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Review

Ultraviolet C irradiation: A promising approach for the disinfection of public spaces?

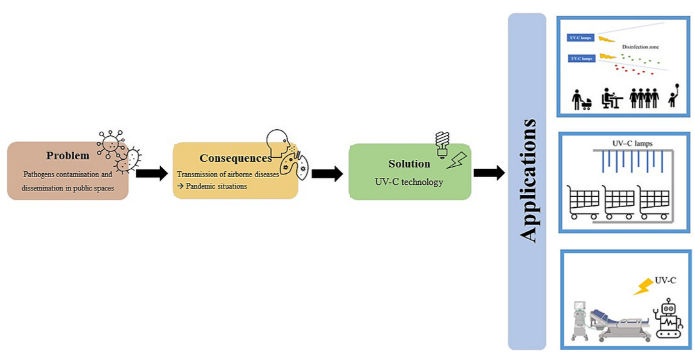
Ana Rita Pereira [a,b], Daniel F.O. Braga [c], Mariana Vassal [c], Inês B. Gomes [a,b], Manuel Simões [a,b,*]

[a] LEPABE - Laboratory for Process Engineering, Environment, Biotechnology and Energy, Faculty of Engineering, University of Porto, Rua Dr. Roberto Frias, 4200-465 Porto, Portugal
[b] ALiCE - Associate Laboratory in Chemical Engineering, Faculty of Engineering, University of Porto, Rua Dr. Roberto Frias, 4200-465 Porto, Portugal
[c] SpinnerDynamics, Lda., Rua da Junta de Freguesia 194, Escariz, 4540-322 Arouca, Portugal

HIGHLIGHTS

- UV-C emerges as an alternative to harmful and (eco)toxic chemical disinfectants.
- Far-UV-C can eliminate pathogens in spaces with simultaneous human presence.
- Autonomous UV-C-based devices/robots reduce manual work and process costs.
- No consensus exists on UV-C safety and human exposure.

GRAPHICAL ABSTRACT



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ABSTRACT

Ultraviolet irradiation C (UVC) has emerged as an effective strategy for microbial control in indoor public spaces. UVC is commonly applied for air, surface, and water disinfection. Unlike common 254 nm UVC, far-UVC at 222 nm is considered non-harmful to human health, being safe for occupied spaces, and still effective for disinfection purposes. Therefore, and allied to the urgency to mitigate the current pandemic of SARS-CoV-2, an increase in UVC-based technology devices appeared in the market with levels of pathogens reduction higher than 99.9 %. This environmentally friendly technology has the potential to overcome many of the limitations of traditional chemical-based disinfection approaches. The novel UVC-based devices were thought to be used in public indoor spaces such as hospitals, schools, and public transport to minimize the risk of pathogens contamination and propagation, saving costs by reducing manual cleaning and equipment maintenance provided by manpower. However, a lack of information about UVC-based parameters and protocols for disinfection, and controversies regarding health and environmental risks still exist. In this review, fundamentals on UVC disinfection are presented. Furthermore, a deep analysis of UVC-based technologies available in the market for the disinfection of public spaces is addressed, as well as their advantages and limitations. This comprehensive analysis provides valuable inputs and strategies for the development of effective, reliable, and safe UVC disinfection systems.

* Corresponding author at: LEPABE - Laboratory for Process Engineering, Environment, Biotechnology and Energy, Faculty of Engineering, University of Porto, Rua Dr. Roberto Frias, 4200-465 Porto, Portugal.
E-mail address: mvs@fe.up.pt (M. Simões).

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Contents

1. Introduction

Microbial contamination of confined spaces (e.g. public transport and hospitals) and frequently touched surfaces (e.g. elevator buttons, food contact surfaces, doors handle) is considered a global public health issue due to the potential for causing the spread of pathogens (Raeiszadeh and Adeli, 2020). Environmental contamination by pathogens has a significant impact on their transmission and spread, which in extreme situations, may contribute to pandemic scenarios. The severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) pandemic highlighted the importance of environmental disinfection in bustling indoor areas (Agarwal et al., 2021). Measures to prevent the spread of the virus have been adopted, including social distancing, the use of protective face masks, and frequent handwashing. In addition, the use of traditional chemical disinfectants (i.e. ethanol, quaternary ammonium compounds and sodium hypochlorite) dramatically increased (Parveen et al., 2022). Despite being a strong strategy to inactivate microorganisms, continuous and repeated human exposure to chemical disinfectants during the pandemic (mainly through dermal absorption and inhalation) has raised concerns about exposure-related long-term health risks (Dewey et al., 2022). Respiratory illnesses such as asthma and chronic obstructive pulmonary disease were associated with the massive use of traditional disinfectants. Moreover, bleach in combination with other household chemicals can cause the release of toxic gases (chlorine gas and chloroform) that if inhaled can cause severe respiratory disorders (Dewey et al., 2022). Nevertheless, besides the direct impact of chemical disinfectants, the negative impact of disinfection by-products (DBPs) cannot be disregarded (Parveen et al., 2022). DBPs were already associated with cytotoxicity for the human liver and neuronal cell lines, genotoxicity, endocrine disruption, and carcinogenic effects (Parveen et al., 2022). Representative human health problems associated with exposure to DBPs are presented in Table 1 (World Health Organization, 2000). In addition to negative human health complications, the use of disinfectants and their DBPs can have adverse effects on the environment mainly in aquatic ecosystems, where they get into sewage and contaminate water resources (Dewey et al., 2022). Moreover, microorganisms can adapt and become tolerant to residual levels of disinfectants (Chen et al., 2021). The common bacterial tolerance mechanisms to disinfectants include mutation and horizontal gene transfer, upregulation of efflux pumps, membrane alteration, and biofilm formation (Chen et al., 2021). Acquired bacterial tolerance to benzalkonium chloride by *Salmonella enterica*, *Pseudomonas aeruginosa*, *Enterobacter* spp., *Escherichia coli* and *Staphylococcus saprophyticus* was already reported (Kampf, 2018). Moreover, chlorine-tolerant bacteria, such as species of *Legionella*, *Sphingomonas*, *Mycobacterium*, *Bacillus*, and *Pseudomonas* have been the most reported in the literature (Luo et al., 2021). Increased bacterial tolerance to phenolic compounds, peroxyacetic acid, isopropanol, and hypochlorous acid was also reported (Nontaleerak et al., 2020). To overcome these problems, new alternative methods for disinfection have been implemented, particularly autonomous ultraviolet (UV)-based treatments (Bhardwaj et al., 2021).

Table 1
Negative human health effects of disinfection by-products.

Disinfectants	Negative effects on health
Trihalomethanes	Cytotoxicity in the liver and kidneys of rodents
Haloacetic acids	Toxicological effects in laboratory animals
	Carcinogenic, reproductive, and developmental effects
	Neurotoxic effects
Haloaldehydes and haloketones	Hepatic necrosis and tumours in rats
	Depressant effect on the central nervous system in human
	Haematological effects in rats
Haloacetonitriles	Mutagenic effects
	Tumour initiators in the skin
Halogenated hydroxyfuranone derivatives	Mutagenic effects
	Chromosomal aberrations and induced DNA damage in isolated liver and testicular cells
Chlorite	Oxidative damage to red blood cells
	Mild neurobehavioural effects in rat pups
Bromate	Renal tubular damage in rats
	Tumours of the kidney, peritoneum and thyroid in rats

UV irradiation (100 to 400 nm) is fractionated into four main regions by their wavelength and energy: vacuum UV from 100 to 200 nm, short wave ultraviolet (UVC) from 200 to 280 nm, UV-medium wave (UVB) from 280 to 315 nm, and UV long wave (UVA) from 315 to 400 nm (Khan et al., 2022). Despite UVA irradiation could damage cellular components causing pathogen cell death, UVA emitters are mainly employed for sensing applications (Amano et al., 2020). On the other hand, UVB irradiation is commonly used for phototherapy, including the treatment of skin diseases like vitiligo and psoriasis (Amano et al., 2020). UVA and UVB penetrate tissues and may cause eye cataracts and skin cancer (Amano et al., 2020), whereas UVC is absorbed in the outermost layers of the eye and skin, where cells are continually sloughed and replaced (Garciá De Abajo et al., 2020). UVC light is the most common spectrum used for disinfection purposes being recognized as the germicidal range of UV irradiation, due to its great potential for disinfection (Bhardwaj et al., 2021). It has been applied in sterilization (Raeiszadeh and Adeli, 2020) and was reported to be efficient in reducing transmission of airborne viruses (Hadi et al., 2020). The inactivation of enteric viruses, polioviruses, noroviruses, and non-enveloped viruses (e.g. hepatitis A virus and feline calicivirus) by UVC irradiation was found to be promising, particularly to inactivate aerosols harbouring viruses (Fino and Kniel, 2008). Besides being used for air disinfection (Corrêa et al., 2021), UVC irradiation is intensively used for water (Lui et al., 2014; Wan et al., 2023) and surface disinfection (Elgujja et al., 2020) (Fig. 1). Nevertheless, it can also be applied for food (liquid and beverages) disinfection (Singh et al., 2021).

In comparison to conventional chemical disinfection approaches, UVC is considered economically affordable and an easily deployable strategy to effectively control microbial contamination (can eliminate up to 99.9 % of microbes), without generating harmful chemical residues (Garciá De Abajo et al., 2020). Besides not resorting to frequent manual cleaning and maintenance, the high power density and a higher lifetime of UVC technologies are also advantages in comparison to conventional disinfection procedures. UVC technology could also be controlled by a simple switch on/off with lower warmup times to reach their maximum capacity, enhancing power saving and minimizing the necessity of having human staff controlling it. Moreover, it is possible to select a specific wavelength of UVC technology to target a specific microorganism (Garciá De Abajo et al., 2020). Fig. 2 highlights the main advantages of using UVC technologies in comparison to the use of traditional disinfectants. Therefore, UVC irradiation emerges as one of the most promising solutions to act swiftly on the SARS-CoV-2 pandemic satisfying the requirements of rapid, widespread, and economically viable deployment (Garciá De Abajo et al., 2020). Besides that, there are still human health risks regarding UVC exposure at 254 nm (Khan et al., 2022). To overcome this problem, far-UVC (222 nm) has appeared more recently showing advantages over standard UVC light at 254 nm, including reduced harm to human skin and eyes, being a safer option for disinfection of occupied spaces (Barnard et al., 2020; Bhardwaj et al., 2021). In addition, far-UVC is still effective against airborne pathogens such as viruses, bacteria, and fungi, helping to reduce the transmission of these pathogens in indoor spaces (Demeersseman et al., 2023; Narita et al., 2020).

The dissemination of pathogens of great importance leads to a boom of new UVC technology systems including robots to inactivate pathogens and consequently mitigate the probability of infection by contact transmission or aerosols (Inagaki et al., 2020). These robots have been introduced into the market at a high pace, achieving percentages of microbial reduction between 84 and 99.99 %, while maintaining the normal operations of social infrastructures (Corrêa et al., 2021). However, this disinfection technology should be carefully planned without compromising public health.

This review is focused on the potential of UVC irradiation for the inactivation of pathogens, mainly in indoor public spaces, while providing an extensive overview of the principles of UVC technology. The mechanism of UVC inactivation of pathogens and the advantages in comparison to conventional chemical disinfection are highlighted. Recently developed UVC-based robots and/or devices that are available in the market for disinfection are critically analyzed.

2. UVC mechanism of inactivation and kinetics

The microbial inactivation process by UVC irradiation (Fig. 3) is mainly based on the occurrence of photochemical reactions caused by UV light on the genetic material (DNA or RNA) of microorganisms (Raeiszadeh and Adeli, 2020). The adenine-thymine bond is broken resulting in the formation of a covalent linkage between two adenines named pyrimidine dimer. These dimers (e.g. cyclobutane pyrimidine dimers – CPDs) disrupt the normal assembly of nucleic acids, which consequently affect the correct transcription and replication of RNA and DNA, respectively (Buonanno et al., 2020). For that reason, the mode of action of UVC light on microorganisms is called “inactivation” and not “killing” (Raeiszadeh and Adeli, 2020). The maximum efficiency of microbial inactivation by UVC is best achieved between 250 and 270 nm since that range of energy is strongly absorbed by the nucleic acids of microorganisms (Bhardwaj et al., 2021).

