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REVIEW

Classic and alternative disinfection practices for preventing of hospital-acquired infections: a systemic review

J. Sheikh[1] · T. T. Swee[1,2] · S. Saidin[1,2] · S. A. Malik[3] · L. S. Chua[4] · M. T. F. Thye[1] · L. K. Meng[1] · M. Kun[5]

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Abstract
Ultraviolet (UV) disinfection technologies are well-known tools for microbial prevention in indoor public places which are frequently employed for disinfecting air, surfaces, and water. Such technologies have drawn a great deal of interest due to its potential application, especially in the domain of healthcare. This article discusses the shortcomings of chemical disinfectants and analyzes the current research standing on the development of various types of UV disinfection technologies for their prospective usage in the healthcare industry. Furthermore, the article provides a thorough analysis and in-depth evaluation of the current antibacterial studies using UV lamps and light-emitting diodes (LEDs) for the treatment of frequently encountered pathogens associated with healthcare. According to the systematic review, UV-LEDs have shown to be a potential source for delivering disinfection which is equally efficient or more effective than traditionally used UV lamps. The findings also provide valuable considerations for potentially substituting conventional lamps with LEDs that would be less expensive, more efficient, more robust, non-fragile and safer. With greater effectiveness and advantages, UV-LEDs have shown to be the potential UV source that could fundamentally be able to transform the disinfection industry. Therefore, the study supports the employment of UV-LED technology as a better and workable approach for effective disinfection applications. The study also offers insightful information that will help to direct future studies in the domain of hygienic practices used in healthcare facilities.

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✉ T. T. Swee
tantswee@utm.my

[1] V01, Department of Biomedical Engineering and Health Sciences, Faculty of Electrical Engineering, Universiti Teknologi Malaysia, 81310 Johor Bahru, Malaysia

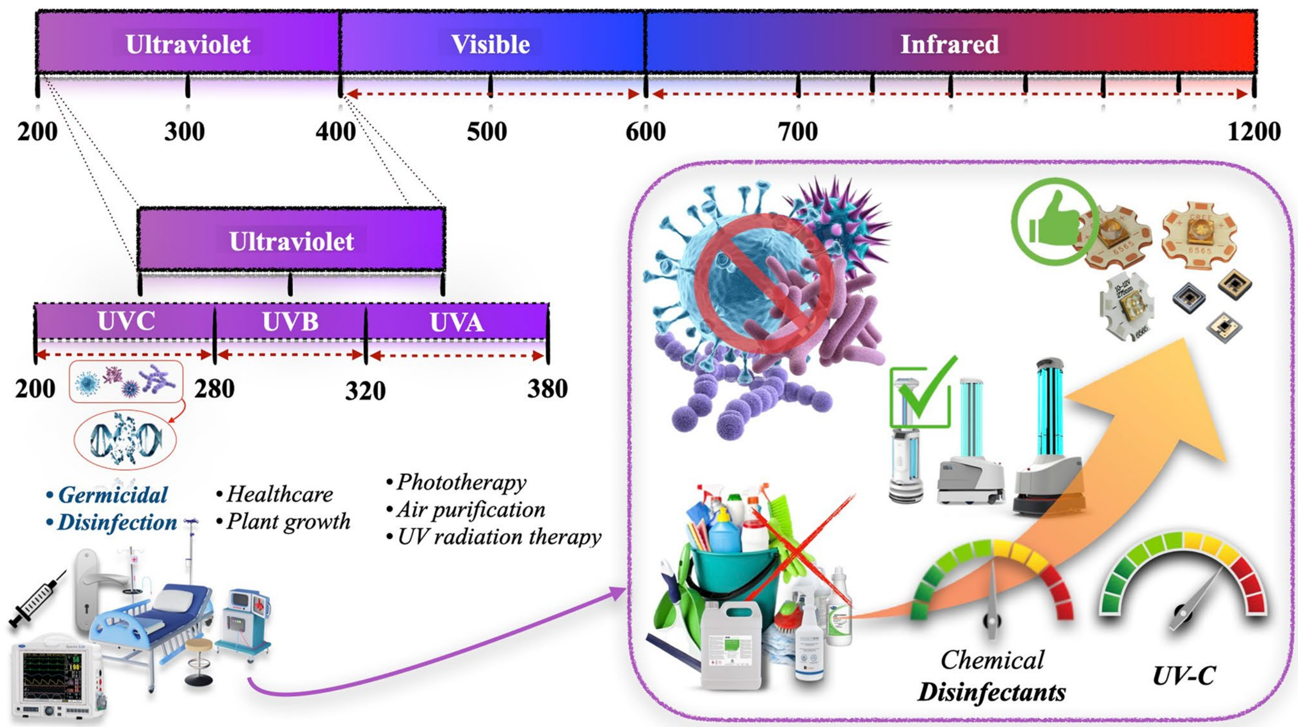
[2] IJN-UTM Cardiovascular Engineering Centre, Institute of Human Centered Engineering, Universiti Teknologi Malaysia, 81310 Johor Bahru, Johor, Malaysia

[3] Department of Bio-Medical Engineering, Faculty of Electrical Engineering, University of Engineering & Technology Lahore-Narowal Campus, Narowal 51600, Punjab, Pakistan

[4] Institute of Bioproduct Development, Universiti Teknologi Malaysia, UTM, Skudai, 81310 Johor Bahru, Johor, Malaysia

[5] General Electric (GE Healthcare), Guangzhou, China

Graphical Abstract



Keywords Bacteria · Decontamination · Disinfectants · Environment · High-touch surface · Low-touch surface · Pathogens · Ultraviolet-C

Abbreviations

HAI	Healthcare associated infection
ICU	Intensive care unit
EPIC	Extended Prevalence of Infection in Intensive Care
NI	Nosocomial infection
HCW	Healthcare worker
MDR	Multidrug-resistant
S. aureus	*Staphylococcus aureus*
E. faecium	*Enterococcus faecium*
K. pneumoniae	*Klebsiella pneumoniae*
A. baumannii	*Acinetobacter baumannii*
P. aeruginosa	*Pseudomonas aeruginosa*
MRSA	Methicillin-resistant *S. aureus*
E. coli	*Escherichia coli*
S. pneumoniae	*Streptococcus pneumoniae*
SSIs	Surgical sites infections
CDC	Centers for disease control and prevention
BSI	Bloodstream infection
CRBCI	Catheter-related bloodstream infections
LRTI	Lower respiratory tract infections
UTI	Urinary tract infection
C. albicans	*Candida albicans*
VAP	Ventilator-associated pneumonia
S. maltophilia	*Stenotrophomonas maltophilia*
HAP	Hospital-acquired pneumonia
K. oxytoca	*Klebsiella oxytoca*
S. marcescens	*Serratia marcescens*
S. maltophilia	*Stenotrophomonas maltophilia*
A. fumigatus	*Aspergillus fumigatus*
H. influenzae	*Haemophilus influenzae*
VRE	Vancomycin-resistant enterococcus
C. auris	*Candida auris*
P. mirabilis	*Proteus mirabilis*
C. parapsilosis	*Candida parapsilosis*
A. fumigatus	*Aspergillus fumigatus*
L. monocytogenes	*Listeria monocytogenes*
E. cloacae	*Enterobacter cloacae*
NTM	Nontuberculous mycobacteria
GN	Gram-negative
BWI	Burn wound infections
NB	Nosocomial bacteremia
REACH	Researching Effective Approaches to Cleaning in Hospitals

NTD	No-touch automated disinfection
VHP	Vaporized hydrogen peroxide
HPV	Hydrogen peroxide vapor
aHP	Aerosolized hydrogen peroxide
UV	Ultraviolet
LED	Light-emitting diode
PX	Pulse xenon
Hg	Mercury
LP	Low pressure
MP	Medium pressure
GaN	Gallium nitride
AGaN	Aluminum gallium nitride
SMD	Surface mount device
TB	Tuberculosis
M. luteus	*Micrococcus luteus*
HED	Handheld electronic devices
ORs	Operating rooms
UR-UVGI-LEDs	Upper-room UV germicidal irradiation LEDs
SPD	Spectral power distribution
MVL	Mercury vapor lamps
AB	Aerobic bacteria
UNEP	United Nations Environment Program
EPS	Extracellular polymeric substances
DSB	Dry surface biofilms

Introduction

Healthcare-associated infections (HAIs) are a substantial contributor to patient mortality and morbidity as well as growing healthcare costs (Magill et al. 2018; Haque et al. 2018). When obtaining care, especially in hospitals, nursing homes, and other ambulatory settings, many infections can be acquired. Through invasive treatments, surgery, and medical equipment, bacterial, viral, or fungal infections can spread and result in an infection. Compared to 6.5% in the European Union/European Economic Area, 3.2% of Americans have HAI, and the frequency is likely higher internationally (Suetens et al. 2016; Allegranzi et al. 2011). Modern medicine frequently uses invasive medical equipment such as ventilators and catheters, which are typically associated with a rise in HAI (CMS 2023). HAIs, according to statistics, are a major issue in both developed and developing countries, with 10 out of 100 hospitalized patients in developing countries and 7 out of 100 hospitalized patients in developed countries, respectively, at risk of contracting such infections (Danasekaran et al. 2014). Intensive care unit (ICU) patients, burn patients, organ transplant recipients, and neonates are a few of the groups who are most prone to HAI (Aljerf 2016). The Extended Prevalence of Infection in Intensive Care (EPIC II) study found that the proportion of infected patients in the ICU might occasionally reach a disconcerting 51%. HAIs are more common than before and are associated with a number of adverse outcomes, such as prolonged hospitalization, long-term disability, increased antimicrobial resistance, economic disturbances, and increased mortality rates (Vincent et al. 2009). Unfortunately, the lack of accurate data on the severity of this issue is mostly due to insufficient monitoring systems and weak preventive measures (Allegranzi 2011).

Location of the research: V01, Department of Biomedical Engineering and Health Sciences, Universiti Teknologi Malaysia, Johor Bahru-81310, Malaysia.

Rise in nosocomial infections (NIs) in healthcare settings

The substantial issue of NI, also known as HAIs, has drawn notable attention as a result of contamination in healthcare settings as illustrated in Fig. 1. These infections not only lower the quality of life for the patients but also increase medical costs. However, healthcare workers (HCW)s can work together to prevent and manage hospital-based infections by putting into practice crucial methods including early diagnosis and isolation of infected patients, effective use of personal protective equipment, and environmental cleaning and disinfection (Aljerf 2016). Such events could also give researchers crucial information about how to prevent and manage the spread of NI in the future (Du et al. 2021). NI is still a problem in infant care despite the fact that advances in medicine have already made it possible for weakened and smaller infants to survive. Longer hospital stays, elevated death rates, and short- and long-term morbidity are all linked to such infections (Ramasethu 2017). Hospital infection rates were also the focus of studies by Li et al. (Li et al. 2017) that emphasized on how NI surveillance systems influenced hospital infection rates. The study found that continuous surveillance exhibited a favorable impact on NI rates, with odds ratios/risk ratios varying from 0.43 to 0.95, respectively.

Overview and rate-influencing factors for nosocomial infection (NI) in healthcare

Common NI cases, which, despite the availability of antibiotics, continue to be a serious public health concern. The microorganisms which trigger NI infections frequently are addressed in Table 1. These infections might lead to extended hospital stays, greater rates of morbidity and death, more frequent use of antibiotics, and higher costs. Multidrug-resistant (MDR) bacteria such *Staphylococcus aureus (S. aureus), Enterococcus faecium (E. faecium), Klebsiella pneumoniae (K. pneumoniae), Acinetobacter baumannii (A. baumannii),* and *Pseudomonas aeruginosa*

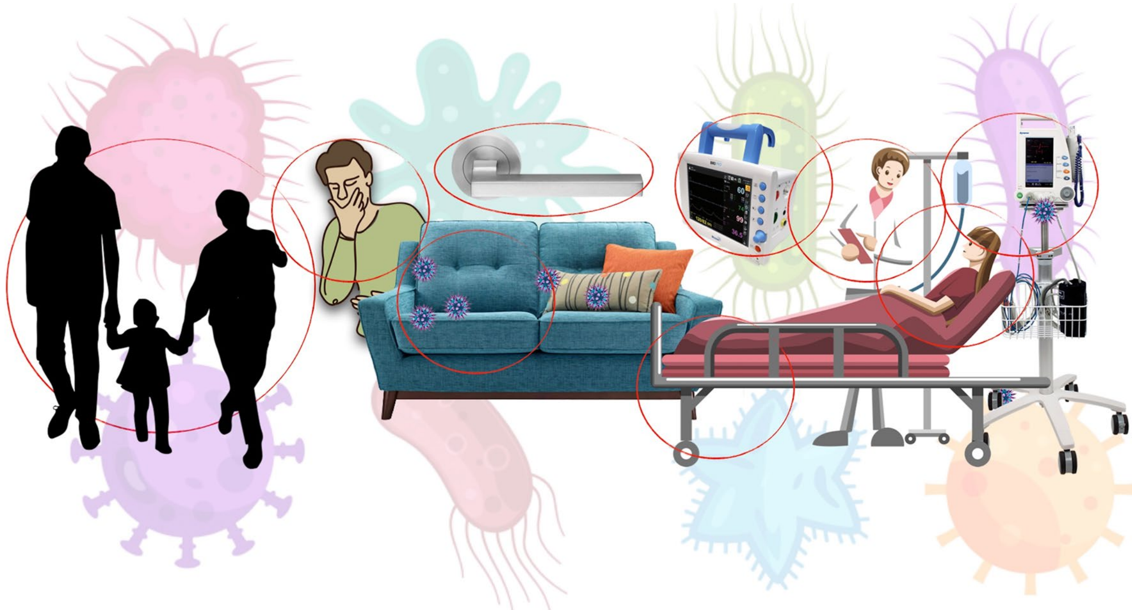


Fig. 1 An illustration of the signs of nosocomial infections (NI) in the medical setting. The circled region demonstrates the origin pathways of NIs

(*P. aeruginosa)* pose a severe threat to public health and have emerged as a result of antibiotic overuse (Darvishi et al. 2020). The three frequently isolated bacterial pathogens such as *A baumannii, K. pneumoniae,* and methicillin-resistant *S. aureus* (MRSA) have shown to be a major cause of such infection (Ananda et al. 2022). The studies have found 54 pathogenic microorganisms to be prevalent in 6.9% of culture-confirmed nosocomial infections (NIs). Among them, Gram-positive bacteria made up 55.6% such as *S. aureus* (18.5%), *Escherichia coli (E. coli)* (16.7%), and *Streptococcus pneumoniae* (*S. pneumoniae)* (14.8%), being the most frequently isolated microorganisms. The most frequently infected surgical sites infections (SSIs) were accounted to be 31.5% which were followed by the bloodstream which were 25.9%. The most prevalent pathogens identified in surgical sites were coagulase-negative *staphylococci* (17.6%), *P. aeruginosa* (17.6%), and *S. aureus* (29.4%). Likewise, *S. pneumoniae* (41.6%) and *Klebsiella spp*. (25%) were the top two pathogens isolated from the upper respiratory tract, and *E. coli* (36.3%), *Proteus spp*. (18.2%), and *Enterococcus spp*. (18.2%) were most frequently isolated from urinary tract infections. It was also found that *S. aureus* and *E. coli* with the prevalence 28.6 and 21.4%, respectively, were the most commonly isolated microorganisms associated with bloodstream infections (Tolera et al. 2018). Surgical site infections (SSIs), which affect 2–5% of patients undergoing surgery, have posed a serious and prevalent complication of hospitalization. According to studies by Anderson et al. (2011), SSIs have been found to be mostly caused by *S. aureus*, which is contributing to up to 37% in community hospitals and 20% in hospitals that reported to the Centers for Disease Control and Prevention (CDC).

