, standard operating procedures, and policy revisions for any UVC disinfection applications in healthcare facilities.

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.
2. Ensure the UVC LED device meets all regional, national, and international disinfection standards.

a. Ensure all 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.*

3. 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 operating parameters and associated critical factors across application areas that are necessary for effective disinfection.

b. Assess the time and space requirements for effective disinfection in contrast to the available time and space for implementation.

c. If the budget allows layer UVC LED disinfection technology (e.g., water, air, surface, and waste; however, given *C. auris'*s primary transmission route, a minimum of surface disinfection devices are strongly suggested.

4. 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.

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 [240,241]

b. **Air** – ASHRAE Standard 185.1 and 241 [242]; ISO 15858:2016 [243].

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c. **Water** - NSF/ ANSI 55 Class A certification [244]
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 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, in the Collection, Analyses, or Interpretation of Data, in the Writing of the Manuscript,

Emerging UVC LED technology development in *C. auris* disinfection has been rapid and critical to advancing human health and well-being. Across applications, additional research is needed to support the standardization of UVC LED disinfection in healthcare facilities as an adjuvant modality or as a first-line prevention and control mechanism. In addition to further exploring the efficacy of UVC LED disinfection across water, air, surface, and waste applications, studies should also focus on the best practices for *C. auris* disinfection parameters and conditions, including wavelength, energy requirements, time of exposure, distance from the UVC source, direct vs. indirect exposures, manual disinfection requirements, and frequency of use. Beyond 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 [245]. Standardization and certification of these operational parameters by a centralized regulating body should be a future goal for researchers and policymakers. 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.

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 the 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.

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

Supplementary Materials - None

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