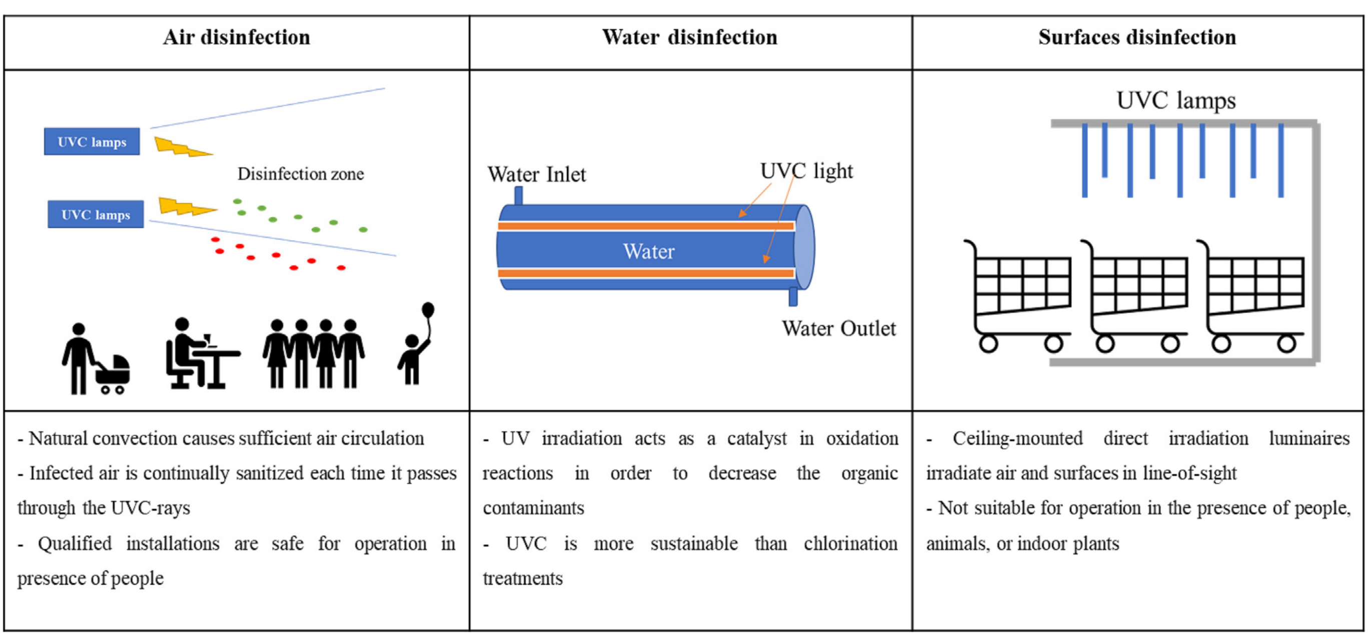

Fig. 1. Applications of UVC irradiation.

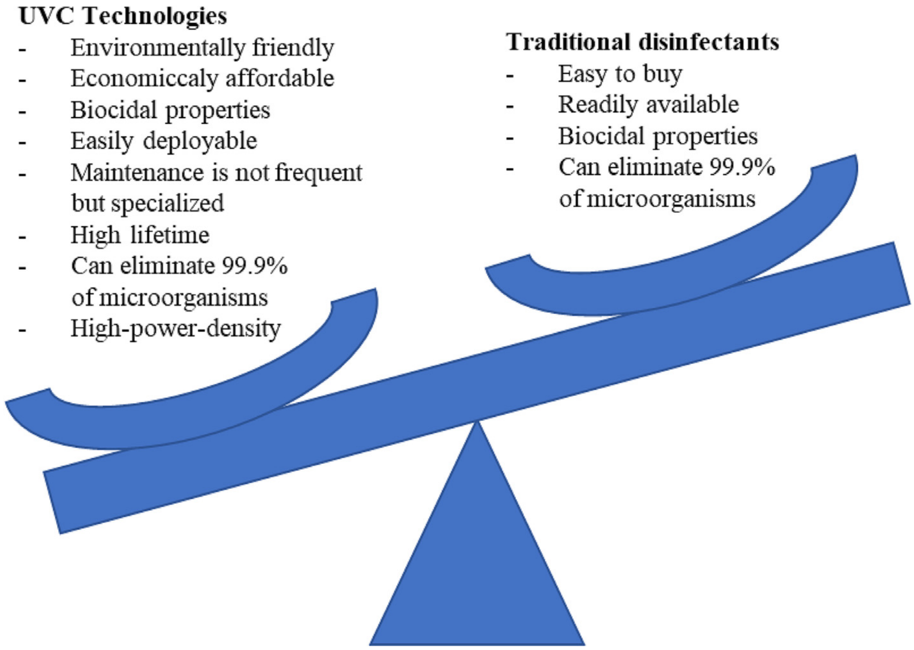

Fig. 2. Advantages of UVC technology when compared with traditional disinfectants.

Moreover, there are some pieces of evidence proposing that photons can also interact with cell envelope components and promote the oxidation of unsaturated fatty acid residues of lipids and phospholipids (Hadi et al., 2020).

2.1. UV inactivation kinetics

The UV inactivation kinetics can be characterized as one-stage or two-stage, depending on the level of resistance of pathogens (Kowalski et al., 2000). The one-stage exponential decay equation is commonly applied for susceptible microorganisms such as *P. aeruginosa*, *Penicillium chrysogenum* and Adenovirus and is obtained by Eq. (1):

$$\frac{N_t}{N_0} = e^{-k \cdot I \cdot \Delta t} = e^{-k.D} \tag{1}$$

where $\frac{N_t}{N_0}$ is the fraction of surviving pathogens (N_0 and N_t are the initial and final microbial populations, respectively). Δt is the time interval of UVC exposure; k is the constant of microbe-dependent inactivation; I is the effective germicidal irradiance received by the microorganism ($\mu W/cm^2$); and D is the UVC dose (mJ/cm^2 - the amount of radiant energy applied for an exposure time to an area) (Singh et al., 2021). Hence, the activity of UVC irradiation is represented by dose $D\ (mJ/cm^2) = I\ (\mu W/cm^2) \times \Delta t\ (s)$. Therefore, the inactivation efficiency increases exponentially with the dose, which is proportional to both the exposure time and the irradiance light.

The two-stage survival curve takes into account the more resistant microorganisms associated with clumping and dormancy, such as *Staphylococcus aureus* and *Serratia marcescens* (Kowalski et al., 2000). Therefore, this model is mathematically the sum of different microbial populations (susceptible vs resistant) that have rate constants k_1 and k_2, respectively, as presented in Eq. (2):

$$\frac{N_t}{N_0} = (1-f)e^{-k_1 \cdot D} + (f)e^{-k_2 \cdot D} \tag{2}$$

where f is the resistant fraction of the total initial population with a rate constant k_2, and (1-f) is the fraction of the vulnerable population with a rate constant k_1 (Kowalski et al., 2000). The UVC dose (D) needed to inactivate 90 % (10-fold decrease) of the microbial population is represented as D_{10} and the decimal reduction time (D value) is the UVC exposure time required to reduce 90 % of the microbial population at a fixed incident surface irradiance (Singh et al., 2021).

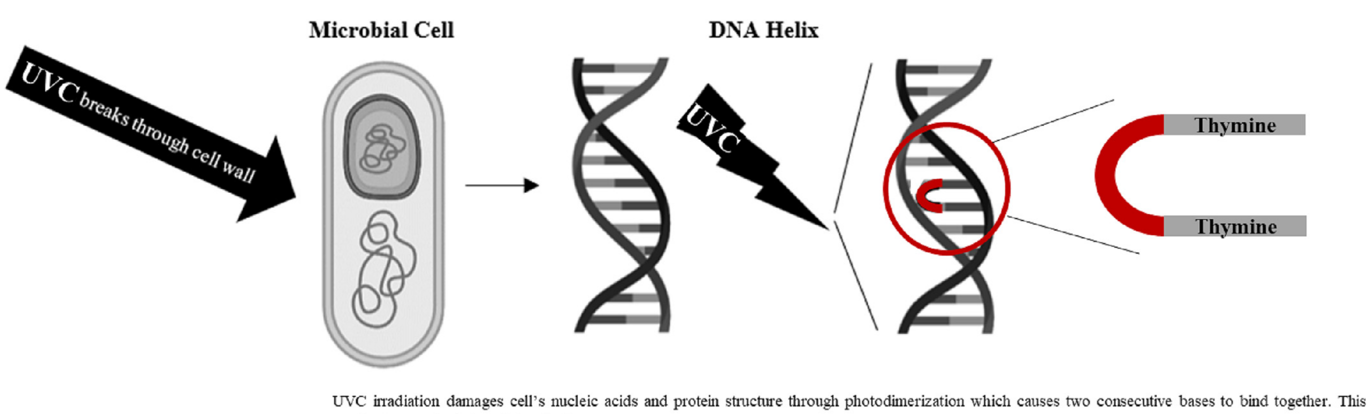

Fig. 3. Mechanism of action of UVC on microbial inactivation.

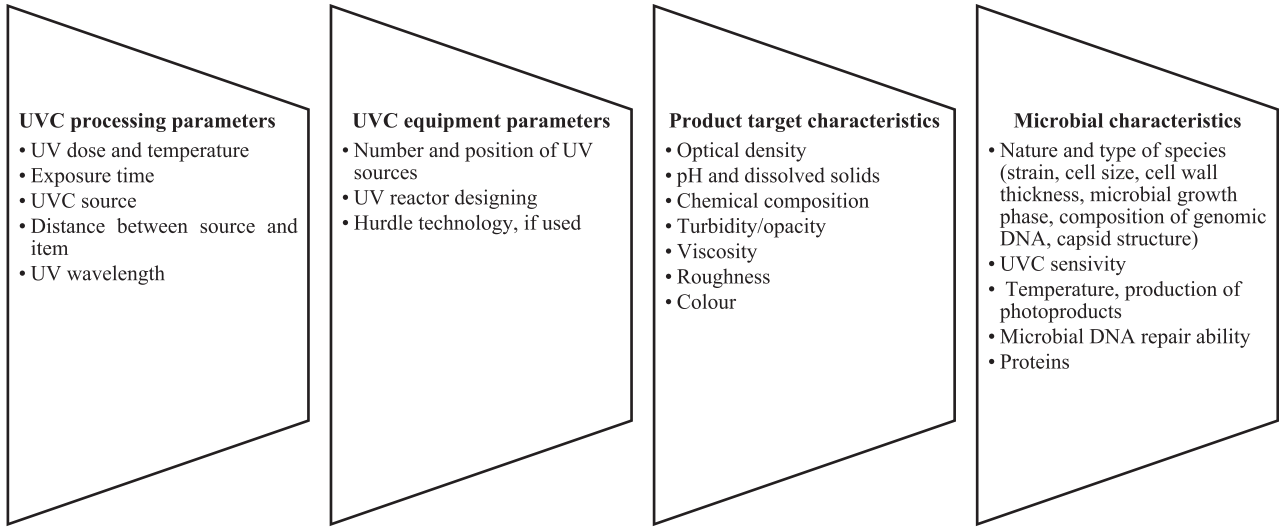

Fig. 4. The main factors that affect UVC light disinfection treatments.