MRSA is not just the most frequent infection in tertiary care facilities and academic institutions, but also the main contributor to SSI in community hospitals. In hospitalized patients, bloodstream infections (BSI), catheter-related bloodstream infections (CRBSI), lower respiratory tract infections (LRTI), and urinary tract infections (UTI) tend to be caused by microorganisms as reported by Bardi et al. (2021). Furthermore, coagulase-negative staphylococci and *Enterococcus faecalis* (*E. faecalis)* were the most common bacteria found in patients with primary BSI. Gram-positive bacteria were also accounted for a large number of CRBSI cases, with *Candida albicans (C. albicans)* being the most common cause, followed by *E. faecalis, Enterococcus faecium (E. faecium)*. Gram-negative bacteria such as *P. aeruginosa* was the most often isolated bacterium in patients with ventilator-associated pneumonia (VAP) and tracheobronchitis. Gram-negative microbes were also observed to be the most common cause of LRTI. Moreover, *S. aureus* was shown as commonly isolated pathogen in the patients with VAP and tracheobronchitis, with a high resistance rate to methicillin observed in 87% of cases. *Aspergillus* spp. were identified in three cases of LRTI. *Enterococcus faecium* and *E. faecalis* were also the most common cause of UTI. Also, according to one article, *Enterobacterales* and non-fermenting Gram-negative bacilli, such as *A. baumannii* and *Stenotrophomonas maltophilia (S. maltophilia)*, were occasionally identified as the causative agents of bacteremia, LRTI, UTI, and soft tissue infections. *Pseudomonas aeruginosa* was

Table 1 Illustrates the most commonly reported bacterium known to cause nosocomial infection in healthcare settings, as identified in the literature

Microorganisms	Association	References
Escherichia coli	BSI, UTI, SSI, intestinal	Tolera et al. (2018), Magill et al. (2014b), Ding et al. (2019), Diseases and Organisms in Healthcare Settings (2016)
Proteus spp.	Urinary tract	Tolera et al. (2018)
Enterococcus spp.	UTI, CRBSI, HAP	Torok et al. (2016)
Staphylococcus aureus	HAP, SSI, Skin, BSI, VAP	Tolera et al. (2018), Anderson (2011), Magill et al. (2014b), Liu et al. (2017), Jamal et al. (2017), Nelson and Gallagher (2012), Blanco-Cabra et al. (2019), Rice (2008), Pal et al. (2019), Apisarnthanarak et al. (2003)
Streptococcus pneumoniae	HAP, BSI	Tolera et al. (2018), Ding et al. (2019)
Klebsiella spp., K. pneumoniae, Klebsiella oxytoca (K. oxytoca),	HAP, SSI, CRBSI, BSI, gastrointestinal	Tolera et al. (2018), Bardi et al. (2021), Magill et al. (2014b), Ding et al. (2019), Diseases and Organisms in Healthcare Settings (2016), Rice (2008), Karlowsky et al. (2017)
Pseudomonas aeruginosa	SSI, BSI, VAP, surface acquired, HAP	Tolera et al. (2018), Bardi et al. (2021), Kalil et al. (2016), Liu et al. (2017), Jamal et al. (2017), Rice (2008), Maldonado et al. (2020)
Acinetobacter	HAP, VAP, human milk	Bardi et al. (2021), Rice (2008), Joshi and Acinetobacter Baumannii (2013), Engur et al. (2014)
Serratia marcescens (S. marcescens)	BSI	Bardi et al. (2021)
Bacteroides spp.	BSI	Bardi et al. (2021)
Coagulase-Negative Staphylococci	BSI, CRBSI	Bardi et al. (2021)
Candida albicans	CRBSI	Bardi et al. (2021)
Enterococcus faecalis	CRBSI	Bardi et al. (2021)
Stenotrophomonas maltophilia (S. maltophilia)	VAP, HAP	Bardi et al. (2021)
Aspergillus fumigatus (A. fumigatus)	HAP/tracheobronchitis	Bardi et al. (2021)
Haemophilus influenzae (H. influenzae)	HAP/tracheobronchitis	Bardi et al. (2021)
Enterobacter spp.		Rice (2008)
Enterococcus spp.		Torok et al. (2016)
Klebsiella pneumoniae	SSI, BSI	Ding et al. (2019), Rice (2008), Karlowsky et al. (2017)

also found to be responsible for HAIs that can manifest as bloodstream infections, urinary tract infections, pneumonia, and infections at surgical sites. It accounted for approximately 7.1–7.3% of all HAIs, according to studies (Magill et al. 2014a; Weiner et al. 2016). Moreover, over the past ten years, *P. aeruginosa* infections have grown increasingly prevalent (Williams et al. 2010; Parker et al. 2008). As much as 22% of all HAIs are caused by hospital-acquired pneumonia (HAP) and VAP, which impose a significant burden on the healthcare system (Kalil et al. 2016). *Pseudomonas aeruginosa* is second only to *S. aureus* in VAP infections, accounting for 10–20% of the isolates (Magill et al. 2014a).

Microbial contamination on environmental surfaces

Recent studies have shown that the transmission of Multidrug Resistant Organisms (MDROs), viruses, mycobacteria, and fungi as the main causes of HAIs that contribute to morbidity and mortality among the patients admitted in hospital which is substantially affected by environmental contamination (Rosenthal et al. 2016; Weber et al. 2010). Reports have also shown that such contamination has a substantial impact on the transmission of these microorganisms (see Table 2) in healthcare settings (Dancer 2014; Sood and Perl 2016; Kirk Huslage 2010). In healthcare environments, the long-term persistence of a variety of nosocomial pathogens including *S. aureus*, Vancomycin-resistant Enterococcus (VRE), MRSA, *A. baumannii*, *C. difficile*, and *P. aeruginosa* has been observed (Boyce 2007; Kramer et al. 2006; Chemaly et al. 2014). These microorganisms continued presence in the environment can act as a source of transmission and spread in hospital settings (Esteves et al. 2016). The type of surface—whether it is smooth, porous, rough, dry, moist, new, or old, influences the degree of contamination. Since rough or porous surfaces tend to harbor more bacteria than smooth ones, it might be challenging

Table 2 Illustrates the most commonly reported bacteria known to cause surface contamination in healthcare settings, as identified in the literature

Sources entitled	Pathogens	Transmission	References
The role of environmental contamination in the transmission of nosocomial pathogens and healthcare-associated infections	*Staphylococcus aureus* VRE *Clostridium difficile*	High-touch surface, cross contamination	Suleyman et al. (2018)
Transfer of multidrug-resistant bacteria to healthcare workers' gloves and gowns after patient contact increases with environmental contamination	*Acinetobacter baumannii* *Pseudomonas aeruginosa* VRE MRSA	Contaminated gloves and gowns, colonized patients	Morgan et al. (2012)
Risk of acquiring multidrug-resistant Gram-negative bacilli from prior room occupants in the intensive care unit	*Staphylococcus aureus* Enterococcus species *Clostridium difficile*	Cross contamination, patient bed rails, bed	Nseir et al. (2011)
The role played by contaminated surfaces in the transmission of nosocomial pathogens	*Clostridium difficile* VRE MRSA *Acinetobacter baumannii* *Pseudomonas aeruginosa* Norovirus	High-touch surface, cross contamination, HCW	Otter et al. (2011)
Transfer of dry surface biofilm in the healthcare environment: the role of healthcare workers' hands as vehicles	MRSA VRE *Staphylococcus aureus* *Clostridium difficile*	High-touch surface, cross contamination	Chowdhury et al. (2018)
Are hospital floors an underappreciated reservoir for transmission of health care-associated pathogens?	*Clostridium difficile*	High-touch surface	Deshpande et al. (2017)
Environmental surfaces in healthcare setting: a great potential risk of pathogens transmission	*Staphylococci* *Staphylococcus aureus* Enterobacter sp. Pantoea sp. Klebsiella sp. *Escherichia coli* *Pseudomonas aeruginosa* Stenotrophomonas spp. Enterococcus spp.	Bed rails, bedside tables, toilets door knobs and room knobs	Bouchra et al. (2019)
Bacterial contamination of hospital surfaces according to material make, last time of contact and last time of cleaning/disinfection	*Pseudomonas aeruginosa* *Staphylococcus aureus*	Wash sink, high-touch surface	Kh et al. (2017)

Table 2 (continued)

Sources entitled	Pathogens	Transmission	References
Best practices for disinfection of noncritical environmental surfaces and equipment in health care facilities: a bundle approach	MRSA VRE Acinetobacter Norovirus *Clostridium difficile*	High-touch surface, medical device	Rutala and Weber (2019)
Antimicrobial activity of a continuously active disinfectant against healthcare pathogens	*Staphylococcus aureus* *Escherichia coli* VRE Enterobacter spp. *Candida auris (C. auris)* *Klebsiella pneumoniae*	Formica, stainless steel, high-touch surface	Rutala et al. (2019)
Beware biofilm! dry biofilms containing bacterial pathogens on multiple healthcare surfaces; a multi-center study	MRSA	High-touch surface	Ledwoch et al. (2018)
Reducing healthcare-associated infections incidence by a probiotic-based sanitation system: a multicenter, prospective, intervention study	*Escherichia coli* *Enterococcus faecalis* *Staphylococcus aureus* *Proteus mirabilis (P. mirabilis)* *Pseudomonas aeruginosa* Staphylococcus spp., Enterobacteriaceae spp. Pseudomonas spp. Acinetobacter *Clostridium difficile* Candida spp.	Low-touch surface	Caselli et al. (2018)
Rapid recontamination with MRSA of the environment of an intensive care unit after decontamination with hydrogen peroxide vapor	MRSA	High-touch surface	Hardy et al. (2007)
Better environmental survival of outbreak versus sporadic MRSA isolates	*Staphylococcus aureus* MRSA *Pseudomonas aeruginosa*	High-touch surface	Wagenvoort et al. (2000)
Staphylococcus aureus surface contamination of mobile phones and presence of genetically identical strains on the hands of nursing personnel	*Staphylococcus aureus*	High-touch surface, mobile phones, fingers, palm	Katsuse Kanayama et al. (2017)
Decontamination devices in health care facilities: practical issues and emerging applications	MRSA	Medical devices	Donskey (2019)

Table 2 (continued)

Sources entitled	Pathogens	Transmission	References
Environmental contamination with Candida Species in multiple hospitals including a tertiary care hospital with a Candida auris outbreak	*Candida parapsilosis (C. parapsilosis)*	Room floor, sink drains, high-touch surface	Kumar et al. (2019)
The role of environmental contamination with small round structured viruses in a hospital outbreak investigated by reverse-transcriptase polymerase chain reaction assay	MRSA VRE *Clostridium difficile* *Pseudomonas aeruginosa* Acinetobacter spp.	High-touch surface	Green et al. (1998)
Introduction of NGS in environmental surveillance for healthcare-associated infection control	Enterococcus spp. *Klebsiella pneumonia* *Escherichia coli* *Acinetobacter baumannii* *Proteus mirabilis* *Pseudomonas aeruginosa* *difficile* *albicans* *Aspergillus fumigatus (A. fumigatus)*	Room floor, sink drains, high-touch surface	Comar et al. (2019)
Antimicrobial properties of a novel copper-based composite coating with potential for use in healthcare facilities	*Staphylococcus aureus* *Pseudomonas aeruginosa* *Escherichia coli* *Listeria monocytogenes (L. monocytogenes)*	High-touch surface	Montero et al. (2019)
A meta-analysis of the rates of Staphylococcus aureus and methicillin-resistant S. aureus contamination on the surfaces of environmental objects that health care workers frequently touch	*Staphylococcus aureus* MRSA	High-touch surface	Lin et al. (2017)
Bacterial contamination of frequently touched objects in a tertiary care hospital of Pokhara, Nepal: how safe are our hands?	*Staphylococcus aureus* MRSA Acinetobacter *Escherichia Coli* *Pseudomonas aeruginosa*	Elevator buttons, biometric devices and door handles	Bhatta et al. (2018)
Recovery of resistant bacteria from mattresses of patients under contact precautions	Acinetobacter spp.	Hospital surfaces (mattresses, medical charts), high-touch surface	Viana Rel et al. (2016)
Microbial contamination of hospital reusable cleaning towels	Aspergillus spp.	High-touch surface, sink waste pipes	Sifuentes et al. (2013)
Prevalence of pathogens and indicator organisms in home kitchens and correlation with unsafe food handling practices and conditions	Campylobacter spp.	Food surfaces	Borrusso and Quinlan (2017)

Table 2 (continued)

Sources entitled	Pathogens	Transmission	References
The domestic kitchen-the "front line in the battle against foodborne disease"	Campylobacter spp.	Sink drains, room chair	Hassan and ElBagoury (2018)
Acquisition of spores on gloved hands after contact with the skin of patients with Clostridium difficile infection and with environmental surfaces in their rooms	*Clostridium difficile*	Bedside rails, bedside tables, toilets door knobs, room knobs	Guerrero et al. (2012)
Hospital microbial surface colonization revealed during monitoring of Klebsiella spp., Pseudomonas aeruginosa, and non-tuberculous mycobacteria	*Staphylococcus aureus*	High-touch surface, cross contamination, EEG wires, medical chart	Geadas Farias et al. (2017)
Microbial evaluation of foodservice surfaces in Texas child-care centers	Salmonella spp.	Food surfaces, high-touch surface	Staskel et al. (2007)
Hospital microbial surface colonization revealed during monitoring of Klebsiella spp., Pseudomonas aeruginosa, and non-tuberculous mycobacteria	Pseudomonas spp.	High-touch surface, low-touch surface	Geadas Farias et al. (2017)
Contamination of medical charts: an important source of potential infection in hospitals	Klebsiella spp.	High-touch surface, low-touch surface, medical charts	Chen et al. (2014)
Hospital-wide comparison of health care-associated infection among 8 intensive care units: a retrospective analysis for 2010–2015	*Escherichia Coli*	High-touch surface, low-touch surface, medical charts	Yue et al. (2017)
Microbial contaminants isolated from items and work surfaces in the postoperative ward at Kawolo General Hospital, Uganda	*Staphylococcus aureus* *Klebsiella pneumoniae*	Infusion stands, patient beds	Sserwadda et al. (2018)
Study of bacterial flora associated with mobile phones of healthcare workers and non-healthcare workers	*Acinetobacter baumannii* MRSA	Mobile phones	Morubagal et al. (2017)
Antimicrobial resistance of 3 types of Gram-negative bacteria isolated from hospital surfaces and the hands of health care workers	*Pseudomonas aeruginosa* *Enterobacter cloacae (E. cloacae)* *Klebsiella pneumoniae*	High-touch surface, cross contamination	Wang et al. (2017)
Contaminated stethoscopes revisited	MRSA *Staphylococcus aureus*	Stethoscopes	Smith et al. (1996)
Environmental contamination of contact precaution and non-contact precaution patient rooms in six acute care facilities	MRSA VRE Carbapenem-resistant *Enterobacteriaceae* or *Acinetobacter*	Mobile equipment in acute care, intensive care, transplant units	Tanner et al. (2021)
Survival capability of healthcare-associated, multidrug-resistant bacteria on untreated and on antimicrobial textiles	*Klebsiella pneumoniae* *Acinetobacter baumannii* *Staphylococcus aureus* *Enterococcus faecium*	Antibacterial cotton textile	Hanczvikkel et al. (2018)

Table 2 (continued)

Sources entitled	Pathogens	Transmission	References
Bacterial contamination and antimicrobial susceptibility patterns of intensive care unit medical equipment and inanimate surfaces at Ayder Comprehensive Specialized Hospital, Mekelle, Northern Ethiopia	*Escherichia coli* *Staphylococcus aureus*	Medical devices	Darge et al. (2019)
Degree of bacterial contamination of mobile phone and computer keyboard surfaces and efficacy of disinfection with chlorhexidine gluconate and triclosan to its reduction	Specie of *Bacillus* *Staphylococcus aureus*	Mobile phones, computer keyboards	Koscova et al. (2018)
Environmental contamination by bacteria in hospital washrooms according to hand-drying method: a multicenter study	MRSA	Multiple surfaces, dust, washroom footfall	Best et al. (2018)
Mobile phones represent a pathway for microbial transmission: a scoping review	RNA viruses *Staphylococcus aureus* Coagulase-negative Staphylococci *Escherichia coli* MRSA Acinetobacter sp. Bacillus sp.	Mobile phones	Olsen et al. (2020)

to effectively clean and disinfect the surface. Additionally, microorganisms have the capacity to form biofilms on surfaces, which may provide a secure habitat that enables them to persist for a longer period of time (Boer 2006). While certain pathogens can survive for a few days, others can last for weeks or even months. HCW can also contaminate their hands with MRSA, GRE, and Gram-negative *bacilli* when they come into contact with colonized or infected patient's environments (Bernard et al. 1999; Bhalla et al. 2004). High-touch surfaces, devices, equipment, and life-support systems require advanced disinfection techniques in hospital settings to avoid contaminating inanimate surfaces (Hayden et al. 2008; Adams et al. 2017). Bacterial contamination may also occur through transmission directly from infected or colonized patients or through the hands of HCWs (see Fig. 2). Objects near patients are more likely to become contaminated, and infections frequently lead to higher levels and rates of bacterial contamination (Rohr et al. 2009; Bonten et al. 1996). Huslage et al. (2010) found out that the bed rails, bed surfaces, supply carts, over-bed tables, and intravenous pumps were among the most frequently touched surfaces by HCW (Shams et al. 2016). In addition, medical equipment and devices like hemodialysis machines, infusion pumps, stethoscopes, electronic thermometers, and blood pressure cuffs may act as potential reservoirs for the transmission of nosocomial infections (Sehulster 2003).

In addition, there is a growing consensus that bacteria in dry surface biofilms may contribute to HAI. The risk of HAI is also derived from the direct transfer of pathogens from biofilms to patients, especially when cleaning and decontamination are insufficient. By touching surfaces, individuals, including staff, patients, and visitors, might acquire infections on their hands and fingertips. They may then inoculate a possible infection site or spread pathogens to additional sensitive regions. This raises serious concerns regarding the effectiveness of typical cleaning techniques for hospital surfaces. These microbial occupants develop defense mechanisms to ensure their survival while also increasing their chances of transferring to more favorable environments (Chowdhury et al. 2018; Tahir et al. 2019). As a result, a biofilm can be thought of as a "microbial village," with a distinct infrastructure that supports a diversified population of bacteria, viruses, fungi, protozoa, and spores contained within extracellular polymeric substances (EPS) (Lindsay et al. 2006).

One study focused on the occurrence of dry biofilms on hospital surfaces, which has gotten minimal attention compared to wet biofilms associated with medical devices. According to the study, the practically ubiquitous presence of multi-species dry biofilms of Gram-positive bacteria were discovered in three UK hospitals. Notably, MRSA was found in 58% of the samples. Despite a uniform physical cleaning, there were differences in dominant species among hospitals. The study further emphasized the possible underestimating of dry biofilms' significance in HAI transmission, particularly when combined with ineffective cleaning techniques. It implied that present cleaning processes should be reassessed and improved in order to successfully manage

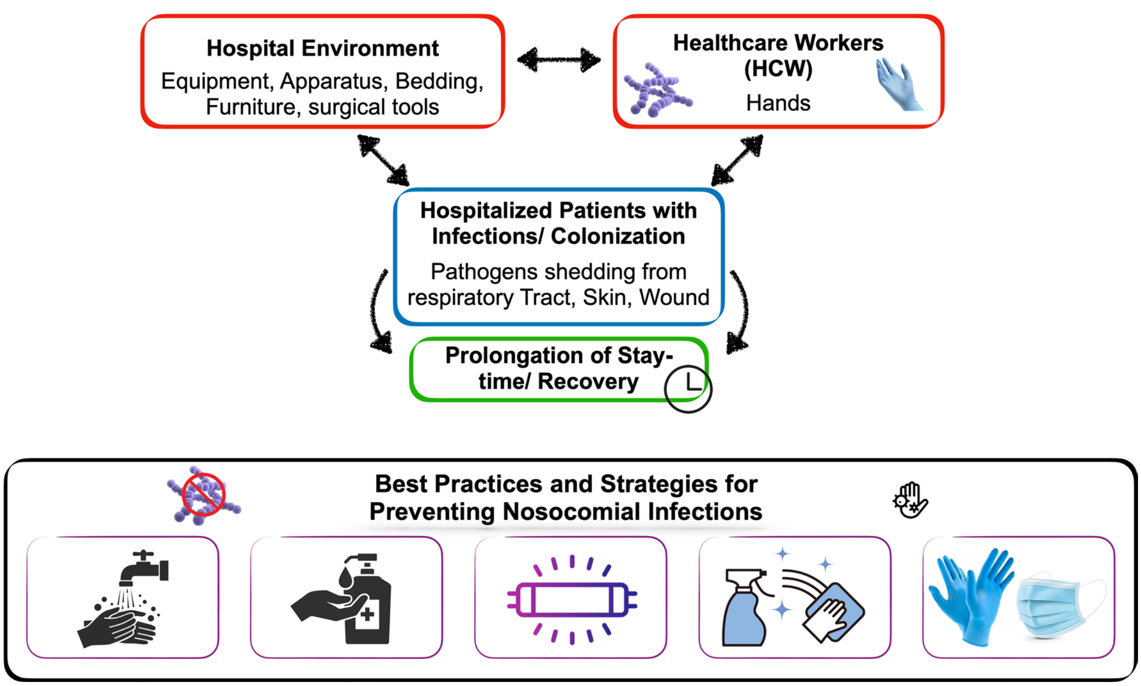


Fig. 2 Spread of nosocomial infection posing threat to the environment and individuals versus best practices and strategies for preventing it

this often-overlooked source of infection (Ledwoch et al. 2018). In addition to this, another study (Chowdhury et al. 2018) looked into the transmission of dry surface biofilms (DSBs) in hospitals. The researchers sought to determine if DSBs were potentially transferred from surfaces to the hands of HCWs. As per findings, 5.5–6.6% of DSB bacteria were reported to be migrated to hands with one touch. The study confirmed hands as the potential transmission route of DSB bacteria, implying their persistence as pathogen sources and emphasizing their potential significance in HAI transmission.

To counter such challenges, one study (Desrousseaux et al. 2013) sought to investigate potential solutions associated with device-related infections in healthcare. A specific technique involved coating or covalently bonding a biocidal chemical onto materials, with the potential for biocide release or contact killing without release. The study emphasized on modifying the chemical or physical surface characteristics of materials to prevent microbe attachment. Another study (Uneputty et al. 2022) highlighted the multifunctional approaches to combat biofilms on surfaces, categorized into four main groups: anti-adhesive, contact active, biocide attached/biocide release, and topographical alteration to prevent bacterial biofilms on the surface. The anti-adhesive procedures may attempt to minimize bacterial attachment to solid surfaces, hence preventing contamination, contact active techniques may entail attaching antibacterial chemicals to offer continuing antibacterial properties, biocide attached/biocide release may combine the controlled release of toxic substances to combat microorganisms on surfaces, and topographical alteration may generate minor structural elements that target biological components in order to eradicate microorganisms. To date, fresh approaches to addressing the challenge of biofilm formation on surfaces are being investigated, particularly in response to the growing problem of antibiotic resistance.

Understanding the microbial transmission pathways

Patients may get transmitted from a wide variety of sources such as HCWs who have not properly or routinely maintained hand hygiene, low- and high-touch surfaces, air and water, which subsequently increases the risk of infection and prolong the recovery period. Aspiration, inhalation, contact with infected people, exposure to contaminated surfaces or medical equipment, and numerous other ways could be a reason of microorganism or virus transmission. These possible routes of transmission highlight the need of putting in place comprehensive infection prevention strategies in hospital settings, including rigorous hand hygiene, regular surface cleaning, and disinfecting medical equipment (Sehulster 2003).

Airborne and water transmission

Concerning airborne transmission, direct transmission can occur when individuals come into contact with substantial aerosolized droplets (> 5 μm) coming from the infected individual's oral or nasal secretions, while indirect transmission can take place when tiny spores (1–5 μm) containing viable microorganisms shed over long distances with the help of air circulation (Fig. 3) (Gamage et al. 2016).

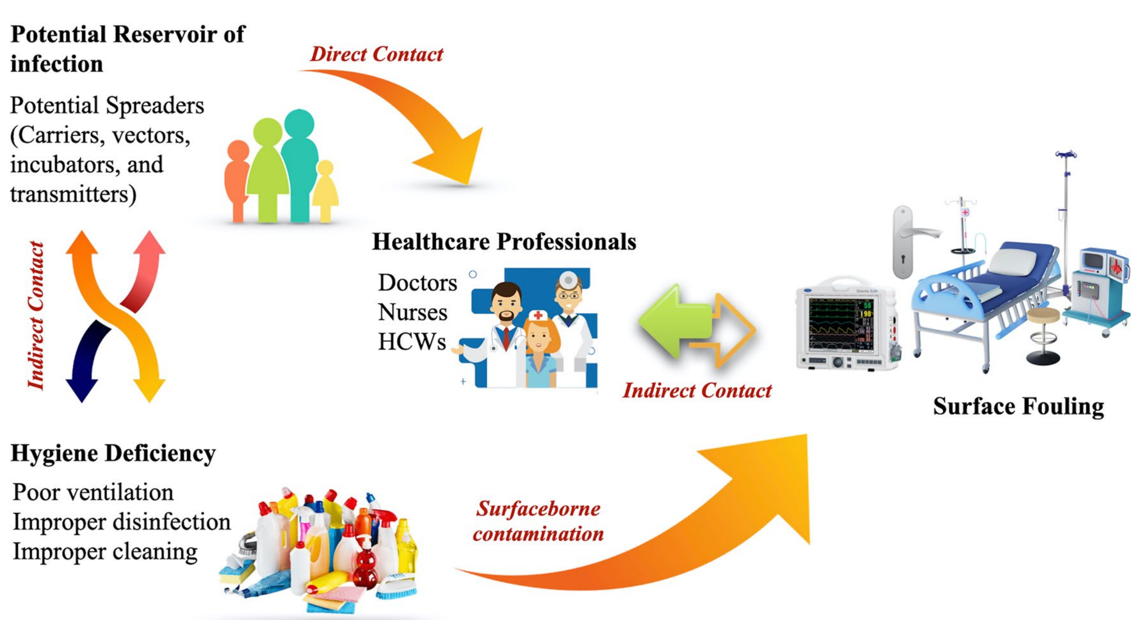


Fig. 3 Major origins, reservoirs, and trends in the transmission of pathogens in patients admitted and visiting to hospitals

Nontuberculous mycobacteria (NTM) and Gram-negative (GN) bacteria are commonly linked to the first four modes of transmission, including contact, droplet, airborne, and vector-borne, according to studies by Sehulster et al. (2003). In addition to being linked to various different mechanisms of transmission, NTM and Acinetobacter species may also thrive in moist settings. According to the study, a number of sources, including air conditioning units, ornamental fountains, showers, respiratory therapy devices, humidifiers, and taps, develop contaminated aerosols that are associated to pathogen outbreaks in hospital settings (Kanamori et al. 2016). According to studies by Beggs et al. (2015), *S. aureus* can travel through the air from contaminated mattresses and clothing, depositing itself on a variety of surfaces. It has been reported that patients may come into direct contact with *Legionella* and other GN bacteria like *Pseudomonas* through the aerosols produced by showers and faucets. Moreover, microorganisms including *Legionella, Pseudomonas, Aeromonas, Burkholderia, Acinetobacter*, ESBL-producing and carbapenem-resistant *Enterobacteriaceae*, *Aspergillus*, and NTM, are able to transmit through water causing rise in HAIs. The healthcare environment, especially hospital water systems, is shown to be a significant reservoir of *Pseudomonas* spp. According to studies, hospital water systems are the primary source of *P. aeruginosa* propagation (Juan et al. 2017).

Transmission through direct contact or indirect contact

Vulnerable patient groups, particularly those who work in healthcare facilities, are at high risk of developing infections owing to these kinds of transmission. Another study found that HCWs who come into contact with patients who are sick either directly or indirectly through contaminated high-touch surfaces may pass along MRSA to patients (Boyce et al. 1997). Person-to-person transmission of VRE when exposed to contaminated HCW hands, contaminated surfaces, and equipment such as thermometers and electrocardiogram machines, as well as previous exposure to VRE-contaminated rooms, according to one recent study, are all risk factors for VRE acquisition (Drees et al. 2008; Falk et al. 2000). Pathogenic bacteria, such as *C. difficil*e, VRE, and MRSA, have been found frequently persist on hospital floors and may come into contact with HCW by means of frequently touching objects (as schematically depicted in Fig. 3), yet they are often overlooked as potential sources of infection transmission (Koganti et al. 2016).