3. Factors affecting UV inactivation

According to the UV inactivation kinetics, it is easy to understand that the efficiency of disinfection depends on irradiation volume, intensity, exposure time, and UV wavelength, as well as on the absorption coefficient of the material/product that receives the irradiation (Graeffe et al., 2023). The UV efficacy is higher for lower absorption coefficients. Gayán et al. (2011) demonstrated that the UV efficacy for controlling *Escherichia coli* decreased in the range of absorption coefficients from 8.56 to 22.28 cm^{-1} resulting in logarithmic cycles of inactivation between 6.35 and 0.74, respectively.

Nevertheless, other factors can affect UV treatments, including the equipment specifications and the microbial characteristics (Fig. 4) (Hadi et al., 2020).

3.1. Microbial characteristics

Representative examples of disinfection treatments using UVC irradiation for microbial inactivation are presented in Tables 2 and 3 (only related to far-UVC). From these tables, it is possible to observe that different UVC doses from distinct UVC sources (explained in detail in Section 4) cause different antimicrobial effects, depending on the target microorganisms. Thus, UVC tolerance may be species-dependent. In general, Gram-negative bacteria seem to be more susceptible to UVC radiation than vegetative Gram-positive bacteria, yeast, bacterial spores, moulds, and viruses (Singh et al., 2021).

Over the years, different studies showed the inactivation of foodborne pathogenic bacteria by UVC irradiation - e.g. *E. coli* (Corrêa et al., 2021), *Listeria*, *Salmonella* (Singh et al., 2021), *Staphylococcus* (Crook et al., 2015), *Bacillus*, *Aeromonas*, *Cladosporium* and *Alicyclobacillus* species (Gayán et al., 2013); *Lactobacillus* species (Gayán et al., 2011); and *Saccharomyces cerevisiae* (Diesler et al., 2019).

Singh et al. (2021) reported that the use of UVC doses from 1.7 to 7.4 mJ/cm^2 caused a 90 % of reduction of yeasts, *E. coli*, *Serratia marcescens*, *Staphylococccus haemolyticus*, *Salmonella enterica* Typhimurium, *Streptococcus viridans*, *Staphylococcus albus* and *Shigella paradysenteriae* in food products. However, higher UVC doses (<22 mJ/cm^2) were needed to inactivate *Salmonella* spp. and *Listeria monocytogenes* (Singh et al., 2021). The differences in susceptibility can be explained by the differences in the cell envelope composition and cell size, compromising the ability of UVC irradiation to penetrate inside cells (Singh et al., 2021). DNA repair mechanisms may also be a factor that influences microbial susceptibility to UV irradiation (Raeiszadeh and Adeli, 2020). Diesler et al. (2019) reported a remarkable inactivation (6 log reduction) of yeasts (*Saccharomyces cerevisiae* and *Hanseniaspora uvarum*) in grape must, using high UVC doses <0.8 kJ/L.

In recent years, a boom of studies evaluating the impact of UVC irradiation on viruses emerged due to the critical situation of the SARS-CoV-2 pandemic (Buonanno et al., 2020). However, the mechanism of viral inactivation by UVC irradiation remains to be fully described (Hadi et al., 2020). The inactivation of SARS-CoV-2 was recently reported by different authors using far-UVC light (Kucharski et al., 2020) and pulsed-xenon UVC (Drph et al., 2020). In general, coronavirus inactivation requires lower UV energy compared to bacteria (Raeiszadeh and Adeli, 2020). Other viruses, including aerosolized human coronaviruses (Buonanno et al., 2020), airborne PRRSV and influenza (Hadi et al., 2020), bacteriophage MS (Guettari et al., 2021) and rotaviruses (Kucharski et al., 2020), were also inactivated by different UVC light-sources. While a UVC dose of 3.7 mJ/cm^2 was enough to inactivate 3 log of SARS-CoV-2 in a culture medium (Biasin et al., 2021), higher UVC doses were required (25-140 mJ/cm^2) to inactivate 3 log of rotavirus and adenovirus (Bhardwaj et al., 2021). This may be attributed to the fact that non-enveloped viruses are more resistant to UVC than enveloped ones (SARS-CoV-2 and influenza virus) (Raeiszadeh and Adeli, 2020). The proteins and lipids present in the envelopes of the virus are broken easier than other viral components (Raeiszadeh and Adeli, 2020). Moreover, single-stranded (ss) viruses are more susceptible to UVC irradiation than double-stranded (ds) ones due to the redundancy of genetic information in a second strand, which allows the reparation of the damage (Tseng and Li, 2005). For example, stronger UVC doses (3.80-8.13 mJ/cm^2) are required to inactivate 90 % of viral dsDNA and dsRNA than to inactivate ssDNA and ssRNA (1.32-4.47 mJ/cm^2). In general, it is necessary to apply a UVC dose twice as higher as that applied to achieve 90 % viral inactivation to ensure a viral inactivation of 99 % (Tseng and Li, 2007).

3.2. Target product characteristics

The UVC doses needed for microbial inactivation in different environments (i.e. air, liquid, and surfaces) are different (Raeiszadeh and Adeli, 2020). The disinfection of bio-contaminated air and surfaces with UV radiation is more practical and predictable in comparison to a liquid (Gora et al., 2019). A study reported that 90 % of viral inactivation in air disinfection is easily achieved when compared to surface disinfection, due to surface heterogeneity and the potential presence of biofilms (Raeiszadeh and Adeli, 2020). The presence of biofilms (organized microbial communities embedded within a matrix of extracellular polymeric substances produced by the resident microorganisms attached to surfaces) hinders the

Table 2
Studies evaluating the inactivation of pathogens by UVC lamps (mercury-vapour; LEDs, pulsed-xenon and excimer-lamps UVC).

UVC lamps (wavelength)	Type of pathogens	Name	Characteristics of UVC lamp (e.g.: dose)	Time of exposure	Effect	References
Mercury-vapour UVC (254 nm)	Bacteria	*A. acidocaldarius*	23,720 J/L	N.A.	3.24 log reduction	(Gayán et al., 2013)
		A. hydrophila	1300 J/L		5 log reduction	(Crook et al., 2015)
		B. cereus	23,720 J/L		2.93 log reduction	(Gayán et al., 2013)
		B. coagulans			2.25 log reduction	
		B. licheniformis			3.85 log reduction	
		S. liquefaciens	N.A.	60 min	Total reduction	(Aisha and Maznah, 2018)
		E. coli	1500 J/L	N.A.	5 log reduction	(Crook et al., 2015)
			2.08 mW/cm^2	1 h	99.9 % reduction	(Corrêa et al., 2021)
				5 min	84-91 % reduction	
			6 mJ/cm^2	N.A.	4 log reduction	(Narita et al., 2020)
			N.A.	N.A.	Inactivation rate constant *Z*-value: 4.6 cm^2/mJ	(Zhang and Lai, 2022)
		P. alcaligenes			Inactivation rate constant Z-value: 7.0 cm^2/mJ	
		S. epidermidis			Inactivation rate constant Z-value: 5.5 cm^2/mJ	
		E. coli ATCC 25922	11.18 J/mL	N.A.	99.99 % reduction	(Gayán et al., 2011)
		E. coli ATCC 35218	N.A.	5 min	4.5 log reduction	(Char et al., 2010)
		E. coli ATCC 11229	1.2 kJ/m^2	3 min	7.2 log reduction	(Schenk et al., 2011)
			3.3 kJ/m^2	8 min	8.5 log reduction	
		E. coli O157:H7	13.22 J/mL	N.A.	99.99 % reduction	(Gayán et al., 2011)
			75 mJ/cm^2		1.95 log reduction	(Yin et al., 2015)
			0.87 mW/cm^2		5 log reduction (DNA damage)	(Kang et al., 2018)
		E. coli STCC 4201	16.60 J/mL		99.99 % reduction	(Gayán et al., 2011)
		E. coli STCC 471	14.36 J/mL			
		E. coli STCC 27325				
		L. innocua ATCC 33090	1.2 kJ/m^2	3 min	4.7 log reduction	(Schenk et al., 2011)
			3.3 kJ/m^2	8 min	7.2 log reduction	
		L. monocytogenes	21.6 mJ/cm^2	N.A.	1.0–1.6 log reduction	(Singh et al., 2021)
					2.4–2.6 log reduction	
			0.87 mW/cm^2		5 log reduction (DNA damage)	(Kang et al., 2018)
		M. pulcherrima	>1.2 kJ/L	N.A.	4 log reduction	(Diesler et al., 2019)
		Micractinium sp.	N.A.	240 min	Total reduction	(Aisha and Maznah, 2018)
		Mycobacterium parafortuitum		N.A.	83–98 % reduction	(Hadi et al., 2020)
		Mycobacterium bovis BCG			96–97 % reduction	
		P. aeruginosa	N.A.	5 min	Total reduction	(Aisha and Maznah, 2018)
			6 mJ/cm^2	N.A.	4 log reduction	(Narita et al., 2020)
		P. guilliermondii	N.A.	5 min	Total reduction	(Aisha and Maznah, 2018)
		R. dairenensis		30 min	Total reduction	
		Salmonella spp.	21.6 mJ/cm^2	N.A.	1.0–2.6 log reduction	(Singh et al., 2021)
		S. aureus	1450 J/L		5 log reduction	(Crook et al., 2015)
			0.87 mW/cm^2		5 log reduction (DNA damage)	(Kang et al., 2018)
			6 mJ/cm^2		4 log reduction	(Narita et al., 2020)
		S. enterica serovar Typhimurium	18.03 J/mL		99.99 % reduction	(Gayán et al., 2012b)
			0.87 mW/cm^2		5 log reduction (DNA damage)	(Kang et al., 2018)
		S. marcescens	1500 J/L		5 log reduction	(Crook et al., 2015)
		S. marcescens	N.A.		Inactivation rate constant *Z*-value: 3.0 cm^2/mJ	(Zhang and Lai, 2022)
		S. senftenberg	2000 J/L		5 log reduction	(Crook et al., 2015)
		Stenotrophomonas sp.	N.A.	5 min	Total reduction	(Aisha and Maznah, 2018)
		Synechococcus sp.		240 min	Total reduction	
		Y. enterocolitica	1500 J/L	N.A.	5 log reduction	(Crook et al., 2015)
		C. sporogenes	72 mJ/cm^2		Log reduction to undetectable limit	(Narita et al., 2020)
	Spores	*B. subtilis* spores	N.A.		46–80 % reduction	(Hadi et al., 2020)
			40.4 mJ/cm^2		2 log reduction	(Wang et al., 2010)
		G. stearothermophilus spores	23.72 J/mL		4.05 log reduction	(Gayán et al., 2013)
		A. niger spores	250 mJ/cm^2		Log reduction to undetectable limit	(Narita et al., 2020)
		T. rubrum spores	36 mJ/cm^2		Log reduction to undetectable limit	
	Fungi	*S. cerevisiae* KE162	0.7 kJ/m^2	1 min	7.1 log reduction	(Schenk et al., 2011)
			3.3 kJ/m^2	2 min	Total reduction	
			N.A.	5 min	2.5 log reduction	(Char et al., 2010)
		S. cerevisiae	<0.8 kJ/L	N.A.	6 log reduction	(Diesler et al., 2019)
		Candida sp.	1.0 kJ/L		6 log reduction	
	Yeast	*H. uvarum*	<0.8 kJ/L		6 log reduction	
		P. fermentans	1.0 kJ/L		6 log reduction	
	Viruses	Aerosolized ssRNA viruses	0.71 mJ/cm^2		90 % reduction	(Hadi et al., 2020)
		Aichi virus	0.24 J/cm^2		1.71–4.43 log reduction	(Fino and Kniel, 2008)
		Airborne PRRSV	110 V; 1.21 mJ/cm^2		3 log reduction	(Hadi et al., 2020)
		Bacteriophage MS2	1 mW/cm^2	30 min	5.8 log reduction	(Guettari et al., 2021)
			60–240 μW/cm^2; 3.20 mJ/cm^2	3 s–6 min	1 log reduction	(Tseng and Li, 2007)
			40 W; 4.32 to 7.20 J/cm^2	N.A.	3–4 log reduction	(Vo et al., 2009)

Table 2 (*continued*)

UVC lamps (wavelength)	Type of pathogens	Name	Characteristics of UVC lamp (e.g.: dose)	Time of exposure	Effect	References
		Enveloped Influenza A viruses (H5N1 and H1N1)	1.8 J/cm^2		4 log reduction	(Hadi et al., 2020)
		Feline calicivirus	0.24 J/cm^2		2.12–4.46 log reduction	(Fino and Kniel, 2008)
		Influenza A (H5N1)	15 W; 1.8 J/cm^2		4.5 log reduction	(Lorè et al., 2011)
			6 mJ/cm^2		log reduction to undetectable limit	(Narita et al., 2020)
		MERS CoV	200 mJ/cm^2	5 min	≥3.7 log reduction	(Eickmann et al., 2020)
			N.A.	5-10 min	Total reduction	(Garciá De Abajo et al., 2020)
		MHV	6.6 J/m^2	N.A	90 % reduction	
		Non-enveloped MS2 bacteriophage	4.32 J/cm^2	N.A.	3 log reduction	(Hadi et al., 2020)
		Bacteriophage P22	N.A.		Inactivation rate constant Z-value: 2.9 cm^2/mJ	(Zhang and Lai, 2022)
		Rotaviruses	25 mJ/cm^2		3 log reduction	(Kucharski et al., 2020)
		SARS-CoV	134 $\mu W/cm^2$; 0.12 J/cm^2		4 log reduction	(Kariwa and Takashima, 2006)
		SARS-CoV-1	N.A.	15 min	Total reduction ≤1.0 *$TCID_{50}$ (log) per ml	(Darnell et al., 2004)
		SARS-CoV-2	17,000 $\mu J/cm^2$	20 s	>6 log reduction	(Liang et al., 2021)
		1.3 mJ/cm^2	N.A.	1 log reduction	(Ma et al., 2021)	
		10.4 mJ/cm^2	N.A.	99.99 % reduction	(Sesti-Costa et al., 2022)	
UV-LEDs with UVA (365 nm) pretreatment followed by UVC (265 nm)	Bacteria Virus	*E. coli* Bacteriophage MS2	N.A	N.A.	N.A.	(Song et al., 2019)
UVC-LEDs (255-280 nm)	Bacteria	*P. aeruginosa* biofilms	7.9 mJ/cm^2		4 log reduction	(Taylor et al., 2010)
	Virus	SARS-CoV-2	37.5 mJ/cm^2	1 s 10 s 20 s	87.4 % inactivation 99.9 % inactivation total inactivation	(Inagaki et al., 2020)
			798 $\mu J/cm^2$	10 s	>6 log reduction	(Liang et al., 2021)
Pulsed-xenon UV (200 to 1100 nm)	Virus	Bacteriophage MS2	0.96 J/cm^2 per pulse	1 s	4.87 log reduction (glass beads); 0.64 log reduction (powdered black pepper); 0.12 log reduction (garlic); 0.68 log reduction (chopped mint)	(Loutreul et al., 2013)
		Hepatitis A virus	0.06-0.09 J/cm^2	2–3 s	5 log reduction	(Jean et al., 2011)
		SARS-CoV-2	N.A	5 min	4.79 log reduction	(Drph et al., 2020)
		Murine NoV-1	0.06-0.09 J/cm^2	2–3 s	3.6 log reduction	(Jean et al., 2011)
			3.45 J/cm^2 per pulse	2-6 s	3 log reduction	(Vimont et al., 2015)
Excimer Lamps - XeBr (285 nm)	Bacteria	*E. coli O157:H7*	75 mJ/cm^2	N.A.	1.83 log reduction	(Yin et al., 2015)

Legend: *A. acidocaldarius - Alicyclobacillus acidocaldarius*; *A. hydrophila - Aeromonas hydrophila*; *B. cereus - Bacillus cereus*; *B. coagulans - Bacillus coagulans*; *B. licheniformis - Bacillus licheniformis*; *B. subtilis - Bacillus subtilis*; *E. coli - Escherichia coli*; *G. stearothermophilus* spores - *Geobacillus stearothermophilus* spores; *H. uvarum - Hanseniaspora uvarum*; *L. gormanii – Legionella gormanii*; *L. innocua - Listeria innocua*; *L. longbeachae – Legionella longbeachae*; *L. monocytogenes - Listeria monocytogenes*; *L. pneumophila - Legionella pneumophila*; *M. pulcherrima - Metschnikowia pulcherrima*; MERS-CoV - Middle East respiratory syndrome–related coronavirus; MHV - Murine hepatitis virus; N.A. – not available; *P. aeruginosa - Pseudomonas aeruginosa*; *P. fermentans - Pichia fermentans*; *P. guilliermondii - Pichia guilliermondii*; *PRRSV* - Porcine reproductive and respiratory syndrome virus; *R. dairenensis - Rhodotorula dairenensis*; SARS-CoV-1 - Severe acute respiratory syndrome coronavirus 1; SARS-CoV-2 - Severe acute respiratory syndrome coronavirus 2; *S. aureus - Staphylococcus aureus*; *S. cerevisiae - Saccharomyces cerevisiae*; *S. enterica* serovar Typhimurium - *Salmonella enterica* serovar Typhimurium; *S. liquefaciens - Serratia liquefaciens*; *S. marcescens - Serratia marcescen*; *S. senftenberg - Salmonella senftenberg*; sp – species; *$TCID_{50}$ (Median Tissue Culture Infectious Dose) assay is one method used to verify the viral titer of a testing virus. Host tissue cells are cultured on a well plate titer, and then varying dilutions of the testing viral fluid are added to the wells. After incubation, the percentage of infected wells is observed for each dilution, and the results are used to calculate the $TCID_{50}$ value; *T. rubrum - Trichophyton rubrum*; *Y. enterocolitica - Yersinia enterocolitica.*

disinfection treatment (Simões et al., 2008). Moreover, for surface disinfection purposes, UVC irradiation is more efficient when applied to a thin and smooth surface without shadow areas (Raeiszadeh and Adeli, 2020). For example, the UV disinfection of N95 masks (a porous and multilayer structure) is more than a smooth surface material, due to its irregular and complex structure (Tseng and Li, 2007).

Regarding the use of UVC for liquid disinfection, the dose delivery of UVC light depends on the optical (transparency and absorptivity) and physical properties (viscosity and density) of the medium (Singh et al., 2021). As a result, the antimicrobial activity of UVC light varies with the amount of soluble and suspended solids. The presence of suspended solids induces absorption, and promotes reflection and scattering, decreasing the UVC effectiveness (Delorme et al., 2020). In addition, the presence of soluble solids causes an increase in the viscosity of the medium and consequently attenuates antimicrobial UVC effects (Amano et al., 2020; Singh et al., 2021). This helps to explain the lower UVC inactivation of *E. coli* in orange juice (with the presence of coloured and pulp particles) when compared to peptone water (Char et al., 2010). These authors reported a 4.5 log cycle reduction of *E. coli* in apple juice and peptone water when using 18.7 kJ/m^2 of UVC dose for 5 min, but only observed a 0.5 log cycle reduction when disinfecting the orange juice (Char et al., 2010).

For the disinfection of viruses in aerosols, it is important to ensure sufficient UVC light to disinfect huge volumes of air under distinct environmental conditions, including temperature and relative humidity (Bhardwaj et al., 2021).

3.3. Treatment parameters

The microbial susceptibility to UVC irradiation can be potentiated by heat, but it does not depend on the pH and water activity (a_w) (Gayán et al., 2012b). Values of a_w between 0.94 and 0.99 did not affect the

Table 3
Studies evaluating the inactivation of pathogens by far-UVC lamps at 222 nm.

Type of pathogens	Name	Characteristics of 222 nm far-UVC lamp (e.g. dose)	Time of exposure	Effect	References
Bacteria	*S. aureus*	6 mJ/cm^2	N.A.	4 log reduction	(Narita et al., 2020)
		23 mJ/cm^2	8 h	98.4 % reduction	(Eadie et al., 2022)
		0.29 mW/cm^2	N.A.	Lipid peroxidation	(Kang et al., 2018)
	L. monocytogenes *S. enterica* serovar Typhimurium *E. coli* O157:H7	20 W; 0.29 mW/cm^2		Decrease of respiratory chain dehydrogenase activity Cell membrane damage DNA damage 5 log reduction	
		75 mJ/cm^2		2.81 log reduction	(Yin et al., 2015)
	P. aeruginosa	24 mJ/cm^2		4 log reduction	(Narita et al., 2020)
	C. sporogenes	36 mJ/cm^2		Log reduction to undetectable limit	
	E. coli	N.A.		Inactivation rate constant Z-value: 4.9 cm^2/mJ	(Zhang and Lai, 2022)
	P. alcaligenes			Inactivation rate constant Z-value: 7.5 cm^2/mJ	
	S. marcescens			Inactivation rate constant Z-value: 3.3 cm^2/mJ	
	S. epidermidis			Inactivation rate constant Z-value: 6.3 cm^2/mJ	
Spores	*B. subtilis* spores	21.6 mJ/cm^2		2 log reduction	(Wang et al., 2010)
	A. niger spores	500 mJ/cm^2		Log reduction to undetectable limit	(Narita et al., 2020)
	T. rubrum spores	72 mJ/cm^2			
	B. cereus, C. sporogenes and *C. difficile* endospores	96 mJ/cm^2	N.A.		
Fungi	*C. albicans*	72 mJ/cm^2			
Virus	Aerosolized human coronaviruses (alpha HCoV-229E and beta HCoV-OC43)	1.7 and 1.2 mJ/cm^2		99.9 % reduction	(Buonanno et al., 2020)
		3 mJ/cm^2	8 min	90 % viral reduction	
			25 min	99.9 % viral reduction (aerosols)	
	Influenza A (H1N1)	1.28 mJ/cm^2	N.A.	90 % reduction	
		2 mJ/cm^2; 120 μW/cm^2		1.3 log reduction	(Welch et al., 2018)
		6 mJ/cm^2		Log reduction to undetectable limit	(Narita et al., 2020)
	SARS-CoV-2	0.1 mW/cm^2	10 s	88.5 % reduction	(Kitagawa et al., 2021a)
		3 mJ/cm^2	30 s	99.7 % reduction	
		280 μJ/cm^2	40 s	<2 log reduction	(Liang et al., 2021)
		Inactivation rate constants: 1.52 -1.42 cm^2/mJ	N.A.	N.A.	(Ma et al., 2021)
		Inactivation rate constant: 0.64 cm^2/mJ; dose 8 mJ/cm^2		99.99 % reduction	(Robinson et al., 2022)
		2417.7 mJ/cm^2		99.99 % reduction	(Sesti-Costa et al., 2022)
	Bacteriophage P22	N.A.		Inactivation rate constant Z-value: 3 cm^2/mJ	(Zhang and Lai, 2022)

Legend: *A. niger - Aspergillus niger*; *B. cereus – Bacillus cereus*; *B. subtilis - Bacillus subtilis*; *C. albicans – Candida albicans*; *C. difficile – Clostridium difficile*; *C. sporogenes - Clostridium sporogenes*; *C. sporogenes - Clostridium sporogenes*; *E. coli - Escherichia coli*; *L. monocytogenes - Listeria monocytogenes*; N.A. – not available; *P. aeruginosa - Pseudomonas aeruginosa*; *P. alcaligenes - Pseudomonas alcaligenes*; *S. aureus - Staphylococcus aureus*; *S. enterica* serovar *Typhimurium - Salmonella enterica* serovar *Typhimurium*; *S. epidermidis - Staphylococcus epidermidis*; *S. marcescens - Serratia marcescens*; SARS-CoV-1 - Severe acute respiratory syndrome coronavirus 1; SARS-CoV-2 - Severe acute respiratory syndrome coronavirus 2; *T. rubrum - Trichophyton rubrum.*

susceptibility of *S. enterica* Typhimurium in juices to UVC (Gayán et al., 2012b). However, combined UVC and heat treatment, at temperatures between 50 and 60 °C, was synergistic for inactivation of *S. enterica* Typhimurium (Gayán et al., 2012b). Another study reported a synergistic effect, causing 5 log cycles of inactivation of *E. coli* in liquid food when using UV irradiation (23.72 J/mL) and a temperature of 55 °C for 3.6 min (Gayán et al., 2012a). The number of envelope-injured cells was higher after combined UVC irradiation and heat exposure than after heating treatment alone. The impact of this combined approach was reported to be higher in the outer membrane than in the inner membrane (Gayán et al., 2012a). Thereby, it seems that the combination of UV light with heat promotes the destabilization of cell envelopes or hinders the ability of cells to repair these structures (Gayán et al., 2012a). Another study reported an abrupt increase of 2 log cycles inactivation when applying UVC (27.10 J/mL) at temperatures between 25 and 60 °C, towards *Bacillus coagulans* spores in liquid media (Gayán et al., 2013). Besides that, the influence of temperature depends also on the light source (described in Section 4 UVC light sources) (Demeersseman et al., 2023).