Transmission through low or high-touch surfaces

Additional studies have shown a number of surfaces that are susceptible to infection and aid in the spread of pathogens, including those near patients like bedrails, bedside tables, taps, and knobs in wards (Allegranzi et al. 2007). Additionally, "non-classical" surfaces such as oxygen humidifiers, medical workers' personal computers, and the protective lead jackets worn in operating rooms are all linked to transmission. Considering the possibility that they could get infected while performing caregiving responsibilities by getting interaction with contaminated objects or infected individual (Allegranzi and Pittet 2009; Squeri et al. 2016). Another research discussed concerning the prevalence of *A. baumannii*, a bacterium which is considered more resistant to dry surfaces than *E. coli* and can survive there for longer than 4 months and can remain on glass surfaces for more than 20 days when left at ambient temperature. This demonstrates the toughness of *A. baumannii* and its ability to survive for a long time on inanimate objects (Lee et al. 2011). *Clostridium difficile,* a type of bacteria which is known to cause HAI, has been identified on several high-touch surfaces and equipment within healthcare facilities. Moreover, the hands of healthcare professional, cellphones, computers, doorknobs, medical equipment such as pulse oximeter finger probes and electronic rectal thermometers, prescription carts, bed, mop pads, portable beds, and sinks, aid in transmission of various pathogens (Sooklal et al. 2014; Dumford et al. 2009; Best et al. 2010). In neonatal and critical care units, which are high-risk environments for contamination, there has been an increase in the frequency of infections brought on by *C. parapsilosis* over the past 20 years (Guinea 2014). Based on a review (Ramasethu 2017), HCW represent a substantial source of microorganism transmission in neonatal care. According to the analysis, bacterial counts on healthcare professionals' hands range from 3.9×10^4 to 4.6×10^6 CFU/cm^2 (Bolon et al. 2016), potentially containing bacteria such as *S. aureus*, *K. pneumoniae*, Enterobacter, Acinetobacter, and Candida. Human skin sheds live organisms on a daily basis, which adds to contamination of patient clothing, bed linen, and furnishings. Transmission occurs when healthcare personnel' hands are not properly washed or disinfected before and after contact with patients. Even in the absence of prior colonization, *C. parapsilosis* can survive and proliferate in hospital settings by horizontal transmission from medical devices or outside sources (Trofa et al. 2008). According to the literature (Schechner et al. 2011), contamination by *P. aeruginosa* is also found out as a significant cause of several kinds of infections in healthcare such as burn wound infections BWI, and NB, with a mortality rate exceeding 30%. These infections can be quite threatening for individuals who are having a weaker immune. The importance of improved cleaning procedures in reducing the spread of MRSA and VRE in hospital rooms previously occupied by patients colonized with these pathogens were demonstrated in one of the studies by Datta et al. (2011). Moreover, the recent investigations by Akiko et al. (2017) examined the *S. aureus* isolates swabbed from the palms and fingers of mobile phone users and from their respective mobile phones. The findings imply that mobile phones may serve as a potential reservoir for the spread of infection in hospital environments. The study emphasized the significance of using proper hand hygiene prior interacting with patients, which remains to be the most effective way to decrease HAIs. Even so, MRSA and *S. aureus* could also cause serious infections notably CRI, BI, lung infections, and wound infections (Bal et al. 2016). *Staphylococcus aureus* is noteworthy as the second-most common cause of HAIs poses a serious threat to the safety of patients and their treatment (Smith and Hunter 2008; Dantes et al. 2013). Research has demonstrated that the presence of a biofilm matrix can increase resistance to disinfectants, as it encapsulates and protects the underlying cells (Percival and Cutting 2010; Abdallah et al. 2015). Another recent study by Dancer et al. (2019) used well-established staphylococcal epidemiology techniques to investigate *S. aureus* transmission routes within a 10-bed intensive care unit. Over the course of 10 months, the study thoroughly screened a variety of hand-touch surfaces, staff members' hands, the air, and patients, followed by spa typing, epidemiological analysis, and whole-genome sequencing. The findings showed that there were several cases of transmission between patients and different ecological repositories. The findings provide significant data for the implementation of successful preventative and control strategies as well as for a better understanding of the epidemiology of *S. aureus* in hospital settings. It is also observed that *S. aureus* can easily be spread by the touch and has been proven to stay on surfaces for lengthy periods of time, up to 7 months (Kumari et al. 1998). Among the most recent investigations, Samreen et al. (2023) evaluated the prevalence of *S. aureus* in the hospital environment by collecting 245 environmental samples from a 1030-bed tertiary care hospital. The percentage of *S. aureus* contamination on hospital environmental surfaces in the current study was noted to be 19.1% which was comparable to prior research in Pakistan (Khattak et al. 2015). The hospital environment's role in the transmission of HAIs is still being debated, but there's scientific evidence that nosocomial bacteria can exist as a significant reservoir in various hospital environments such as surfaces, medical equipment, and water systems. Contamination can occur as a result of patients, their family, or healthcare employees, while improper antibiotic administration may result in the selection of multi-drug resistance microorganisms that can thrive and spread within the hospital. Additionally, healthcare workers behavior can facilitate pathogen cross-transmission via environmental and patient-to-patient routes. Proper and routine hospital environmental cleaning, antibiotic management, and educational initiatives aimed at promoting appropriate behavior among healthcare staff are potential answers to this problem.

Strategies for tackling MDRO and mitigating antibiotic resistance in nosocomial infections

In the current scenario, patients referred to hospitals frequently acquire infections triggered by MDR bacteria, which frequently leads to complications and increased mortality rates. The transmission of these diseases in the healthcare is linked to a number of different circumstances. It is critical to implement preventive measures at several levels to precisely address these elements in order to disrupt the transmission chain (Schinas et al. 2023). Preventive measures such as isolation protocols and environmental cleaning are critical in preventing MDR bacteria cross-contamination and dissemination. Despite ongoing issues in achieving compliance, monitoring and resolving hand hygiene adherence are critical components of healthcare hygiene practices. Innovative technology, such as advanced disinfection methods and stringent monitoring systems, can help to reduce the impact of MDR bacteria transmission (Boyce et al. 2016a; Brêda, et al. 2021). Furthermore, advances in healthcare architecture and hospital engineering have demonstrated remarkable possibilities for combating MDR transmission (Elbehiry et al. 2022).

Hand hygiene

The recently published update of "Strategies to Prevent Healthcare-Associated Infections through Hand Hygiene" by the Society for Healthcare Epidemiology of America (SHEA), which was put together through a robust joint effort by numerous notable organizations, has comprehensively addressed the essential practices for preventing HAIs in the healthcare, particularly in ICU (Glowicz et al. 2023). Advocating for the hygiene of the hands and fingernails, using alcohol-based hand sanitizers (ABHS) in various clinical situations, and complying to hand hygiene protocols outlined by the CDC or WHO (prior to patient contact, before aseptic procedures, after exposure to body fluids, following patient contact, and after touching the patient's surroundings are practical guidelines that promote hand hygiene in acute-care settings (Chou et al. 2012). Promoting short, natural fingernails and making hand moisturizers widely available are essential for reducing dermatitis among healthcare workers. Essential practices also include selecting suitable hand hygiene products, assuring supply accessibility, proper glove use, and minimizing environmental contamination near sinks and drains. According to research, altering washbasin modification, such as increasing washbasin bowl depth and lowering water flow rates, reduces the danger of infection dispersion significantly (Gestrich et al. 2018).

Cleaning of environment

Mechanical, chemical, and human factors are the three basic categories of environmental hygiene interventions. Mechanical interventions, such as plastic isolators, negative pressure ventilation, and air curtains in patient rooms, as well as technologies like as ultraviolet (UV) disinfection and portable high-efficiency particulate absorption (HEPA) filters, have shown efficacy in reducing certain multidrug-resistant (MDR) infections and bacterial contamination on diverse surfaces and equipment in specific environments (Peters et al. 2022). Chemical interventions are frequently used in efforts to sterilize environmental reservoirs of MDRs. Testing numerous active chemicals and formulations, such as ethanol, propanol, formaldehyde, peroxides, inorganic chlorine releasers, and phenol derivatives, is the foundation of sterilization efforts. When selecting disinfectants for use in healthcare, it is critical to evaluate their effectiveness against a wide range of pathogens, including bacteria, viruses, yeasts, mold spores, and bacterial spores (Tapouk et al. 2020).

Determining factors associated with colonization risk

Given the variable efficacy of preventative techniques against specific bacterial species, additional research is needed to find the best effective measures for preventing MDR bacterial colonization. High colonization pressure is typically associated with the proliferation of MDROs in healthcare settings, indicating an increased risk of patient cross-transmission. According to one study, colonization pressure was discovered as an independent risk factor for MDR bacteria in the ICU in a single-center prospective cohort research (Odds Ratio (95% CI) 4.18 (1.03–17.01), $p = 0.046$), emphasizing its importance in contributing to the spread of such organisms (Masse et al. 2017). The recognition of patient risk factors for MDR bacterial colonization in healthcare is a proposed method that could serve as both a preventive intervention and a treatment strategy in certain patient populations, such as immunocompromised individuals.

Monitoring and responsible management of antimicrobials

The ability of physicians, chemists, microbiologists, and infection control specialists to work together effectively is essential to the success of these programs. Understanding the role, paths, and patterns of contamination from the environment in the transmission of MDR bacteria enables physicians and researchers to implement better procedures, reducing risks in healthcare settings. Environmental cultures, including as swab tests, agar slides, and air and water samples, provide vital information about the presence and persistence of MDRs in the environment. These approaches aid to establishing a clearer link between environmental contamination and pathogen uptake. Direct observation, as previously stated, as well as the use of fluorescent markers and adenosine triphosphate (ATP) bioluminescence, are other approaches for objectively assessing environmental cleanliness (Chen et al. 2021).

Contemporary technological innovations in antimicrobial coatings

Active antimicrobial coatings Antimicrobial coatings with active qualities contain antiseptics or antibiotics that are either ionic or covalently linked inside a polymeric matrix (Polívková et al. 2017). Coatings containing noble metals can be injected into or coated onto polymeric surfaces as an alternative strategy (Dizaj et al. 2014). Bactericidal characteristics are exhibited by certain metallic compounds or their oxides, including silver (Ag), selenium (Se), silver oxide (Ag_2O), titanium dioxide (TiO_2), iron oxides (Fe_2O_3, Fe_3O_4), zinc oxide (ZnO), and copper oxide (CuO). These materials can be used in the form of nanoparticles or ions, especially when the increased toxicity of the bulk metal is a concern for in vivo applications (Barnes et al. 2019; Gusev et al. 2022; Kranz et al. 2019; Toplitsch et al. 2021). Due to its exceptional antimicrobial activity, coatings containing zinc oxide (ZnO) and silver oxide (Ag_2O) have recently gained popularity, owing to breakthroughs in nanotechnology (Dizaj et al. 2014).

Antimicrobial metal coating For more than three decades, silver has been widely studied for its antibacterial characteristics. It has been used successfully in applications such as urinary catheters. It is now being investigated as a covering for endotracheal tubes (ETTs), which are a substantial contributor to VAP infections. Silver coatings have now been commercialized for medicinal uses due to their success in several clinical trials (Kollef et al. 2008).

Antimicrobial photodynamic therapy (aPDT) Antimicrobial Photodynamic Therapy (aPDT) is made up of three main components. It requires a visible light source with a certain wavelength to properly activate the photosensitizer, a non-toxic photosensitizer (PS), and the presence of ambient oxygen. When initiated, this process produces cytotoxic reactive oxygen species (ROS), which cause the targeted cells to be inactivated. It has recently emerged as a unique and noninvasive therapeutic approach, with success in treating localized and superficial infections caused by bacteria in biofilms, fungi, and viruses. This novel process offers novel therapeutic approaches and has implications in dentistry for the treatment of biofilm-caused oral infections (Koshi et al. 2011).

Therapeutic mouthwash Therapeutic mouthwash has the ability to improve oral hygiene by lowering dental plaque and gingivitis efficiently. Dental plaque, which is mostly made up of bacteria, creates a biofilm on teeth and can cause dental decay and gum inflammation. Mouthwash's antibacterial qualities contribute to its antiplaque efficiency, using common antiseptic components such as chlorhexidine (CHX), Listerine and essential oils. CHX is widely used as a disinfectant in a variety of medical sectors, including dermatology and surgery, due to its powerful antibacterial characteristics (Lim 2008). One recent study (Liu et al. 2023) examined on how short-term gargling with chlorhexidine (CHX) and Listerine® mouthwashes affected oral flora in hospitalized patients. According to the findings, both mouthwashes caused considerable changes in the composition of oral bacteria, with differences noted in the specific bacterial genera affected and the magnitudes of these changes. Notably, CHX had more significant effects, but its use has been linked to higher mortality, possibly due to nitrate-reducing bacteria. Listerine, despite exhibiting lesser magnitude changes than CHX, targeted bacterial species that were less related to nitrate reduction.

General practices for cleaning applied in healthcare

Microorganisms have the ability to survive on surfaces for extended periods of time and can transmit to patients through direct contact with nearby surfaces or indirectly through the hands of HCWs, particularly in situations where HCW hand hygiene compliance is low, with reported rates hovering around 40% (Otter et al. 2011; Sunkesula et al. 2017). Many investigations have shown that if persistent surface contamination remains after terminal cleaning and disinfection, subsequent patients have a chance of contracting the same pathogen as the prior individual (Mitchell et al. 2015; Chen et al. 2019; Shaughnessy et al. 2011). The findings of the Researching Effective Approaches to Cleaning in Hospitals (REACH) trial show that comprehensive environmental cleaning has a substantial influence on the prevention of HAIs (Mitchell et al. 2018). Various studies have suggested to implement a comprehensive cleaning strategy that must incorporate training, technique, product, audits, and communication components, and the performance and the knowledge services staff could be improved (Mitchell et al. 2018; Mitchell et al. 2019a; Hall et al. 2020). Enhanced cleaning and disinfection techniques have been shown to reduce the prevalence of HAIs (Donskey 2013). Additionally, Dancer et al. (2009) demonstrated the inclusion of an extra environmental cleaning services to perform enhanced hand-touch site cleaning in surgical wards having high prevalence of *S. aureus* resulted in a 32.5% reduction in microbial contamination levels and a 26.6% decrease in new MRSA infections in comparison with control wards. Also, the enhanced terminal cleaning resulted in a 94% reduction in contamination with epidemiologically significant pathogens, according to a prospective research by Rutala et al. (2018).

It is vital to distinguish between critical and non-critical surfaces as well as low-touch and high-touch surfaces when assessing risks related to patient care, staff safety, and pathogen transmission. Low-touch surfaces, such as floors and walls, are less likely to have contact with skin since they are not often handled by patients or HCWs. On the other hand, because it is close to patients and are frequently touched by HCWs, high-touch surfaces like bedrails, door knobs, and medical equipment pose a serious threat of spreading diseases (Weber et al. 2010; Kirk Huslage 2010; Adams et al. 2017; Otter et al. 2011; Boyce et al. 1997; Koganti et al. 2016; Sunkesula et al. 2017). The fact that surfaces and locations outside the patient zone, such hospital canteens or elevator buttons, can potentially host germs, makes them it a significant concern (Christiansen et al. 2004; Matthew Mulle and Armstrong 2018). However, critical surfaces have a higher risk of infection than non-critical surfaces since it comes into contact with objects like needles and intravenous catheters, as well as blood and intravenous catheters (Diseases and Organisms in Healthcare Settings 2016; Friedman et al. 1996). As a result, there is a substantial risk of infection even from low-touch surfaces used for medical procedures or the administration of intravenous medication. In order to reduce the transmission of infections, it is imperative to adopt the proper cleaning and disinfection methods for all types of surfaces.