In general, higher relative humidity induces a decrease in the UVC-based inactivation of microorganisms (Demeersseman et al., 2023). The reduction in susceptibility occurs due to the formation of a water layer around the microorganisms, protecting them against UVC-induced DNA or RNA disruption (Demeersseman et al., 2023). The impact of relative humidity on UVC disinfection is more pronounced for bacteria than for viruses (Raeiszadeh and Adeli, 2020). This is reinforced by the results of Tseng and Li (2007) who reported that the susceptibility to UVC of the influenza virus, *S. marcescens*, mycobacteria, and *E. coli* increased with a decrease in the relative humidity. Moreover, the UV dose to achieve the same viral reduction on surfaces under 85 % relative humidity was higher than that needed for 55 % of relative humidity (Tseng and Li, 2007).

3.4. Equipment parameters and design

Different UVC equipment can be selected for disinfection, depending on the process conditions. In general, UVC reactors, UVC lamp units, and UVC robots are the most common equipment. It is further essential to select a suitable light source (explained in Section 4) and positioning to ensure desired disinfection levels (Mehta et al., 2023).

The design of the equipment is also extremely important to avoid non-irradiated areas and to ensure homogenous disinfection. For example, in UVC-based liquid disinfection, different designs of UV reactors cause distinct inactivation efficacy (Gayán et al., 2011). The bacterial inactivation increases with turbulence since the turbulent flow guarantees a homogeneous distribution of UVC irradiation (Koutchma et al., 2007). Numerical simulations could be applied to predict UV disinfection performance if reliable dose-response information is available for the target microorganism

(Sun et al., 2022). Thereby, UV systems could be designed to output the required fluence at the designed flow rates and UV transmittance to ensure a powerful inactivation of pathogens (Sun et al., 2022). More recently, novel algorithms were described for UVC robots development aiming to potentiate disinfection effectiveness (Mehta et al., 2023).

4. Applications of UVC light sources

A wide range of light sources have been used under UVC wavelengths: mercury-vapour UVC lamps; UVC light-emitting diodes (UVC-LEDs); continuous and pulsed xenon arc lamps; excimer lamps: krypton chloride excimer (KrCl) lamps and krypton-bromide excimer (KrBr) lamps (Guettari et al., 2021); and microplasma lamps (Raeiszadeh and Taghipour, 2019). Data about pathogens reduction using UVC light sources are presented in Tables 2 and 3. The main advantages and limitations of the different UVC light sources are listed in Table 4.

4.1. Mercury-vapour UVC lamps

Mercury-vapour lamps can be divided into three classes, namely low-pressure (254 nm), medium-pressure (220-580 nm), and high-pressure lamps (220-1000 nm) (Demeersseman et al., 2023). The conventional UVC light at 254 nm with 30–40 % power efficiencies generated by low-pressure mercury-vapour lamps remains the most common disinfection unit source due to the electrical efficiency and low cost (Hadi et al., 2020). These lamps have a lifetime of 8000 h, and a 30 W power output with peak emission at 254 nm (Guettari et al., 2021). However, precautions should be taken when using such lamps, due to the presence of mercury, their low mechanical stability, and the potential generation of ozone. Mercury-vapour lamps need warm-up time contrarily to UVC-LEDs and pulsed xenon UVC lamps (Demeersseman et al., 2023). Moreover, the output of mercury-vapour lamps varies greatly with temperature, whereas this effect is much smaller for the other light sources (Demeersseman et al., 2023).

It is considered that 254 nm is the optimal wavelength for maximum germicidal action, inactivating in some cases bacterial spores, which are much more resistant to inactivation than their vegetative cells (Blatchley et al., 2005). As an example, a low-pressure mercury lamp at 254 nm, with doses in the range of 15 to 20 mJ/cm^2 causes 90 % (1 log) of *Bacillus cereus* spores inactivation, and for doses up to 30 mJ/cm^2, inactivation of 4 log could be achieved for aqueous suspensions of spores (Blatchley et al., 2005). Another study showed higher *Bacillus subtilis* spores inactivation in dairy products through a pretreatment for 60 s using a UVC lamp (254 nm; 2.37 J/mL) followed by thermal treatment at 110 °C for 30 s (Delorme et al., 2020). Conventional UVC lights were also able to eradicate *Stenotrophomonas* sp. and *P. aeruginosa* after a relatively long period (5 min) of exposure in cave wall paintings (liquid) (Aisha and Maznah, 2018). Other authors demonstrated a 99.9 % inactivation of *E. coli* from air disinfection using a UVC-light source (254 nm) for 60 min (Corrêa et al., 2021). Higher exposure periods (3 h) can be sufficient to eliminate MS2 virus droplets, which were reduced by 3 log after exposure to a 4.32 J/cm^2 UVC dose at a wavelength of 254 nm (Vo et al., 2009). However, other airborne viruses, including the influenza virus and non-enveloped viruses, were also inactivated with lower UVC (254 nm) doses (1.21 mJ/cm^2) (Hadi et al., 2020). Garciá De Abajo et al. (2020) reported a total reduction of murine coronavirus mouse hepatitis virus A-59 (MHV-A59) and Middle East respiratory syndrome coronavirus (MERS-CoV) after 10 min exposure to UVC at 254 nm.

4.2. UVC light-emitting diodes (UVC-LEDs)

To overcome the potential environmental and health warns of mercury, UVC-LEDs (emitting between 255 and 280 nm) have emerged as an alternative solution with efficiencies more than nine times higher than the conventional mercury-vapour UVC lamps (254 nm) when used for water disinfection (Guettari et al., 2021).

Typically, the semiconductor material for UVC-LEDs is aluminum gallium nitride, revealing advantages when compared to UVC lamps such as energy-saving, longer lifetime (25,000–100,000 h), and compact size, but are more expensive than UVC lamps (Nyangaresi et al., 2018).

A recent study showed 87.4 %, 99.9 % and a total inactivation of SARS-CoV-2 after 1, 10 and 20 s of treatment by UVC-LED (280 nm; 37.5 mJ/cm^2), respectively (Inagaki et al., 2020). Moreover, UVC-LEDs have opened a new set of user safety experiences around the healthcare occupational settings reducing by 70 % the bacterial load in medical devices (Ragusa et al., 2020). UVC LED ranging between 16 J/s and 18 J/s were found to reduce *P. aeruginosa*, *S. aureus* and *E. coli* colonies on the stethoscope membrane after >240 h and 2900 cycles of use (Ploydaeng et al., 2021). A UVC dose of 78 J/m^2 was also able to promote 99.99 % inactivation of *P. aeruginosa* biofilms on Teflon and silicone catheter tubes (Taylor et al., 2010). The combination of different UVC-LEDs resulted in a significant increase in pathogens inactivation (Song et al., 2019).

Table 4
Advantages and disadvantages of different UVC light sources.

UVC light sources	Advantages	Disadvantages
Low-pressure mercury lamps (254 nm)	- High efficiency (30-40 %) - Low cost - Technical maturity	- Mercury environmental and health concerns - Significant warm-up time - Their high heat may require additional cooling systems, which increases equipment cost and security risk
Medium-pressure (220-580 nm) and high-mercury lamps (220-1000 nm)	- Can emit a continuous spectral base overlapped	- Possible ozone production
UVC light-emitting diodes (255–280 nm)	- Disinfection efficacy - Application flexibility - Safety (did not use mercury) - Greater efficacy than conventional mercury lamps - Lower energy consumption and a longer lifetime - No warm-up time - Continuous and pulsed	- Missing detectability - Unnoticed loss of up to 70 % of intensity during usage - Low durability of the source - Low investment protection
Pulsed-xenon lamps (200-c1000 nm with a peak at 254 nm)	- Power can reach >50 kW, leading to very high intensity in a single pulse - Rapid - Effective treatment - No chemical residue - No peculiar odour - No warm-up time	- High energy consumption - Critical heat dissipation
Excimer lamps (far-UVC lamps at 222 nm)	- Effective inactivation of microorganisms and viruses - Reduced harm to exposed mammalian skin and eyes - Safe use in occupied spaces - Longer lifespan of UV lamps - Continuous and pulsed	- High energy consumption - Ozone production

When comparing UVC-LEDs with other UVC sources, the first one is reported to be more effective in the inactivation of fungal spores in water environments (Wan et al., 2020). Wan et al. (2023) reported UVC-LEDs as capable to eliminate fungi from drinking water and swimming pools, including species of *Aspergillus*, *Penicillium*, and *Trychophyton*. Hence, in addition to the UVC irradiation disinfection properties, UVC-LEDs are small-sized, do not produce any identified harmful by-products, have broad-spectrum inactivation, and have low maintenance costs (Guettari et al., 2021).

4.3. Pulsed UVC light

Pulsed UVC light has a broad spectrum (200-1000 nm with a peak at 254 nm) emitted from a xenon flash lamp that is delivered in a series of pulses (100 ns to 2 ms). Pulsed UVC light represents a fast and residue-free technology with higher light energy and intensity and deeper penetration than the alternative UVC light sources (Demeersseman et al., 2023). Although having gained approval from Food and Drug Administration (FDA) (<12 J/cm^2), this light source has not been used on a large scale by the food industry (Rowan, 2019). This occurs because there is a lack of basic information about pulsed UV light treatments, such as details of lamp manufacture and geometry, and effects on food products. The target products, the degree and nature of microbial contamination, and the process parameters influence the efficiency of this light source (Rowan, 2019). However, emerging applications include ready-to-eat, freshly-cut, fruit and vegetables along with decontamination of meat and fish products and associated packages (Rowan, 2019). This technology is only efficient for in-package disinfection if packaging materials allow the penetration of UV-pulsed light (glass and plastic) (Heinrich et al., 2015).

Although the main application of pulsed UV is related to food packaging and container disinfection, this technology could be also applied for water disinfection. Pulsed UV-LED irradiation at 280 nm is an attractive alternative for *E. coli* inactivation in water in comparison to continuous UV irradiation, particularly in terms of energy efficiency (Zou et al., 2019). Moreover, this technology is also used for the disinfection of healthcare devices/equipment. Significant inactivation of SARS-CoV-2 from N95 respirators and hard surfaces (>4.79 log and >4.12 log, respectively) was reported from the use of pulsed-xenon UV irradiation for 5 min (Drph et al., 2020).

4.4. Excimer lamps: far-UVC light

Excimer lamps, namely xenon-bromide - XeBr (285 nm), krypton-bromide - KrBr (207 nm) and krypton-chlorine - KrCl (222 nm), could inactivate a wide range of pathogens. For example, xenon lamps inactivated *E. coli*, hepatitis A virus, Murine NoV-1 and SARS-CoV-2 in suspension and on food-contact surfaces (Jean et al., 2011). Moreover, under lower wavelengths, KrBr lamps can inactivate methicillin-resistant *S. aureus* (MRSA) (Hadi et al., 2020).

The most commonly used excimer lamps for UVC disinfection are these of KrCl that emit light at 222 nm, being recognized as far-UVC technology. Far-UVC is a relatively new and effective disinfection method, without high risks to human health as at this wavelength (222 nm) UV light is not able to penetrate the outer layer of skin or the tear layer in the eye, whereas standard UVC light (254 nm) can penetrate and cause damage (Barnard et al., 2020; Bhardwaj et al., 2021). Therefore, contrary from standard UVC light, far-UVC could be used simultaneously with the presence of humans. However, there is a regulatory limit for UVC exposure at 222 nm without being harmful to human health, which is 23 mJ/cm^2 per 8 h of exposure (International Commission on Non-Ionizing Radiation Protection, 2004). Even though, controversies exist regarding its safety (Demeersseman et al., 2023). Ozone production can be considered a side effect of far-UVC lamp operation (Martínez de Alba et al., 2021). Besides that, far-UVC technology has a longer lifespan than the UVC lamps used at 254 nm, which reduces the need for frequent replacement and maintenance (Buonanno et al., 2020). A SWOT analysis comparing strengths, weaknesses, opportunities, and threats between far-UVC and UVC lamps is presented in Fig. 5.

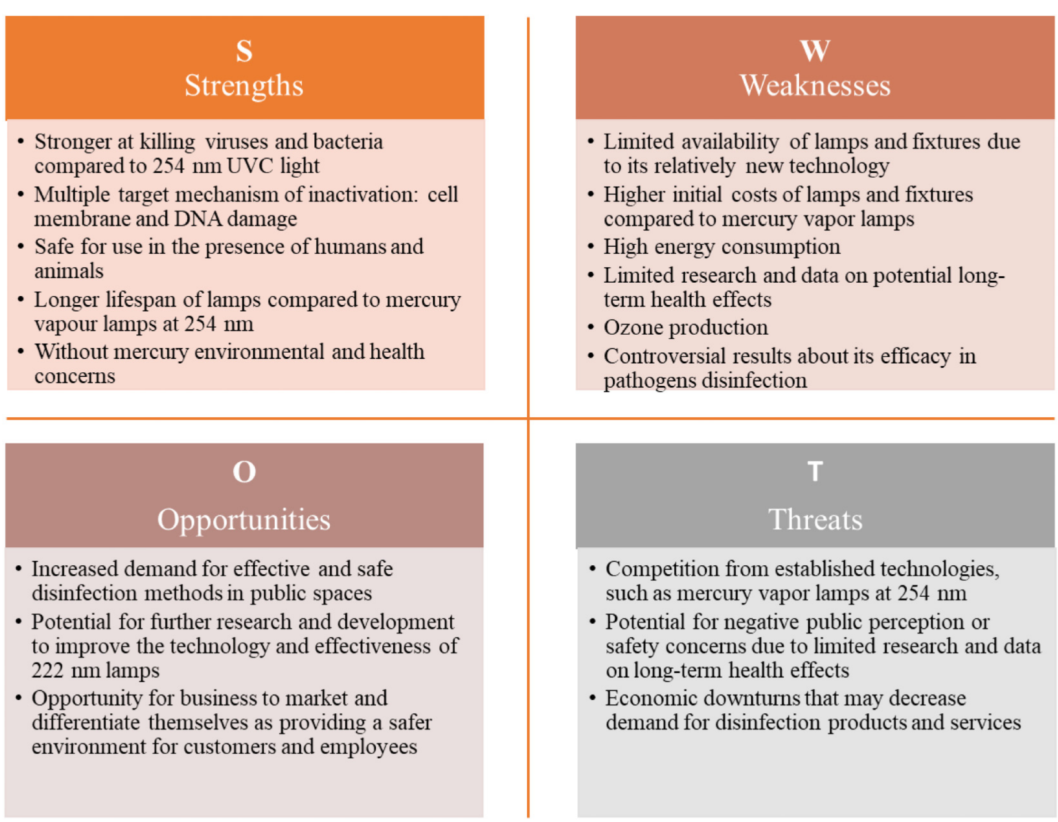

Fig. 5. SWOT analysis of far-UVC (222 nm) in relation to standard UVC light sources.

4.4.1. Far-UVC light: an alternative to standard UVC light sources

Far-UVC is considered to be more efficient for disinfection than standard UVC light sources, including mercury lamps at 254 nm; UVC-LEDs at 280 nm and pulsed-xenon lamps (Ma et al., 2021; Narita et al., 2020; Kang et al., 2018; Zhang and Lai, 2022). Far-UVC lamps irradiating at 222 nm can inactivate Gram-positive bacteria such as *S. aureus* and L. *monocytogenes* and Gram-negative bacteria including *S. enterica* Typhimurium and *E. coli* O157:H7 in a higher extent than standard UVC lamps (254 nm) in phosphate-buffered saline (Kang et al., 2018). This occurs because the bactericidal mechanisms of far-UVC light are different from standard UVC lamps as different cellular materials absorb different UVC emitting wavelengths (Kang et al., 2018). In this case, the mechanism of inactivation of far-UVC irradiation is attributed to cell membrane damage (inactivation of enzymes and lipid peroxidation) in addition to DNA damage, whereas UVC irradiation at 254 nm only affect bacterial DNA (Kang et al., 2018). Far-UVC light can affect the cellular enzymes or lipids in the membrane because amino acids or phospholipids especially absorb UVC radiation of 222 nm (Kang et al., 2018). Moreover, at 222 nm, the production of reactive oxygen species (ROS) occurs, which affect DNA indirectly by inducing oxidative DNA damage (Kang et al., 2018). Diverse studies reinforce the higher efficacy of far-UVC light in relation to alternative UVC sources. Using a UVC dose of 75 mJ/cm^2, *E. coli* O157:H7 in apple juice was greatly inactivated by far-UVC light at 222 nm, achieving a bacterial log reduction of 2.81 (Yin et al., 2015). With the same UVC dose (75 mJ/cm^2), a standard UVC lamp at 254 nm and a XeBr lamp at 285 nm, promoted lower log reduction values (1.95 and 1.83, respectively) (Tables 2 and 3) (Yin et al., 2015). The same occurred for *Bacillus subtilis* spores, with higher inactivation levels at 222 nm (KrCl) (2 log reduction) than at 254 nm, or 172 nm (XeBr), using fluence doses of 21.6, 40.4 and 8710 mJ/cm^2, respectively (Wang et al., 2010). Therefore, far-UVC at 222 nm can be considered a relevant alternative to conventional UVC wavelengths for disinfection, affecting multiple bacterial targets (Kang et al., 2018).

Far-UVC light is currently considered the most effective UVC light source for inactivating airborne viruses (including coronaviruses), causing reductions of 99.9 % (with doses of 1.2-1.7 mJ/cm^2) of aerosolized human coronaviruses such as α-HCoV-229E and β-HCoV-OC43 (Buonanno et al., 2020). Moreover, a far-UVC dose of 1.28 mJ/cm^2 caused 90 % inactivation of influenza virus (Buonanno et al., 2020). Other authors also corroborate this outmost effects of far-UVC (222 nm) in the inactivation of viruses (SARS-CoV-2), with inactivation rates in the range of 1.52-1.42 cm^2/mJ, when compared with UVC-LED at 270 nm (inactivation rates from 0.53 to 0.93 cm^2/mJ) and low-pressure mercury-vapour lamp at 254 nm (inactivation rate of 0.79 cm^2/mJ) (Ma et al., 2021). Eadie et al. (2022) reported that far-UVC was more effective against airborne viruses, including SARS-CoV-2, than bacteria. The enhanced inactivation of viruses by far-UVC was attributed to protein damage (Beck et al., 2018). Kitagawa et al. (2021a) reported the inactivation of 88.5 % and 99.7 % of SARS-CoV-2 in air public spaces by using far-UVC light at 0.1 mW/cm^2 for 10 and 30 s, respectively. The available studies suggest that airborne virus disinfection with far-UVC light (222 nm) at the current regulatory limit would provide a huge reduction in the ambient level of airborne virus in occupied indoor environments (Buonanno et al., 2020). Besides that, some controversial results about far-UVC airborne disinfection efficiency in relation to other UVC sources still exist (Liang et al., 2021). Liang et al. (2021) tested three different UVC sources against SARS-CoV-2 and found that the UVC LED (275 nm) had the best virucidal activity, with log reduction higher than 6 after 10 s of exposure. The mercury lamp (254 nm) reached similar virucidal activity after 20 s of exposure, but the excimer lamp (222 nm) showed limited log reduction (<2) after 40 s of exposure (Liang et al., 2021). Moreover, UVC at 254 nm showed to be more efficient than UVC at 222 nm in inactivating SARS-CoV-2 present in human saliva (Sesti-Costa et al., 2022). In fact, while a dose of 2417.7 mJ/cm^2 at 222 nm was necessary for 99.99 % inactivation of the virus, only 10.4 mJ/cm^2 of UV 254 nm was required for the same effect (Sesti-Costa et al., 2022). Narita et al. (2020) showed that both 222 nm and 254 nm UVC had comparable efficacy towards vegetative bacterial cells, yeasts and viruses (Tables 2 and 3). This similar efficacy of far-UVC (222 nm) and standard UVC (254 nm) in airborne microorganisms inactivation (*E. coli*, *Pseudomonas alcaligenes*, *S. marcescens*, *Staphylococcus epidermidis* and bacteriophage P22) in duct flows was also reported by Zhang and Lai (2022).

4.5. Microplasma UVC lamps

Microplasma UVC lamps were reported as attractive for planar UV water purifiers, due to their ability to monochromatically and spatially homogeneous irradiate at different wavelengths and with distinct pulsation frequencies (Raeiszadeh and Taghipour, 2019). A microplasma UVC dose of 9.9 mJ/cm^2 caused a significant (4 log reduction) inactivation of *E. coli* (Raeiszadeh and Taghipour, 2019). This new mercury-free technology consists of thin microplasma UV lamps that are triggered by at least two interlaced arrays of microcavities, which improves the power output and efficiency of the lamp compared with other UVC light sources (Raeiszadeh and Taghipour, 2019).

5. Complementary UVC disinfection strategies

UVC-based disinfection methods can be implemented in combination with other disinfection strategies to potentiate the antimicrobial action, allowing the use of low UVC doses and/or exposure time (Rutala et al., 2013). The combination of UVC with chemical disinfectants has been widely studied because each treatment has different mechanisms of action and molecular targets, causing complementary antimicrobial effects (Zhang et al., 2020). The combination of hydrogen peroxide vapour or gaseous ozone and UVC irradiation increased *C. difficile* inactivation, in comparison to the action of each treatment alone (Anderson et al., 2018). The pre-treatment with UVC light for 5 min followed by hydrogen peroxide disinfection increased significantly (>30 %) the inactivation of MRSA, vancomycin-resistant enterococci (VRE), and *C. difficile* on surfaces of hospital rooms (Wong et al., 2016). Recently, it was found that the combination of UVC light with gallic acid (a natural molecule with modest antimicrobial activity) promoted a higher antimicrobial disinfection response against *E. coli* in food products when compared to the individual antimicrobial activity of gallic acid (Singh et al., 2021).