Cleaning is the process of physically removing dirt and dust until the area is clearly clean using water, either with or without detergent, and physical action. To reduce the danger of infection and prevent cross-contamination, disinfection, on the other hand, aims to eliminate the majority or all harmful bacteria (Matthew Mulle and Armstrong 2018; Peters et al. 2018; Rutala et al. 2008). Disinfection is typically done in conjunction with cleaning to lessen the impact of organic matter and the amount of contamination. Because of this, normal cleaning and disinfection are frequently integrated, performed once daily on general wards, as well as in targeted measures immediately after surfaces are contaminated with blood or other human fluids (Christiansen et al. 2004; Matthew Mulle and Armstrong 2018). If necessary, a disinfectant is often used for cleaning. Once a patient has been released, terminal cleaning and disinfection is carried out in order to stop the spread of dangerous infections to the subsequent patient using a hospital room. In this process, surfaces that are generally hard to reach when a room is occupied, including the mattress and other ones that could have gone unnoticed during the patient's stay, are cleaned in addition to those that are routinely cleaned (WHO 2019).

An overview of commonly employed disinfectants for cleaning and disinfection

There are a number of novel disinfection products on the market or in research, in addition to the frequently utilized disinfectants like alcohol, chlorine, aldehyde, amine, oxidative (such hydrogen peroxide and peracetic acid), phenolic and quaternary ammonium compounds. They include liquid disinfectants that contain enhanced hydrogen peroxide, peracetic acid and hydrogen peroxide combinations, hydrogen hypochlorite, and polymeric guanidine. Additionally, there are cleaning/disinfectant products that combine both functions available on the market (Matthew Mulle and Armstrong 2018; WHO 2019). However, with the benefits, there are several significant drawbacks of using such disinfectants that must be considered (see Table 3).

No-touch UV disinfection systems: exploring microbial control strategies with disinfection technologies

Surfaces in health centers are frequently infected with harmful microorganisms that may endure routine cleaning and disinfection (Rutala and Weber 2013). The utilization of hydrogen peroxide mist, vapor, or UV radiation is what has conventionally been the focus for most of the studies in regards of no-touch disinfection systems (Simmons et al. 2013; Rutala and Weber 2016b; Sitzlar et al. 2013). Additional no-touch methods, such as high-intensity narrow-spectrum light, quaternary ammonium fogging, and alcohol-mist (Jury et al. 2010), ozone gas, superoxide water, and steam vapor, have also been developed (Sexton et al. 2011). The use of no-touch automated disinfection (NTD) is a successful and promising method for lessening the prevalence of HAIs. NTD systems use a variety of disinfectants to clean surfaces and equipment in healthcare facilities, including vaporized hydrogen peroxide (VHP), hydrogen peroxide vapor (HPV), chlorine dioxide, gaseous ozone, dry mist of hydrogen peroxide (DMHP), and aerosolized hydrogen peroxide (aHP). To increase the effectiveness of these disinfectants, they are frequently combined with other substances including silver cations, aerosolized peracetic acid, quaternary ammonium compounds, high-intensity narrow-spectrum (405 nm) light, ultraviolet (UV) light-emitting diode and pulsed-xenon UV (PX-UV) radiation. Healthcare facilities can successfully lower the risk of HAIs by implementing NTD systems, which might also improve patient health outcomes, lower healthcare costs, and maximize patient satisfaction (Aljerf 2016). NTD systems are especially helpful in settings with complex equipment or high-touch surfaces when conventional cleaning and disinfection techniques are ineffective or impractical (Dancer 2014; Rutala et al. 2008; Otter et al. 2014).

UV radiations

When compared to aHP systems, germicidal UV-C radiation disinfection is much quicker. It provides methods that are controlled and effective for eliminating bacterial contamination specially within medical facilities. Healthcare facilities can offer a secure environment for patients and healthcare staff and lower the risk of HAI by implementing these no-touch disinfection techniques (Kelly et al. 2022; Andersen et al. 2006). UV light refers to radiation with wavelengths between 100 and 380 nm. It is divided into three zones: UV-A (320–380 nm), UV-B (280–320 nm), and UV-C (100–280 nm). UV-A, comprising about 6% of solar energy, is considered the least harmful. Conversely, UV-B, accounting for approximately 1.5% of UV light, can have adverse effects on plants. The most harmful type, UV-C or deep UV-C, poses severe risks to living organisms. Thankfully, the ozone layer acts as a natural shield, absorbing most UV-C radiation, safeguarding the Earth's biosphere from its harmful impact. Short-wavelength UV radiation (UV-C in the 200–280 nm range) causes DNA/RNA damage in microorganisms, hindering cellular metabolism and replication. Employing portable UV-C lamps or ceiling-mounted fixtures for microbial decontamination significantly contributes toward the disinfection processes (Guerrero-Beltr and Barbosa-C·novas 2016; Hollosy et al. 2002; Conner-Kerr et al. 1998).

Development of UV-based technologies for disinfection purpose

Mercury vapor technologies Low-pressure mercury (Hg) vapor lamps are the conventionally used in UVGI air disinfection applications. Although these lamps resemble conventional Hg fluorescent bulbs, there are two key distinctions. First off, there is no fluorescent phosphor in the lamp's tube. Second, fused quartz is employed to build the tube rather than glass. Commercially available lamps are essentially divided into two groups: low output powered by traditional magnetic ballasts; high output powered by electronic ballasts (Van Osdell et al. 2002). Many variables, including lamp pressure, electrical current, voltage, excitation waveform, discharge ignition, and internal gas composition, have an impact on the energy production and spectrum properties of lamps. The high-output lamps are driven at greater power by increasing the current input into the bulbs to produce more output radiation, whereas low-output lamps are normally operated at low power. LP amalgam lamps are one of the newer technologies produced by recent improvements in

Table 3 Summary of benefits and drawbacks of conventionally used disinfectants for cleaning and disinfection

Disinfectants used	Benefits	Drawbacks	References
Alcohol (60–80%)	Effective against bacteria, fungus, viruses, mycobacteria Harmless Inexpensive Rapid acting Non-staining Non-corrosive Can be submerged for cleaning	Requires cold storage Requires a ventilated environment for storage Flammable May dissolve shellac lens mountings Coagulates protein Can harden or swell plastic tubing Harmful to silicone Can cause glue to degrade Can render brittleness Neutralizes organic materials	Sehulster (2003), Rutala and Weber (2016a), Canada (1998), Omidbakhsh et al. (2014)
Sodium Hypochlorite (Bleach)	Effective against bacteria, fungus, viruses, mycobacteria Inexpensive Quick acting Non-flammable Resistance to water hardness Safe and dependable	Requires a higher concentration to effectively serve against microorganisms Corrosive to metals Can be neutralized by organic material such as blood Can cause skin irritation Should be immediately used after dilution Should be stored in closed containers Should be stored away from heat Can cause degradation	Rutala and Weber (2016a), Canada (1998), Han et al. (2015)
Hydrogen Peroxide Solution (0.5%)	Non-toxic Environmentally Sage Works swiftly Non-corrosive Non-flammable Non-staining Active with organic compounds Serve as good cleaning agent	Should not be used on non-ferrous metals such as copper and brass	Rutala and Weber (2016a), Canada (1998), Rutala et al. (2008)
Hydrogen Peroxide Solution (4–5%)	Harmless Provides environmental protection Effective against spores	The gel formation allows the disinfectant to stick to vertical surface Expensive Not recommended for screens, monitors, televisions	Rutala and Weber (2016a), Han et al. (2015)
Phenol	Non-flammable Non-staining Can serve as additional detergent for cleaning purpose Effective against microorganisms	Poses threat to infants and newborn Not recommended to apply it on equipment that comes near to infants Not recommended to apply them to areas that come into contact with food Has the ability to absorb through the skin Leaves a coating on ambient surfaces Penetrates porous materials	Rutala and Weber (2016a), Canada (1998), Han et al. (2015), Rutala et al. (2008)

lamp hardware which can have input conversion efficiencies that are greater than 38%, and operate at higher temperatures (Miller et al. 2013). A germicidal lamp emits UV radiation in the 200–300 nm region (Ryan et al. 2010; Kowalski et al. 2009). LP mercury systems do not have spectral emission profiles. They effectively emit monochromatically at 254 nm. The very small 185 nm peak is filters by the quartz sleeve (Kowalski et al. 2009). In contrast, an MP lamp emits a wide spectrum of wavelengths from 200 to 600 nm and is mostly utilized for advanced oxidation, water treatment, and surface treatment (Kowalski et al. 2009; Kowalski 2009). Mercury-based UV-C lamps are still employed in UVGI systems despite the fact that Minamata Convention on Mercury's 2013 which made a stipulation against any device containing mercury be banned by 2020 for the protection of human health and the environment. Nonetheless, as shown by recent research in this field, attempts are still being made to substitute out such lamps with UV-C-LEDs (Kessler 2013). The production of ozone using LP mercury lamps is constrained by technical and financial factors including efficiency and lamp lifetime, according to one of the recent researches by Levin et al. (2013). Nevertheless, LP lamps are now more efficient and dependable as a source of visible (V) vacuum UV ozone formation. In one research, the author contrasts the effectiveness of LP UV irradiation with UV-LEDs against *E. coli* and MS-2. The study achieved 4-$\log_{10}$ reductions in *E. coli* and reduction in non-enveloped virus (MS-2) with both lamp and LEDs at 260 nm (Sholtes et al. 2016).

Limitations Despite its advantages and germicidal potency, the lamp continues to have a lot of shortcomings. For monochromatic performance, the lamp works at around 130 degrees Celsius, and for polychromatic activity, at a minimum temperature of 300 °C up to more than 500 °C. Also, MP only have a maximum lifespan of 8000 h before they need to be replaced, and LP have a limited lifespan of 8000–10,000 h throughout the germicidal UV lifecycle.

Development of PX-UV technologies PX-UV, which uses intense UV light pulses to deliver a powerful germicidal effect, is a possible alternative to traditional UV technologies. Since PX-UV exposure is rapid and intense, it could take less time to reach fatal dosages, making it a desirable alternative. PX-UV light, as opposed to other UV lamps, may be more efficient due to its broad spectrum and higher intensity. In a laboratory environment, PX-UV is a strong substitute for conventional UV methods for producing germicidal effects (Levin et al. 2013). According to study by Haddad et al. (2017), using PX-UV as an additional step to a regular cleaning routine causes levels of bacterial contamination to drop. Studies by Jinadatha et al. (2014, 2015) found PX-UV as an effective technology by successfully reducing the presence of identified pathogens in comparison with conventional manual room terminal cleaning by offering an efficient and effective method of disinfection. A source of UV that is not abundantly observed in commercial disinfection equipment is xenon. The absence of mercury vapor has been described as one of its primary benefits over LP. In contrast to mercury, it produces UV radiation using Xenon gas, which hold promise in generating UV-C with a wavelength range of 185–600 nm (Chemaly et al. 2014; Bolton et al. 2008).

Limitations The primary disadvantages of xenon lights are related to their operational requirements, which result in significant power consumption and high working temperatures of about 500 °C, requiring considerable maintenance, warmup requirement etc. Moreover, the lamp's lifespan is limited and its output light consistency is inefficient, necessitating frequent lamp replacement that simultaneously add huge cost to the users (Lamont et al. 2004).

Development of UV-LED technologies The research and development industries have given UV-LED technology a significant amount of focus, which has caused a surge in UV-LED producers in recent years. UV-LEDs have proven to be a strong contender, especially for disinfection applications, due to the rapid advancement that is replacing conventional disinfection techniques. Advancements in nitride semiconductors have led to the commercial availability of UV-C LEDs. III-nitrides, which emit UV light at wavelengths spanning from 210 to 365 nm, are the most widely used UV-LED materials. Examples include gallium nitride (GaN), aluminum nitride (AIN), and aluminum gallium nitride (AGaN) (Jang et al. 2010). According to recent research, UV-LEDs are a useful tool for disinfecting water, food, and healthcare applications since they are most efficient at germicidal activity with wavelengths between 100 and 300 nm (Khan et al. 2005), since Pankove et al. created the first AGaN LED in 1972 (Crawford et al. 2005), which have advanced in a remarkable way. These LEDs have broad spectrum, spanning from infrared to UV spectral ranges attributed to the widespread usage of group III nitride materials (Pankove et al. 1873). The development of high-efficiency deep UV-LEDs as a potential replacement for low-pressure mercury lamps has been encouraged by the International Minamata Convention of 2013, which aims to protect the environment. These LEDs have flexibility to change the light-emitting band by modifying the epitaxial structure, making them suitable for a variety of applications. It should be noted, nevertheless, that some organic substances can release UV-C radiation. Organic molecules are colorless in solution and transparent to high-energy light in the UV (200–400 nm) and visible (400–700 nm) regions of the electromagnetic spectrum (Han et al. 1998; Lambert et al. 1998).

Limitations In spite of the numerous advantages of UV-LEDs, such as their potent antibacterial properties, compact package sizes, extended lifespan, affordability, and low operating voltage and temperature, they do have certain limitations. Notably, UV-LEDs tend to offer lower intensity and face challenges in achieving high irradiance at longer distances, in comparison with traditional lamps. However, recent research has indicated the possibility of enhancing the intensity and improving the disinfection capabilities by integrating multiple arrays of LEDs into a single circuit.

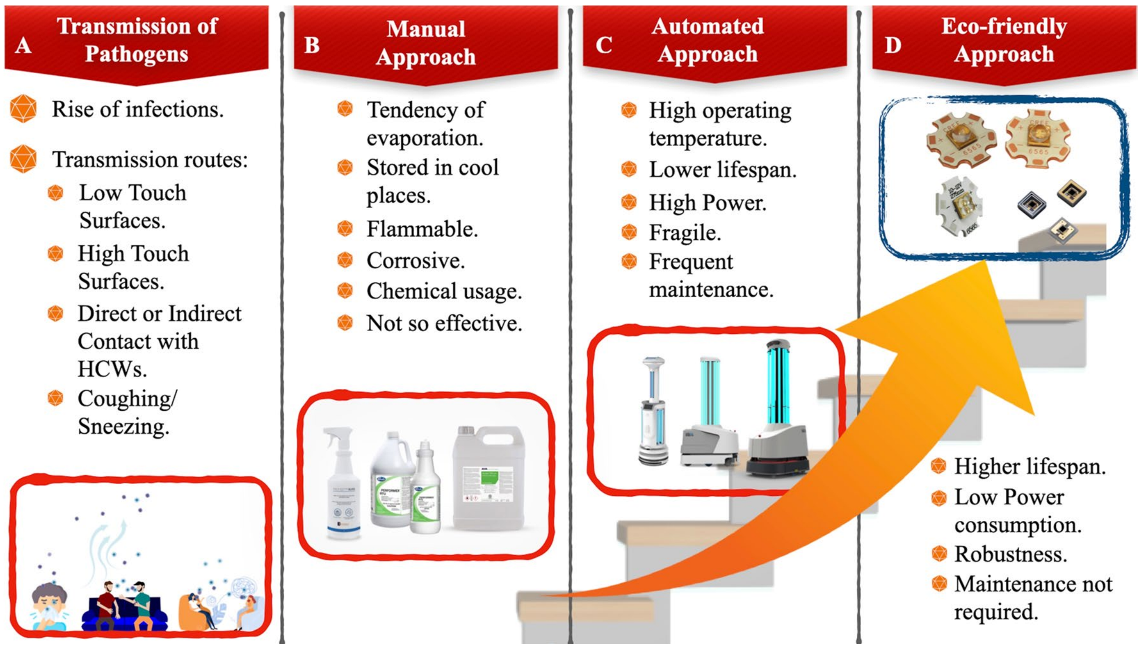


Fig. 4 The progression of technology from traditional methods to modern innovations. **A** Microorganism and pathogen transmission pathways, **B** manual cleaning method by employing liquid disinfectants, **C** robotic disinfection systems that use mercury vapor or Xenon gas for UV– C generation, **D** UV-C LEDs directly mounted over SMD chips which comes in various package sizes

Overall, the use of no-touch disinfection sources that employ UV-C is replacing the use of chemical disinfectants in the context of environmental cleaning, which is experiencing a technological revolution depicted in Fig. 4. Despite the fact that UV-C has been shown to be effective against bacteria and viruses, advances in UV-C technology have compelled professionals to come up with a tool that is robust, energy-efficient, operates at lower temperatures, and is inexpensive. In such regards, UV-C SMD LED sources have exhibited various advantages to accomplish overcome the limitation posed by traditional UV lamps. The comparison of aforementioned commercially available UV sources is compared in Table 4.