In addition to chemical disinfectants, UVC treatments can also be combined with complementary approaches, such as reflective walls to increase UVC disinfection efficiency (Rutala et al., 2013). The reflectivity of the material of a disinfection reactor influences the UVC light dose received across all sides of a contaminated object, increasing the effectivity on more remote and shadowing zones that in the absence of reflective walls would receive lower UV doses (Stojalowski and Fairfoull, 2021). Polytetrafluoroethylene is a great reflective material, but other strategies applied reflective wall coatings or paints (Stojalowski and Fairfoull, 2021). According to Rutala et al. (2013), combining UVC lamps with a reflective wall coating (Lumacept) promoted a faster inactivation of *S. aureus* (5 log CFU/cm^2 reduction) and *C. difficile* (3 log CFU/cm^2 reduction), to <20 and 30 min, respectively, than when only UVC lamps were used. This coating, Lumacept, contains nanoscale inorganic crystal oxides which are transparent to the penetration of UVC and polymer binders as well as functional additives with chemical structures that are minimally absorbent of UVC (Rutala et al., 2013). Moreover, a 20 % increase in UVC effectiveness can be achieved by the employment of reflective paint and humidifiers (Guettari et al., 2021).

6. UVC technological devices: robots

The adoption of automatic UVC technological devices (robots) during the Covid-19 pandemic gave support to fight the spread of pathogens in enclosed areas where contact between people was frequent, particularly in hospitals (Graeffe et al., 2023), work offices (Srivastava et al., 2021), schools, shopping centers, and airports (Robots, 2021). These devices already played a significant role in avoiding manual supervision and maneuvering of the disinfection treatment, helping to mitigate the potential spread of pathogens (Mehta et al., 2023). Moreover, UVC devices are a valuable alternative to ecotoxic disinfectants (do not lead to any residues), making them an environmentally friendly disinfection method.

The average market price of the prevailing UVC robots is approximately $55,165, ranging between $10,000 and $125,000 (Zaman et al., 2022). Overall, such robots are composed of more than one UVC lamp mounted on mobile platforms that offer movement autonomy (Mehta et al., 2023). However, additional accessories can be included, increasing their cost. UVC devices are usually validated by the manufacturer of the disinfection product and by a certified laboratory, using detailed protocols provided by the Ultraviolet Germicidal Irradiation Handbook (Inagaki et al., 2020). Representative commercially available UVC devices (including robots) and recent research contributions for UVC robots development are presented in Table 5.

AVA UV disinfection robots showed to be ideal for office, warehouse, and factory cleaning by disinfecting air and surface with UVC light achieving percentages of microbial reduction of 99.99 % (AVA Robotics Inc., 2021). These robots from AVA Robotics use four UVC lamps with 30 W to perform disinfection treatments autonomously and take advantage of intelligent features to schedule the disinfection treatments (AVA Robotics Inc., 2021). After completing the treatment, the lights turn off and the robot returns to the charging station on its own (AVA Robotics Inc., 2021). Moreover, the administrator receives an email report to confirm completion (AVA Robotics Inc., 2021). Since it has 99 % effectiveness against SARS-CoV-2, it is considered an effective disinfection approach (AVA Robotics Inc., 2021).

For air disinfection, upper-room ultraviolet germicidal irradiation systems are commonly installed on top of indoor spaces, allowing the safe occupancy of the spaces below (Park et al., 2022). RaLUX® UVC Stand (Radium, 2022) and Soluva® Air F, W, M10, D, V models were certified to inactivate 99.91 % of viruses, bacteria and other pathogens. These UVC devices can be applied to the disinfection of public transport or in large rooms and buildings with forced-air heating and cooling systems (Heraeus, 2023). RaLUX conceals UVC bulbs within, ensuring no light exposure outside of the device, to protect humans (Radium, 2022). The UVD robot is also a recent device with the ability to disinfect airports and transport stations, keeping travellers safe by providing a microbiologically safe environment (Robots, 2021). It inactivates up to 99.99 % of pathogens, including MRSA and *C. difficile* (Robots, 2021).

A new UVC robot named UVC-PURGE was recently developed and shown to be able to cause bacterial inactivation up to 95.33 % (Zaman et al., 2022). Although it was not tested against SARS-CoV-2, the authors found that UVC-PURGE successfully inactivated *S. aureus* using a UVC dose of 6.06 mJ·s/cm^2, being this dose much higher than the conventional inactivation dose for SARS-CoV-2 (3.75 mJ·s/cm^2) (Zaman et al., 2022). Therefore, it is expected that UVC-PURGE could effectively disinfect indoor environments contaminated with SARS-CoV-2. UVBot robot was developed to mitigate the spread of noroviruses in occupational spaces. With a UV dose of 45 mJ/cm^2, this robot inactivated 99.9 % of the tulane virus in 30 s, which is sufficient to inactivate other airborne viruses (including SARS-CoV-2) and bacteria (Wang et al., 2022).

The high efficiency of UVC devices to disinfect air may be explained by their ability to increase the equivalent ventilation rate, which is a solution to create microbiologically safe indoor environments (Reed, 2010). When UVC devices inactivate 63 % of infectious microorganisms in a room, one Equivalent Air Change (Eq ACH) has occurred (Reed, 2010). It is important to compare various air disinfection strategies in terms of Eq ACH per hour to evaluate their efficacy (Reed, 2010). The greater the infectivity, the greater the Eq ACH needed for protection.

Among different purposes for UVC robots, most of them are used to fight microbial spread in hospital environments and even in ambulances (Table 5). Examples of these robots are i-Robot UVC (Guettari et al., 2021), Tru-D™ (Mahida et al., 2013), Violet from Akara Robotics (McGinn et al., 2021), THOR UVC™ (Finsen technologies LTD, 2021), SteriPro (Graeffe et al., 2023) as well as many others presented in Table 5. Tru-D™ claims to reduce on average 99.99 % of nosocomial pathogens including MRSA, VRE, and *C. difficile* in healthcare environments, after 45 min of exposure (Nerandzic et al., 2010). This system is considered a more efficient alternative than vapourized hydrogen peroxide or dry-mist hydrogen peroxide, both commonly used for terminal disinfection of patient rooms (Nerandzic et al., 2010). Tru-D™ can promote a log reduction higher than 4 after 30-40 min and 60-90 min to decontaminate single rooms at 12 mJ/cm^2 (for vegetative bacteria) and 22 mJ/cm^2 (for spores), respectively (Mahida et al., 2013; Nerandzic et al., 2010). This device has eight sensors, which measure the reflected UVC intensity of surfaces and walls and automatically stop if sensors detect the threshold reflected UVC dose, completing its disinfection cycle (Mahida et al., 2013; Nerandzic et al., 2010). The other UVC robots share some characteristics such as being portable, lightweight, and easy to operate. Similar disinfection efficiencies in the elimination of harmful pathogens were also reported for these UVC robots. In addition, monetary savings of >5000 € a day for hospitals resulted from avoiding manual work for surface disinfection (Elaine, 2020).

It is important to highlight that some UVC robots provide complementary disinfection strategies. For example, the TMiRob (Mobile Robot Guide, 2020) and the DR1001 (Medical Expo, 2023), have dual-mode disinfection using UVC lamps and hydrogen peroxide. Robot Y-C2 developed by VitroSteril uses three different technologies based on the operators` needs: cold plasma, hydrogen peroxide and UVC rays (VitroSteril, 2022).

Xenex Disinfection Services recently developed a pulsed-xenon disinfection system to reduce the load of SARS-CoV-2 on hard surfaces and N95 respirators (Drph et al., 2020). The use of this system resulted in log reductions up to 4.12 and 4.79 of SARS-CoV-2 after 5 min in hard surfaces and N95 respirators, respectively (Drph et al., 2020). The inactivation of 99.9 % SARS-CoV-2, with total doses of 1.8 mJ/cm^2, 3.0 mJ/cm^2, and 23 mJ/cm^2 and exposure times of 5, 15 and 30 s was obtained by the use of UVC-LED at 265, 280, and 300 nm wavelength, respectively (Minamikawa et al., 2021).

MUVi-UVC recently developed by Mobile UV Innovations Pty Ltd. for medical equipment disinfection was able to inactivate 99.999 % of *S. aureus*, *P. aeruginosa*, *Candida auris*, SARS-CoV-2, *E. coli* and *S. enterica* Typhimurium for 5 min (Khan et al., 2022). However, the same robot needs more time (30 min) to inactivate *Aspergillus niger* spores (Khan et al., 2022).

Other applications for UVC robots include the sterilization of liquids and packaging using pulsed UVC light. An example is PureBright, which uses flashlamps filled with inert gases (xenon, krypton) causing 4.8-7.2 log reductions of different viruses with a dose of 1.0 J/cm^2 (Table 5) (Mandal et al., 2020). The UVC robot system developed by MIT's Computer Science and Artificial Intelligence Laboratory (CSAIL) in collaboration with Ava Robotics and the Greater Boston Food Bank is considered a great strategy for fast room disinfection, due to its power to disinfect a warehouse floor in 30 min with fast disinfection cycles of 5.1 s (Rachel, 2020).

The general part of these devices can disinfect objects at 360° overcoming shadowing issues like the HERO 21 robot, which in a period of 5 to 10 min can disinfect 14 rooms with 8-UVC lamps at 254 nm inactivating *B. subtilis* spores and human coronavirus 229E (ICA Group, 2022). Another robot, UV-360 Room Sanitizer, certified by the US Environmental Protection Agency for safety on air pollutants, reduced 72 % of microorganisms presented in operating theatres, after 5 min of exposure (Bosco et al., 2022). Among these different UVC devices/robot, only three of them use far-UVC light at 222 nm: Care222™ (Kitagawa et al., 2021b); Cleanse® Portal (Healhté By Lighting Science, 2020) and Germicidal Robot (G-robot) (Mehta et al., 2022).

6.1. Algorithms in technological UVC devices

Complex UVC technology devices require a symbiotic interaction between a wide set of technologies including robotics, electronics, mechanics, and programmation (Guettari et al., 2021). Current research has been

Table 5
Examples of UVC robots and devices developed for disinfection purposes.