UV absorption, penetration, spectral power distribution (SPD), and penetration depth to human skin

Radiation having wavelengths between 100 and 380 nm is referred to as UV light. UV-A (320–380 nm), UV-B (280–320 nm), and UV-C (100–280) are the three zones that fall under such category (Guerrero-Beltrán et al. 2004). UV-A's spectrum is thought to be the least damaging region of the UV radiation spectrum and makes up around 6% of all solar energy. Contrarily, UV-B is known to have a variety of negative impacts on plant while making up just around 1.5% of the entire UV light spectrum.

Table 4 Comparison of commercially available UV technologies

	Mercury vapor lamp	PX UV lamp	LEDs	References
Power Requirement (W)	~15–1000	~500	1-10	Kushwaha (2011), Miyashita et al. (2001), Arques-Orobon et al. (2020)
Warm up requirement	Yes	Yes	No	Kushwaha (2011), Sheikh et al. (2023)
Warm up time (min)	~15	No	No	Sheikh et al. (2023), NLPIP (2010), Gaston et al. (2012)
Heat generation (°C)	~500–950	~500	Negligible	Sheikh et al. (2023), Gaston et al. (2012)
Lifecycle (h)	~8000	~463	~9000/15,000	Gaston et al. (2012), Rajkhowa (2020)
Fragile	Yes	Yes	No	Kushwaha (2011)
Mercury content (mg/lamp)	5–200	No	No	Bolton et al. (2008)
Hazardous	Yes	Yes	No	Kim et al. (2016)
Maintenance	Yes	Yes	No	Sheikh et al. (2023), Claus (2021)

The most harmful kind of UV radiation, known as UV-C or deep UV-C (Sharma and Demir 2022), is capable of severely damaging living organisms. Yet, the ozone layer in the stratosphere serves as a natural filter and absorbs most UV-C radiation, protecting the Earth's biosphere from its negative affects (Hollosy et al. 2002). Microorganisms undergo DNA/RNA damage from short-wavelength UV radiation in the 200–280 nm range, or UV-C. This damage actively prevents cellular metabolism and replication. Using either portable UV-C lamps or ceiling-mounted UV-C light fixtures to irradiate various surfaces and spaces for microbial decontamination can enhance the disinfection effectiveness of UV-C radiation (Kowalski et al. 2009). Pyrimidine dimerization is associated with increased incidence for the photoinduced harm caused to microorganism's DNA and RNA. Particularly, thymine, which is only found in DNA, produces cyclobutene dimers when exposed to UV light. This dimerization prevents nucleic acid replication, and even when replication does occur, it typically produces errors that make the microbe unviable (Conner-Kerr et al. 1998). UV-A is nearly visible and is known to cause damage to skin cells. Due to its shorter waveband, UV-B is also a significant contributor to skin damage and sunburn throughout the day. Both UV-A and UV-B cause harm to our skin because of its deep penetration into human tissue (Kowalski 2009). It is known that all UV wavelengths have some photochemical effects, but high-energy photons in the UV-C range preferentially harm cells as they are absorbed by proteins as well as DNA and RNA (Fig. 5A). The germicidal peaks between 260 and 265 nm, which also happens to be when bacterial DNA and RNA absorbs the most UV energy (Kowalski et al. 2009). Figure 5C depicts spectral comparisons between different UV light sources in relation to the typical absorption spectra of DNA/RNA (also known as the germicidal effectiveness curve (GEC)) and the absorption spectrum of proteins. As demonstrated in Fig. 5C, low-pressure mercury lamps are particularly effective at killing pathogens since they emit the majority of their optical output (around 85%) at a wavelength of 254 nm, which is quite close to the GEC peak (260–265 nm). Recently, excimer lamps have also gained popularity due to their emission at 222 nm, which is thought to be safer due to their shallow depth of penetration in human tissue (Fig. 5B). The 254 nm UV-C range is largely absorbed by DNA/RNA, as shown in Fig. 5B, and it can penetrate further into the epidermal layer of the human skin and disrupt DNA in skin cells, which may lead to the development of cancer. The polychromatic emission pattern of MP UV lamps has a strong peak at about 365 nm. Figure 5C illustrates the monochromatic emissions of LP UV lamps, which are instead centered around 254 nm. LP UV lamps have been

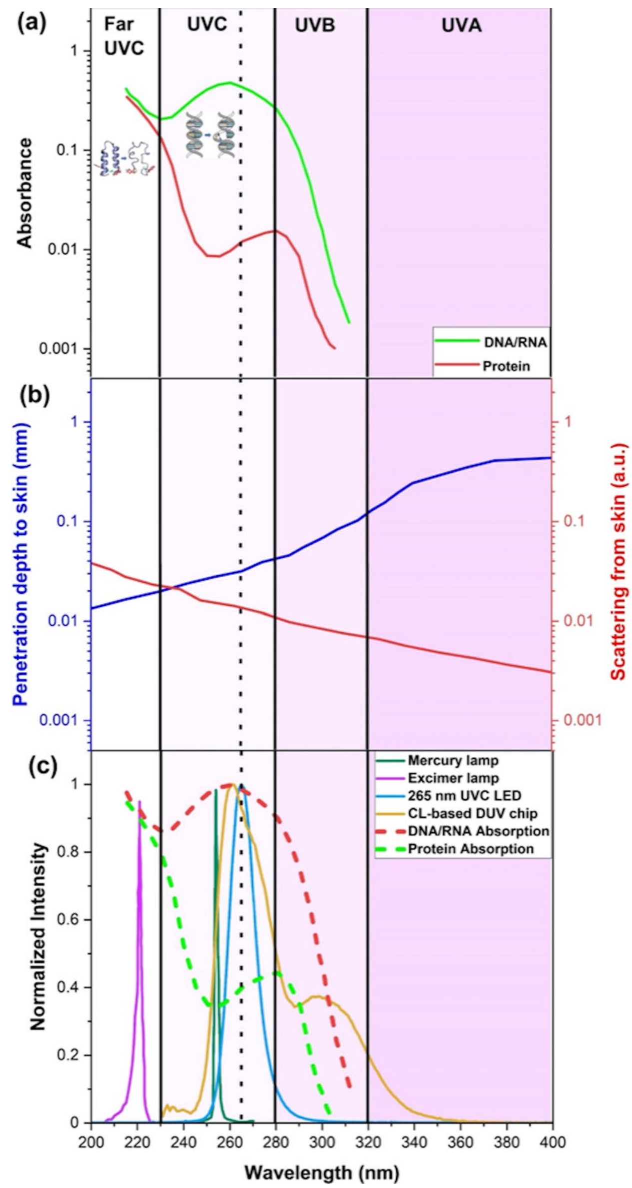


Fig. 5 **A** The absorption spectrum for DNA and RNA, also known as the germicidal effectiveness curve, peaks at 265 nm (shown with a vertical dashed line). While the absorption spectrum for proteins tends to increase toward shorter wavelengths. **B** The wavelengths showing the depth to which UV radiation can penetrate human skin in addition to the degree to which it scatters. The penetration depth and scattering values are specifically 18 μm, 27 μm, and 32 μm over the wavelengths of 222 nm, 254 nm, and 265 nm, respectively. **C** The typical absorption spectra of DNA/RNA and proteins are compared to those of various UV-C light sources. Reprinted from "Bright Future of Deep-Ultraviolet Photonics: Emerging UVC Chip-Scale Light-Source Technology Platforms, Benchmarking, Challenges, and Outlook for UV Disinfection," Kumar, ACS Photonics, Copyright 2022 (Sharma and Demir 2022)

used in disinfection as a result because their emission is close to the germicidal curve's peak (Schalk et al. 2005). Because the far-UV-C wavelength range only penetrates a relatively small depth into human skin, excimer lamps are thought to be safer than mercury lamps (see Fig. 5B) (Sharma and Demir 2022).

Overall, while UV radiation is highly effective in disinfection, it possesses the ability to penetrate beyond the superficial layers of the skin and reach the epidermal layer where our skin cells are located. When UV radiation comes into contact with these skin cells, it has the potential to induce DNA disruption. This DNA disruption within skin cells can have severe consequences, as UV-induced DNA damage is a well-established risk factor for skin cancers. Furthermore, Erythema develops as a consequence of a photochemical reaction in which the skin turns red as a result of high UV-B and UV-C light exposure, namely about 30 J/cm^2 at a wavelength of roughly 270 nm. Moreover, the initial challenge lies in the fact that UV-C light requires an unobstructed passage to an object in order to disinfect it efficiently. However, it is conceivable that the light will be obstructed by other objects or will only reach one side of the object. This is known as "shadowing," and it indicates an increased risk of active pathogens remaining in places that are not exposed to light (Kowalski et al. 2009; Kowalski et al. 2009; Schalk et al. 2005).

Nevertheless, the compact size of UV-LEDs (Bolton et al. 2008; Khan et al. 2005), on the other hand, stands out as a main advantage, allowing for the combination of single or several wavelength outputs to maximize pathogen inactivation. Furthermore, the availability of UV-LEDs in various compact sizes allows for easy integration into a wide range of applications, particularly those featuring intricate designs. When faced with challenges like shaded areas or obstructed passages that can impede traditional UV disinfection equipment, UV-LEDs emerge as an ideal choice for fostering the development of handheld disinfection systems, employing UV SMD LEDs. This flexibility highlights UV-LEDs' significant potential as a powerful tool in future advancements. In addition, the use of photocatalytic oxidation using titanium dioxide (TiO_2) coating and mild ultraviolet A (UVA) light to reduce bacterial contamination on surfaces has been explored as a promising alternative to conventional disinfection system in one study (Klaus et al. 2003). This method produces reactive OH-radicals that effectively kill microorganisms. Rather than using direct UV-C irradiation, the study deployed focused light guiding and a UVA-transmittant Plexiglass layer to ensure bacterial inactivation across the entire surface, overcoming the challenges posed by shaded and obstructed areas.

Recent studies on microbial inactivation using UV technologies

Mercury vapor lamps inactivation experiments

LPML, in particular, are frequently used as the main UV source for disinfection purposes on an industrial scale due to its high wall plug efficiency, which is over 30–35% (Koutchma et al. 2019). Furthermore, their monochromatic emission is close to the peak of DNA absorption which is about 260 nm (Fig. 7A). Various researches have been conducted to evaluate the efficacy of mercury vapor lamps against environmental bacteria. One of the studies by Correa et al. (2017) assessed the efficacy of a handheld device (Surface UV) against diverse clinical pathogens obtained from various surfaces of a public health hospital by employing LPML for treatment. The study showed reduction by a factor of 6.5, 6.7, 6.2, 5.4, 5.4 and 6.7 $\log_{10}$ inactivation against *S. aureus, S. mutans, S. pneumoniae, E. coli, P. aeruginosa* and *C. albicans*, respectively, upon exposure to the dose of 0.78 J/cm^2, demonstrating a noteworthy reduction in microorganisms in the healthcare setting. Another study addressed the usage of germicidal mercury vapor UV lamp for treating airborne particles, including tuberculosis (TB). The researchers developed a test procedure in a 36 m^3 room where bacterial samples are cultured. Upon treatment, the findings indicated that the concentrations of *B. subtilis*, *Micrococcus luteus (M. luteus)*, and *E. coli* were all suppressed by 50% and nearly 100%, respectively, by a single 15 W germicidal lamp(Miller and MacHer 2000). Another study aimed to determine at what extent an automated UV-C lamp could eradicate bioburden from hospital's computer keyboards. Upon treatment against *Staphylococcus, Streptococcus, Enterococcus, Pseudomonas, Pasteurella, Klebsiella, Acinetobacter,* and *Enterobacter*, a reduction of greater than 99% in bacteria was observed when pre- and post-UV decontamination median CFU counts were compared. The study therefore validated the performance of UV lamps for disinfecting keyboards existed in healthcare (Gostine et al. 2016).

PX-UV lamps inactivation experiments

Several researches have revealed the effectiveness of PPX-UV in reducing the total environmental bioburden, which suggests its potential to be utilized in conjunction with standard cleaning techniques (Green et al. 2017). One study has shown the effectiveness of a UV-C disinfection system (Codonics D6000™) in lessening contamination on mobile device screens and protective cases. According to the study, the Codonics D6000™ PX-UV-C disinfection equipment managed to keep tablets and cell phones used in healthcare facilities disinfected following the routine treatment (Muzslay et al. 2018), proving Codonics D600™ as an effective tool for disinfection. Three distinct types of handheld electronic devices (HEDs) that are regularly used in hospitals were identified as having infections in a various study. The effectiveness of employing UV-Smart® D25 to disinfect these devices with PX-UV-C radiation was investigated by the researchers (Cremers-Pijpers et al. 2021). The study employed 800 samples obtained from two departments. The results showed that colony-forming organisms were present in more than 50% of the initial measurements in moderately or highly contaminated settings. Yet, compared to the original measurement, 87% of samples following disinfection showed no signs of CFU. According to the study, the UV-Smart® D25 could serve as an effective method for routinely disinfecting non-critical HEDs. In Japan, the effectiveness of PX-UV disinfection in reducing contamination of medical facilities was studied. MDRO containing *C. difficile* spores were subjected to PX-UV which are often found in hospitals. The results showed that PX-UV disinfection for 15 min significantly reduced the growth of *C. difficile* spores by more than 3-log CFU/cm^2, while PX-UV disinfection for 5 min significantly reduced the growth of all MDRO by more than 5-log CFU/cm^2. According to the study, clinical MDROs containing *C. difficile* responded effectively to PX-UV disinfection (Kitagawa et al. 2020). In one similar study, the research was carried out in 23 hospitals across the USA to validate the PX-UV disinfection's capability for minimizing contamination on high-touch surfaces in operating rooms (ORs) following manual cleaning. Surface specimens from 732 high-touch surfaces in 136 ORs were obtained. The results revealed that manual cleaning alone only eliminated 67% of the bacteria from surfaces, whereas PX-UV disinfection reduced the number of positive surfaces to 38%, indicating a reduction of 44%. According to the study, PX-UV disinfection, when used after deep cleaning, significantly lowers the contamination on high-touch surfaces specially in ORs (Simmons et al. 2018). The viral load on hard surfaces and N95 respirators was also examined by Simmons et al. (2021) to evaluate the performance of PX-UV disinfection system. According to the findings, the PX-UV disinfection for 1, 2, and 5 min lowered the viral load on hard surfaces by 3.53 $\log_{10}$, > 4.54 $\log_{10}$, and > 4.12 $\log_{10}$. N95 respirators were disinfected with PX-UV for five mins, which lowered the pathogen load by > 4.79 $\log_{10}$. These findings confirmed the efficiency of PX-UV at reducing the load of SARS-CoV-2 on N95 respirators as well as on hard surfaces. Another study assessed the effect of portable PX-UV devices on the microbiological load in four Veterans Affairs hospitals. The study compared the manual cleaning and PX-UV disinfection at two locations. As compared to only 25–30% with manual cleaning alone, the results showed that PX-UV significantly reduced aerobic bacteria counts and MRSA by 75.3 and 84.1%, respectively. The researcher recommends using PX-UV devices in routine cleaning to lessen the infectious burden typically brought on by aerobic bacteria and MRSA (Zeber et al. 2018). Another study looked at how well a PX-UV disinfection system worked to reduce the environmental bacterial load and pathogens that form biofilms on surfaces in clinical laboratories (Chen et al. 2020). According to the results obtained, PX-UV was able to significantly reduce the colony counts of *P. aeruginosa, S. aureus*, and *K. pneumoniae*. The authors suggested the use of PX-UV as a potent UV source for disinfection in clinical laboratories. In a similar research, another investigation examined PX-UV against two *Candida* species: *C. auris* and *C. parapsilosis,* that are commonly associated with epidemics in hospital environments and persist on surfaces for a prolonged time. During a 5 min cycle at 1 m distance, the study reported 99.4 and 98.5% reduction in *C. auris* and in *C. parapsilosis,* respectively, making PX-UV a significant approach for disinfection (Maslo et al. 2019).

UV-C LEDs inactivation experiments

UV-C LEDs have recently come into focus by researchers due to the several advantages over conventional lamps and robots. In one recently investigated study, Nunayon et al. (2020) evaluated the antimicrobial efficacy of upper-room UV germicidal irradiation LEDs (UR-UVGI-LEDs) at 270 nm (schematically represented in Fig. 6) for disinfecting bioaerosols in enclosed environments. The efficiency of the UR-UVGI-LED at 270 nm was contrasted with that of the more traditional UR-UVGI mercury vapor lamps at 254 nm. The results revealed that the effectiveness of both systems for disinfection against *S. marcescens* and *E. coli* was comparable, and that the UR-UVGI-LED system had the most potential to be a credible source of disinfection against indoor airborne pathogens. Another study utilized UV-C LED irradiation to evaluate the antibacterial effectiveness on toilet seats against three bacterial strains (Lai and Nunayon 2021). The study utilized three different combinations (3, 5-two variants, and 8-LEDs), as well as two different 5-LED configurations for evaluation. According to the study, the effectiveness of disinfection initially rose with the number of LEDs but decreased with 8 LEDs. This concluded the mean disinfection efficiency for surfaces and aerosols, which varied from 8.81 to 72.80% and 24.16 to 70.70%, respectively. Another recent review highlighted the key factors which offers several advantages to LEDs in comparison with traditional mercury vapor lamps (MVL), such as longer lifecycle, robustness, compactness, flexibility, and the absence of non-hazardous material. The review found that UV-C LEDs have been applied in various fields, ranging from health applications to wastewater or food decontamination, and in some cases, LEDs even provide better results than MVLs. The complexity of the targets being decontaminated, such as multilayers or thicker individual layers, might, however, reduce the effectiveness of UV-C disinfection (Nicolau et al. 2022). The SMD LEDs are not being in focus by the researchers due to its compact design and availability of various package sizes. One of the most recent studies by Sheikh et al. (2023) evaluated the effectiveness of Everlight's 275 nm UV-C surface mounted device (SMD) against *S. aureus* by quantifying inhibitory zones at varied exposure

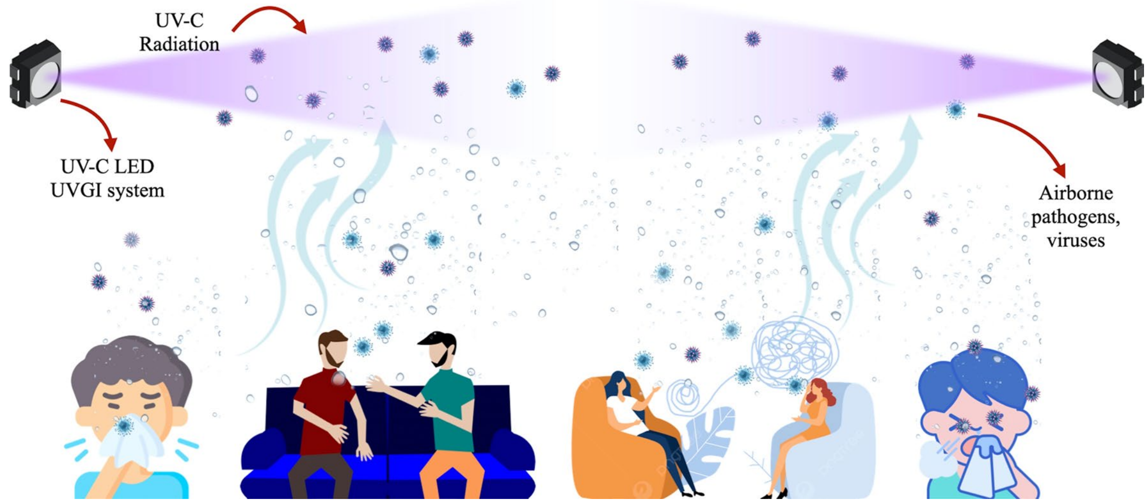


Fig. 6 Schematic representation of UVGI system using LED for disinfecting bioaerosols contamination in an enclosed environment

settings. The results reported that at longer exposure times larger inhibition zones were produced. In a similar study by Sheikh et al. (2021), the impact of 275 nm UV-C LED on human skin fibroblast cells and bacteria (*P. aeruginosa*, *S. aureus)* was investigated for prototyping a wound disinfection system. The study employed quantitative analysis in which bacterial inhibition zones at three exposure distances and two exposure durations were assessed. The results demonstrated that greater inhibition zones were caused by longer exposure durations and distances. The study also confirmed that the low exposure duration did not affect human skin cells and found out the viability within the acceptable level which can be adequate for wound treatment. A regular 3 mm LED emitting visible light was also compared to UV-A LED in one of the investigations by Malik et al. (2017) against *E. coli*. In comparison, the UV-A LED samples reached maximal inactivation with only 0.0043×106 CFU/mL, while the conventional LED, which lacks UV light emission, failed to achieve any microbial inactivation. Another study assessed the inactivation of biofilm-bound *P. aeruginosa* by employing a 265 nm UV-C LED. The bacterial load was observed to reduce to a factor of 1.3 ± 0.2 $\log_{10}$, which was lower than that of planktonic *P. aeruginosa* when inactivated by UV-C LEDs. This result attributed to the greater UV inactivation resistance shown by bacteria that were already attached to biofilms (Gora et al. 2019). In another recent research by Nyangaresi et al. (2023), the efficacy of single UV-C and combined UV-A and UV-C LED irradiation in eradicating various waterborne bacteria was evaluated. The study found that the sensitivity of the different bacteria to UV radiation varied, and that only *E. coli* produced evidence of healing. The synergistic effect seen in *E. coli* and *B. spizizenii* spores was attributable to the different inactivation processes of UV-C and UV-A wavelengths. In comparison with the 267 nm UV-C LED, which had the highest inactivation efficiency, the 278 nm UV-C LED had a better inactivation efficacy and required less energy. Yang et al. (2019) additionally evaluated the Hyper Light Disinfection Robot, an automatic mobile device that used UV-C irradiation to kill pathogens that are MDR, including *P aeruginosa*, *A. baumannii*, MRSA, VRE, *M. abscess*. After 5 min of UV-C irradiation at a distance of 3 m from the device, vegetative bacteria colonies were reduced by a factor of more than 3 $\log_{10}$ with the exception of VRE and *M. abscessus*, proving the device's effectiveness in eliminating MDR pathogens. Also, at a distance of 1 m, substantial reductions in colony counts were seen for all examined microorganisms, regardless of exposure time. The effectiveness of various UV-C radiation wavelengths for inactivating SARS-CoV-2 on high and low-touch surfaces and in indoor air was also examined in the study by Liang et al. (2021). The efficacy of the prototype UV-C light devices was examined using cell-based assays using UV-C light with wavelengths of 275, 254, and 222 nm. The UV-C LED (275 nm), followed by the mercury lamp (254 nm) and the excimer lamp (222 nm), exhibited the best viricidal activity against SARS-CoV-2, according to the data. In comparison with the other lights, the UV-C LED (275 nm) showed superior SARS-CoV-2 disinfection activity. Furthermore, in one study, the effectiveness of 222-nm UV-LED in eradicating MRSA and aerobic bacteria (AB) on mobile phone surfaces was investigated by Kaiki et al. (2021). It was reported in the study that mean $\log_{10}$ MRSA CFU reductions of 2.91 and 3.95, respectively, were attained following exposure for 1.5 and 2.5 min. Moreover, 9 mJ/cm^2 of dose was required to significantly decrease mobile phone AB contamination. In a different pilot crossover trial that was carried out in November 2017, surgical tools that had been infected with *S. aureus, E. faecalis*, *P. aeruginosa,* and *S. marcescens* were placed in a box reactor comprising a number of UV-C LED light sources. It was noticed after being exposed for 10 min, the findings revealed no evidence of bacterial growth, demonstrating the high degree of disinfection efficacy of the UV-C device. These findings suggest that the device's capacity to eliminate bacterial contamination from surgical instruments may have a significant effect on the reduction in infections associated with medical care (Spataro et al. 2019). The study conducted by Guettari et al. (2021) also examined the use of UV-C LED radiation as a physical disinfectant to prevent the spread of COVID-19 in confined spaces including hospitals, public transportation, and airlines. The article researchers claimed that the i-Robot UV-C robot was able to eradicate 99.999% of bacteria and viruses using i-Robot.

Various studies (see Table 5) have been conducted using UV technologies for the purpose of disinfection and to assess their antimicrobial efficacy. One such comparative investigation (Raeiszadeh and Adeli 2020) was conducted to evaluate the effectiveness of MP, LP, and UV-C LEDs by comparing the actual UV susceptibility of *E. coli* bacterium and MS-2 virus to the UV absorption value of DNA and RNA (Fig. 7A). It was observed that a UV-LED with a peak wavelength of 265 nm had 1.15 times higher germicidal power than a standard 274 nm mercury UV lamp for inactivation. In other words, compared to a UV disinfection system with a 254 nm, a system with a 265 nm emitting UV source required lower UV dose to accomplish the same amount of DNA/RNA damage. In order to determine the germicidal effectiveness of a UV disinfection system, it is essential to comprehend how the SPD of the UV source being used (Fig. 7C) interacts with the UV susceptibility of microorganisms over the UV-C spectrum. Moreover, as illustrated in Fig. 7B, absorbed UV-C photons could severely damage the genomic structure of microorganisms, impairing their ability to replicate and survive. The adenine–thymine bond collapses, and a covalent linkage identified as a pyrimidine dimer develops between two adenines as a result, rendering the cell incapable of replicating. Because of this, the impact of UV irradiation on microorganisms is referred to as "inactivation" rather than "killing."

Study remarks, gaps, and future perspective

The hospital contaminated environment has shown to be an issue of serious concern and it continues to be a major origin for transmitting microorganisms to the healthy individuals. The everyday use of chemical disinfectants for cleaning and disinfection has raised serious concerns due to the fact that it gives rise to several complications while delivering insufficient disinfection (Sehulster 2003; Rutala and Weber 2016a; Canada 1998; Omidbakhsh et al. 2014; Han et al. 2015; Rutala et al. 2008). Also, it has been seen that the procedures that involve chemical products for cleaning purposes are less effective regardless of how expensive the products are Sheikh et al. (2021). However, for such concerns, extensive studies have already been conducted to identify the methods which could significantly substitute the usage of chemical with "no-touch" disinfection technology for disinfection practices. As a result, the interest in an alternative disinfection method is continuing to grow particularly in healthcare facilities. In such regards, researchers have come across UV technologies which have drawn a significant attention due to its efficient and practical capacity to disinfect water, food, air, and surfaces (Kaiki et al. 2021; Duering et al. 2023; Hessling et al. 2023, 2021; Mariita et al. 2022; Nunayon et al. 2022; Nyhan, et al. 2021; Gardner et al. 2021; Grist et al. 2021; Rios de Souza et al. 2020; Cheng et al. 2020; Vernez et al. 2020; Mitchell et al. 2019b; Wallace et al. 2019; Alhmidi et al. 2018; Kim et al. 2017; Kim et al. 2015; Boyce et al. 2016b; Anderson et al. 2013; Mahida et al. 2013; Moore et al. 2012; Sommers et al. 2010; Rutala et al. 2010; Yaun et al. 2004; Palma et al. 2022). Conventionally, low pressure (< 1 atm.) mercury lamps are employed (Liang et al. 2021; Kaiki et al. 2021; Spataro et al. 2019; Guettari et al. 2021; Raeiszadeh and Adeli 2020) to generate shorter wavelength UV radiation. Despite of its high level of disinfection, the component; mercury, poses hazard to the environment (Torok et al. 2016), rapidly absorbs into the skin or respiratory system, accumulates in the body, and frequently have a deadly toxic impact on human being (Palma et al. 2022). As a result, the United Nations Environment Program (UNEP) has formally announced an unconditional ban on the production of mercury-containing products after 2020 with the Minamata Convention on Mercury in 2013 (Larson 2014). This also implies that new approaches are required to replace mercury lamps, which could serve as reliable substitute of such technology and effectively serve as potential source for antibacterial procedures. In such regards, UV technologies have grabbed the attention due to its potential characteristics and advantages over liquid disinfectants as demonstrated in Fig. 8.

With recent advancements, all such limitations are certainly sidestepped by UV-C LEDs, which is why LEDs are gaining popularity in the recent times. Nevertheless, in addition to UV-C LEDs, other UV lamp types, such as the excimer technology (pulsed xenon lamps, krypton-chloride excimer lamps), have gained popularity and have shown to be a worthy replacement to LP mercury vapor lamp. Such technology has several benefits in common with UV-C LEDs, such as being free from the mercury component, longer lifespan with no warm-up requirement time. However, due to the pulsatile nature of these lamps and their poor efficacy, the use of excimer lamps, such as pulsed xenon lamps, in a continuous air disinfection

Table 5 Analysis on the recent studies: antimicrobial efficacy evaluation using UV disinfection systems for reducing the surface bacterial burden

Authors (Year) ↓	Bacteria/virus	UV-C wavelengths	Required dosage	Log reduction	Percentage reduction	Bacterial association	References
Duering et al. (2023)	*Escherichia coli*	272 nm	150 mJ/cm^2	1.5	NA	Dry surface	Duering et al. (2023)
Hessling et al. (2023)	*Staphylococcus aureus*	222 nm	23 mJ/cm^2	1.9	90%	Hand/ gloves	Hessling et al. (2023)
Mariita et al. (2022)	Human norovirus	269 nm	22.5 mJ/cm^2	3	99.9%	Hospital surface	Mariita et al. (2022)
Nunay et al. (2022)	*Escherichia coli*	NA	0.134 mJ/cm^2	NA	84.6%	Upper-room	Nunayon et al. (2022)
Liang et al. (2021)	*SARS-CoV-2*	275 nm	3.192 mJ/cm^2	> 6	99.9999%	Hospital surface	Liang et al. (2021)
Nyhan et al. (2021)	*Escherichia coli*	270 nm	32 mJ/cm^2	3.8	NA	Plastic surface	Nyhan et al. (2021)
Nyhan et al. (2021)	*Salmonella Typhimurium*	270 nm	16 mJ/cm^2	4	NA	Plastic surface	Nyhan et al. (2021)
Nyhan et al. (2021)	*Listeria monocytogenes*	270 nm	64 mJ/cm^2	2.2	NA	Plastic surface	Nyhan et al. (2021)
Kaiki et al. (2021)	MRSA	222 nm	15 mJ/cm^2	3.95	NA	Healthcare associated mobile phone	Kaiki et al. (2021)
Gardner et al. (2021)	*peritonitis virus*	265 nm	101 mJ/cm^2	3	NA	Media	Gardner et al. (2021)
Grist et al. (2021)	SARS-CoV-2	254 nm	1000 mJ/cm^2	> 3	99.9%	Facepiece	Grist et al. (2021)
Hessling et al. (2021)	Staphylococci	254 nm	40 mJ/cm^2	5	99.999%	Touchscreen	Hessling et al. (2023)
De Souza et al. (2020)	*Penicillium expansum*	277 nm	500 mJ/cm^2	2	99%	Food	de Souza et al. (2020)
Cheng et al. (2020)	*Listeria innocua*	280 nm	7.13 mJ/cm^2	5	NA	Stainless steel	Cheng et al. (2020)
Cheng et al. (2020)	*Escherichia coli*	280 nm	22.18 mJ/cm^2	6	NA	Stainless steel	Cheng et al. (2020)
Vernez et al. (2020)	Staphylococcal bacteriophages	254 nm	60 mJ/cm^2	> 3	NA	Facepiece	Vernez et al. (2020)
Mitchell et al. (2019)	*Clostridium difficile*		16 mJ/cm^2	3	NA	Stainless steel	Mitchell et al. (2019b)
Wallace et al. (2019)	MRSA, *Clostridium difficile*	254 nm	625.4 mJ/cm^2	2.3	99.83	Glass coupons	Wallace et al. (2019)
Alhmidi et al. (2018)	MRSA	254 nm	3330 mJ/cm^2	3.2	NA	Touchscreen	Alhmidi et al. (2018)
Kim et al. (2017)	*Escherichia coli*	266, 270, 275, 279 nm	0.2 mJ/cm^2	5	NA	Food	Kim et al. (2017)
Kim et al. (2017)	*Listeria monocytogenes*	266, 270, 275, 279 nm	0.2 mJ/cm^2	1	NA	Food	Kim et al. (2017)
Kim et al. (2017)	*Staphylococcus aureus*	266, 270, 275, 279 nm	0.2 mJ/cm^2	> 2	NA	Food	Kim et al. (2017)
Boyce et al. (2016)	*Clostridium difficile*	254 nm	67.56 mJ/cm^2	3	NA	Hospital surface	Boyce et al. (2016b)
Petti et al. (2016)	MRSA	TiO_2	NA	1.16	93%	PVC surface	Petti (2016)
Kim et al. (2015)	*Salmonella Typhimurium*	275 nm	0.7 mJ/cm^2	> 5	NA	Food	Kim et al. (2015)
Anderson et al. (2013)	*Acinetobacter*	254 nm	12 mJ/cm^2	1.71	NA	Hospital surface	Anderson et al. (2013)

Table 5 (continued)

Authors (Year) ↓	*Bacteria/virus*	UV-C wave-lengths	Required dosage	Log reduction	Percentage reduction	Bacterial association	References
Anderson et al. (2013)	*Clostridium difficile*	254 nm	22 mJ/cm^2	1.16	NA	Hospital surface	Anderson et al. (2013)
Anderson et al. (2013)	VRE	254 nm	12 mJ/cm^2	1.68	NA	Hospital surface	Anderson et al. (2013)
Mahida et. al (2013)	MRSA	254 nm	22 mJ/cm^2	> 4	99.99%	Hospital surface	Mahida et al. (2013)
Moore et al. (2012)	*Klebsiella pneumoniae*	NA	159 mJ/cm^2	2.76		Blood pressure gauge	Moore et al. (2012)
Moore et al. (2012)	*Acinetobacter baumannii*	NA	159 mJ/cm^2	3.44		Blood pressure gauge	Moore et al. (2012)
Moore et al. (2012)	VRE	NA	159 mJ/cm^2	> 5.11		Patient call button	Moore et al. (2012)
Moore et al. (2012)	*Clostridium difficile*	NA	318 mJ/cm^2	4.40		Hospital surface	Moore et al. (2012)
Sommers et al. (2010)	*Salmonella enterica, Listeria monocytogenes, Staphylococcus aureus*	254 nm	3000 mJ/cm^2	1.1–2.8	NA	Food	Sommers et al. (2010)
Rutala et al. (2010)	VRE	254 nm	661 mJ/cm^2	3.90	NA	Patient bed	Rutala et al. (2010)
Rutala et al. (2010)	*Acinetobacter baumannii*	254 nm	627 mJ/cm^2	4.21	NA	Patient bed	Rutala et al. (2010)
Rutala et al. (2010)	*Clostridium difficile*	254 nm	2123 mJ/cm^2	4.04	NA	Patient bed	Rutala et al. (2010)
Rutala et al. (2010)	MRSA	254 nm	472 mJ/cm^2	4.31	NA	Patient bed	Rutala et al. (2010)
Yaun et al. (2004)	*Escherichia coli*	253.7 nm	NA	3.3	99.9%	Food	Yaun et al. (2004)
Klaus et al. (2003)	*Escherichia coli*	356 nm + (TiO_2)	NA	6	NA	Microbiology laboratory	Klaus et al. (2003)
Klaus et al. (2003)	*Pseudomonas aeruginosa*	356 nm + (TiO_2)	NA	6	NA	Microbiology laboratory	Klaus et al. (2003)
Klaus et al. (2003)	*Staphylococcus aureus*	356 nm + (TiO_2)	NA	6	NA	Microbiology laboratory	Klaus et al. (2003)
Klaus et al. (2003)	*Enterococcus faecium*	356 nm + (TiO_2)	NA	6	NA	Microbiology laboratory	Klaus et al. (2003)
Klaus et al. (2003)	*Candida albicans*	356 nm + (TiO_2)	NA	2	NA	Microbiology laboratory	Klaus et al. (2003)

system is limited (Szeto et al. 2020; SHCHEER 2017; Jarvis et al. 2019). UV-C LEDs, on the other side, have overcome such limitations in a number of ways, such as an absence of hazardous component such as mercury, non-pulsatile treatment and employing a metallic substance at a little extent that do not leak out in the case of breakdown or disposal. These LEDs additionally do not produce ozone nor have a high-power density and sustain minimal harm from repeated cycles. Moreover, it does not require warm-up time for maximum intensity output and emits light with various wavelengths. These benefits along with nearly swift starts and adjustable wavelengths offer an abundance of design autonomy for UV-C LED ballasts. It is also essential to emphasize the cost of UV-C LEDs as compared to conventional lamps where UV-C LEDs are typically thought to be more cost-effective. Furthermore, UV-C LEDs have a longer lifespan, which minimizes the need of frequent replacement, eventually giving benefit in terms of buyer's expense by reducing the maintenance and replacement costs. UV-C LEDs are also a long-term financial option because of its lower energy consumption, which also lowers overall power expenses. By implementing such technology for disinfection in healthcare or other indoor settings, the operational expenses could be lessened

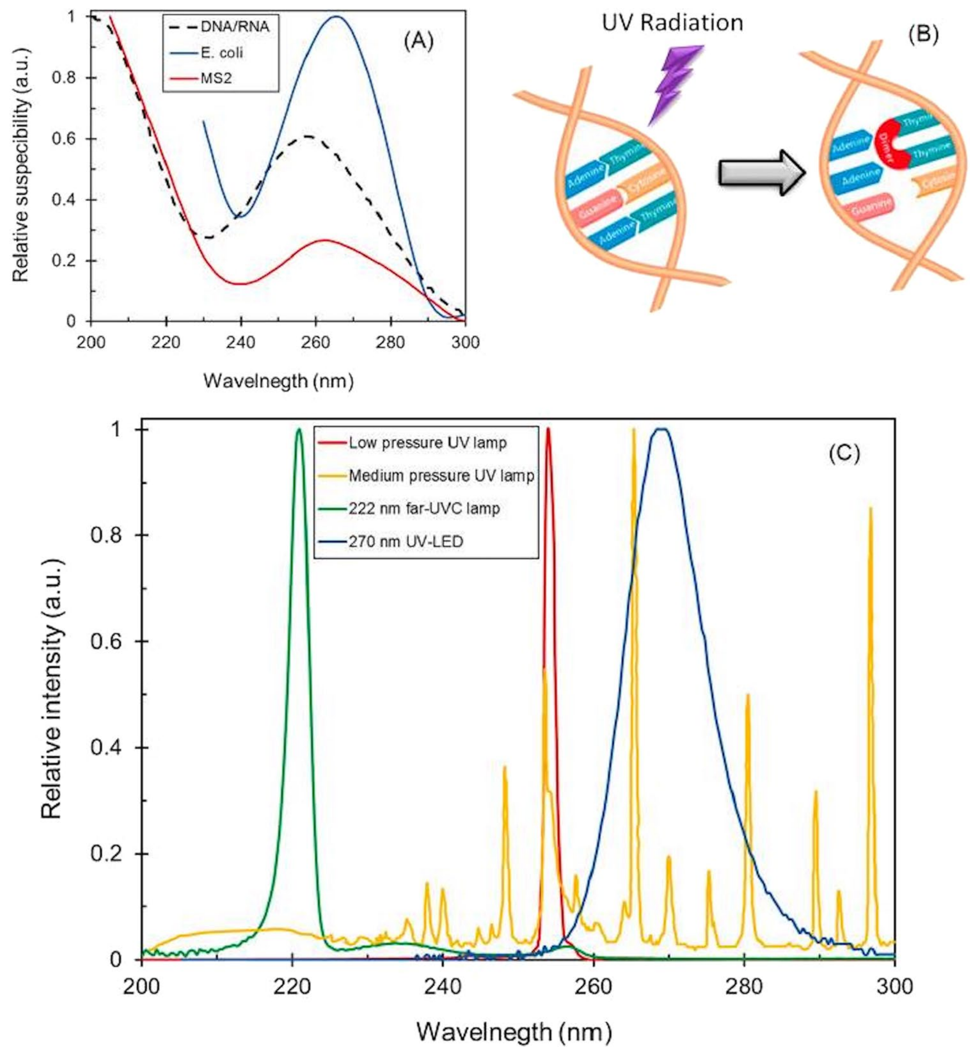


Fig. 7 **A** The germicidal region's relative UV susceptibility of a generic RNA or DNA, as well as *E. coli* bacterium and MS2 virus, **B** Thymine dimerization schematic representation for a UV-exposed double-stranded DNA, **C** SPD of various germicidal UV sources. Reprinted from "A Critical Review on Ultraviolet Disinfection Systems against COVID-19 Outbreak: Applicability, Validation, and Safety Considerations," M. Raeiszadeh., ACS Photonics, Copyright 2020 (Raeiszadeh and Adeli 2020)

while maintaining effective disinfection procedures by implementing the routine disinfection practices.

Conclusion

Ultraviolet (UV) disinfection technologies are tool for microbial prevention in indoor public places which are frequently employed for disinfecting air, surfaces, and water. In conclusion, our research supports the use of UV-C LEDs for environmental disinfection purposes due to its variety of advantages over chemical disinfectants and conventionally used other disinfection procedures utilizing UV technologies. Moreover, it is advisable to combine multiple LED arrays to enhance the overall irradiance and achieve greater disinfection over longer distances. Further research on the arrangement of LEDs and configuration of arrays to maximize intensity while guaranteeing uniform and sufficient UV-C radiation dispersion has a valuable prospect. However, the scalability and efficiency in various applications such as for outdoor environments where the treatment could be affected with the interference of other light sources should be examined. Additionally, ongoing research should also continue to investigate the possible threats to health and safety posed by UV-C LED technology in order to provide useful guidelines and safety measures. By considering all of this, UV-C LED can offer an effective and affordable solution for disinfection, improving hygiene and environmental sustainability. Therefore, it is clear that UV-C LED technologies are promising for disinfection of microorganism present in air, water, food or surface in the healthcare environment.

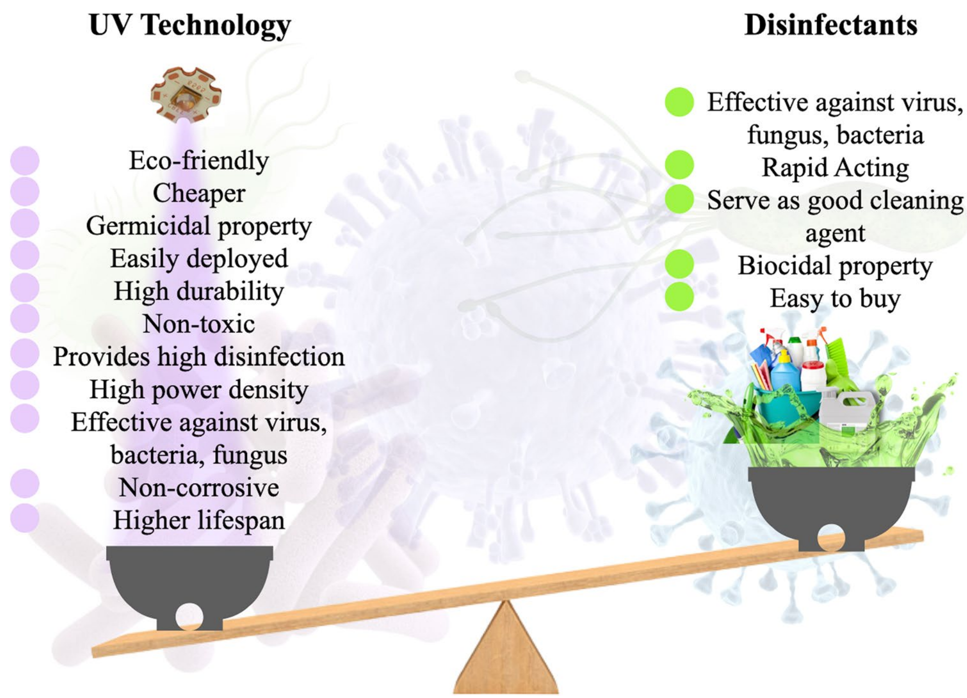


Fig. 8 UV-C advantages in comparison with traditional disinfectants

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Declarations

Conflict of interest The authors have no competing interests to declare that are relevant to the content of this article.

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