UVC devices	Characteristics	Company/origin	References
i-Robot UVC	- Eliminating SARS-CoV-2 in hospital areas - Composed of 10 UVC lamps with a central column	- University of Tunis, Tunisia	(Guettari et al., 2021)
Tru-D™	- Eradication of all microorganisms from an operating theatre - 22,000 μWs/cm^2 resulted in 3-4 log reductions of MRSA, multi--resistant *Acinetobacter*, VRE, and *Aspergillus* - 30-40 min to decontaminate single rooms at 12,000 μWs/cm^2 (for vegetative bacteria) and 60-90 min at the sporicidal setting (22,000 μWs/cm^2) - Does not integrate any navigation function	- Rapid Disinfection Services Ltd., United Kingdom	(Mahida et al., 2013; Nerandzic et al., 2010).
UVC radiation device (Tru-D)	Test rooms: - 12,000 μWs/cm^2, 15 min ➔ >99.9 % vegetative bacteria reduction - 36,000 μWs/cm^2, 50 min ➔ 99.8 % *C. difficile* spores reduction Rooms occupied by patients with MRSA: - 15 min ➔ 1.30 log reduction - $1,25,000	- Lumalier Corporation, United States	(Rutala et al., 2014)
PX-UV disinfection system	- Reduce the load of SARS-CoV-2 on hard surfaces and N95 respirators - Hard surfaces: disinfection for 1, 2, and 5 min resulted in 3.53 log, >4.54 log, and >4.12 log reductions, respectively - N95 respirators: disinfection for 5 min resulted in >4.79 log reduction	- Xenex Disinfection Services, United States	(Drph et al., 2020)
Violet	- Disinfection cycle of 15 min - Can make hospital cleaning up to 8 times faster than the norm, with disinfection taking as little as 5 min - 90-99 % success rate of eliminating germ concentration - Disinfect surfaces in a radiology setting - Can be deployed alongside humans - UVGI successfully inactivated all of measurable microbial load (84-95 %) - Dimensions: 35 × 35 × 150 cm - >1-log reduction of most germs at distances of 1-2 m from the surface	- Akara Robotics, Ireland	(Elaine, 2020; McGinn et al., 2021)
Care222™	- A 222 nm UVC-emitting Kr-Cl excimer lamp module for disinfection of toilet surfaces contaminated with aerobic bacteria - Toilet seat: 0.40 log reduction - Control panel of the electric toilet seat: 0.45 log reduction - Top of the toilet paper holder: 0.80 log reduction - Door handle: 0.20 log reduction - Floor: 0.05 log reduction	- Ushio Inc., Japan	(Kitagawa et al., 2021b)
AVA UV Disinfection Robots	- Clean air and surfaces - disinfection against SARS-CoV-2 - Ideal for office, warehouse, and factory cleaning	- AVA Robots Inc., United States	(AVA Robotics Inc., 2021)
MIT CSAIL	- Disinfect a warehouse floor in 0.5 h	- MIT's CSAIL + Ava Robotics + Greater Boston Food Bank	(Rachel, 2020)
UVD Robots	- Can disinfect larger areas such as airports, hospitals and other transport stations - Destroys 99.99 % of microorganisms after 10 min (254 nm), including SARS-CoV-2 - Can disinfect 4600 m^2/h in large rooms - The lamps require replacement after 12,000 h of use - Does not have the ability to work with the presence of people in the room - Dimensions: 93 × 66 × 171 (cm) - Mobile base, multiple LiDAR sensors, camera, array of UV lamps	- UVD robots, part of Blue ocean robotics, Denmark	(Robots, 2021)
PureBright	- Dose of 1.0 J/cm^2 of pulsed UVC light achieved reductions of 4.8-7.2 log of Sindbis, HSV-1, vaccinia, polio-1, EMC, HAV, CPV, BPV and SV40 - Sterilization of liquid products: annular pulsed-light processing chamber with a pulsed-light lamp inside a highly reflective material; tube-quartz made; arrangement-spherical, spiral; metallic electrodes; flashlamps-filled with inert gases (xenon, krypton) - Sterilization of flexible film for aseptic packaging - Sterilization of preformed containers	- PurePulse® (Maxwell Technologies), United States and Switzerland	(Mandal et al., 2020)
XENEX LightStrike	- Pulsed xenon ultraviolet device (200-325 nm) - Inactivate 99.99 % SARS-CoV-2 and MRSA, 95 % *C. difficile*, and 100 % VRE - Disinfection cycle of 5.1 s - Cost $81,000 - Does not integrate any navigation function	- Xenex Disinfection Services, United States	(Stibich and Stachowiak, 2016)
UVC Robots	- Combat SARS-CoV-2 and other viruses such as MERS and Ebola - Reduce the need for powerful chemicals that present health and safety risks to the operator - Complete the ceiling-to-floor sanitization process within 2-3 h - If a human comes within eight meters of the system, it will automatically shut down	- UV Systems UK, part of the Topline Group, United Kingdom	(OMRON Corporation, 2021)

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Table 5 (*continued*)

UVC devices	Characteristics	Company/origin	References
iBEN-M10	- With wi-fi enabled, tracks, and records its path to provide complete validation that an area is SARS-CoV-2-free - If it fails to sanitize an area due to obstruction, for example, it reports the information so the issue can be resolved - 8 UVC lamps - 3 m light coverage radius - 99.99 % inactivation rate - 600 μW/cm^2 light intensity at 1 m position - Make up for the shortage of fixed-point disinfection, no contamination or residue - Autonomous navigation, flexible obstacle avoidance	- iBen Robot Service, China	(iBEN Robot, 2021)
UVC disinfection chamber	- With 254 nm light, the SmartDosage UV™ technology ensures the correct dose of germicidal energy every time - 100 % reduction in *Klebsiella* - 71.4 % reduction in *Acinetobacter* - Prevent the transmission of *Candida*	- SKYTRON, United States	(SKYTRON, 2021)
THOR UVC™	- Tracking software to give you accurate usage data - Promote bacteria and viruses reductions of 6 log - Used in hospitals, gyms and dentists - Fully portable, easy to transport and operate - Automatic scanning and cleaning with optimum UVC dose - Perfect solution for disinfecting ambulances	- Finsen technologies, United Kingdom	(Finsen technologies LTD, 2021)
Connor UVC disinfection robot	- Indoor SARS-CoV-2 disinfection - Equipped with UVC germicidal lamps (254 nm), automatic disinfectant spray, sensor technology, and battery life of up to 8 h	- RobotLAB technologies, India	(RobotLAB technologies, 2021)
ChargeMax and UVC Wand Sterilizer	- Inactivate the pathogens including viruses and bacteria on surfaces objects - Safe application for hospitals, classrooms, and different work environments	- Cetrix Technologies Ltd., United States	(CETRIX Thinking Fresh, 2021)
DONTICS UVC Tower	- Commonly used to minimize SARS-CoV-2 risk in dental clinics - Disinfect rooms within 5 min - Use a delayed timer to avoid any human exposure	- Dr Ajay Bajaj, India	(Rajeev Chitguppi, 2020)
UVC Scan Plus sanitizing machine	- Able to disinfect objects in 360° and measure the temperature of humans - Has camera and scanner to take photos - Can be used in airports, malls, supermarkets, apartments etc.	- Eurotek Environmental Private Limited, India	(Eurotek Environmental Private Limited, 2021)
Air Sanitizing Bar X50	- Occupants can remain in the room while the device is working	- 59S Global Leader UVC Disinfection, China	(59S Global Leader UVC Disinfection, 2021)
Handsfree UVC Decontamination device	- Automated device - Calculate the dose of UVC energy to the treatment area and decontaminate huge areas in a small-time from distance with remote control	- UVC cleaning systems Inc., United States	(UVC cleaning systems Inc., 2021)
UV air sanitisers and germicidal UV lamps	- Irradiate air and exposed surfaces but it is only used in unoccupied rooms - Rooms as large as 3500 sq. ft. can be treated with one fixture	- Atlantic ultraviolet corporation, United States	(Atlantic Ultraviolet Corporation, n.d.)
UV room disinfection system	- Equipped with modern sensors and can be effective in hospitals and indoor spaces	- Microchem laboratories, United States	(Microchem Laboratory, 2021)
RaLUX® UVC Stand	- The UVC lamp is inside the device. By irradiating the air with UVC light, potentially present viruses can be deactivated by rendering their DNA harmless. Subsequently, the purified air is ejected back into the room	- Radium, Germany	(Radium, 2022)
UVC air disinfection device	- Rheem's third generation products, RM3 - 99.9 % disinfection efficiency to clean air carrying the COVID-19 virus	- Rheem's, United States	(Srivastava et al., 2021)
Claranor Pulsed Light System	- Tecum-Mobile Decontamination Unit with multiple xenon lamps - Light pulse duration of 300 ms; pulse fluence of 3 J/cm2; input voltage of 3000 V - The lamps were 20 cm cylindrical xenon flash lamps - Fluence of 3 J/cm^2 was effective to reduce *L. monocytogenes*, *E. coli*, *S. enterica* typhimurium and *S. aureus* for 2.24, 2.29, 2.25 and 2.12 log CFU/g on the surface of dry fermented salami.	- Claranor, France	(Rajkovic et al., 2017)
Ultra Violet Disinfection Robot® (UVD-R)	- Reduced the microbial growth of *C. auris* on the surfaces after manual cleaning and disinfection in hospital - *C. auris* growth in the lag phase was inhibited by the UVC irradiation but not in the presence of the rim shadows	- Clean Room Solutions, United Kingdom	(Astrid et al., 2021)
Soluva® Air F	- Disinfection of indoor air - Clean viruses (with a tested virus reduction of 99.99 %), bacteria and other pathogens from the room air and almost silently with the help of UVC light - With high air flow rate, it provides fast and safe protection	- Heraeus Group, Germany	(Heraeus, 2023)
Soluva® Air W	- Appropriate for medical practices, waiting rooms, offices, classrooms, meeting rooms and hotel rooms		
Soluva® Air M10	- Possible applications are production areas, cafeterias, cold storage rooms, hotel lobbies or auditoriums in schools - Disinfects up to 1100 m^3/h of air		
Soluva® Zone H	- Surface disinfection: disinfection of vehicle interiors, chairs, sensitive electronics, surfaces and equipment used by rescue workers, police, fire departments		

Table 5 (*continued*)

UVC devices	Characteristics	Company/origin	References
	- Tests with the University Hospital Tübingen confirmed a cleaning effect of 99.999 % (virus) on surfaces		
Soluva® Air D	- Useful for disinfection air in large rooms and in buildings with forced-air heating and cooling systems (hotel, public institution, offices, museum, airport)		
Soluva® Air V	- Air purifier for buses and other public transportation: 2 devices per 12 m of bus are recommended and 1 cycle time per bus (10-12 min) - The UVC (254 nm) purification unit simply mounts on the ceiling of the passenger cabin to protect passengers - 99.91 % inactivation of viruses, bacteria and other pathogens (proven by the Fraunhofer Institute)		
SteriPro	- Hospital-grade device offering a guaranteed 99.9999 % disinfection result - It can be operated continuously 24/7 and takes only 15 min to disinfect an operating room (size 63m^3) with a 6 log reduction. It can perform up to 70 disinfections per day - Automatic room boundary detection (using laser technology) - Total 2000 W UVC lamps - Uses standard 220-240 AC, 16A outlets - Operator-safe by implementing advanced motion detection technology - Remote control with operating tablet - Self-diagnostic features that ensure reliable operation - Own www connection	- UVC solutions, Slovenia	(Graeffe et al., 2023; steripro, 2023)
miniTM UVC	- Safely and autonomously disinfects indoor public space, from hospitals to hotel rooms, airports and commercial centers - Disinfect more quickly or cover larger sites - Disinfects as programmed, every time - Reduce staff absences or healthcare associated infections	- BlueBotics, A ZAPI Group Company, Switzerland	(BlueBotics, 2023)
OhmniClean	- Self-driving UVC disinfection robot that eliminates 99.99 % of pathogens - High-level Disinfection in Significantly Less Time - Thoroughly Disinfect Large Spaces in a Single Cycle - Eliminate Shadowing & Leave Zero Missed Surfaces	- OhmniLabs Inc., California, United States	(OhmniLabs, 2023)
THERAFLEX-UV-Plasma system	- Pathogen inactivation treatment of platelet concentrates - Inactivation of 3 single-strand RNA viruses in platelet concentrates: SARS-CoV-1 ($\geq$3.4 log), CCHFV ($\geq$2.2 log) and NiV ($\geq$4.3 log) with UVC doses of 0.2 J/cm^2	- Macopharma, France	(Eickmann et al., 2020)
UV disinfection robot BKS-UV-200	- Medical grade sterilization High-intensity radiation, 99.99 % sterilization rate - High-intensity radiation superimposition, cumulative UV-light intensity of up to 1500 μW/cm^2, 10-min sterilization area of 40 m^2 (*S. albus*) and 3 min coronavirus elimination - Extermination rate of over 99.99 % against coronavirus, influenza virus, *S. albus*, *E. coli* and other pathogens - Autonomous navigation and smart obstacle avoidance	- BooCax Technology Co., Ltd., China	(Medical Expo, 2023)
UV disinfection robot SIFROBOT	- Indoor use only - Using time: 80 % after 300 cycles - Autonomy: 6 h - Remote control function - Automatic planning/manual route planning - Cost: $12,700–17,950	- SIFSOF, California, United States	(Medical Expo, 2023)
Robot Y-C2	- For environmental sterilization both in human presence and in absence, which provides for the autonomous mapping of the environment - Uses 3 different technologies according to the operator's needs: cold plasma, hydrogen peroxide and UVC rays	- VitroSteril, Italy	(VitroSteril, 2022)
Hospital disinfection robot AMY-M2-W2 UVC	- Able to perform 360-degree full-coverage surface sterilization - The circulation system is equipped by a high-power ultraviolet radiation tube set and microorganisms (fungus, bacteria, and viruses) in the air can be effectively eliminated up to 99.99 % by the intensive UV rays when flowing through the airway of the circulation system - UV radiation mode can be activated when no human activities are sensed	- Hangzhou Amy Robot Co., Ltd., China	(Medical Expo, 2023)
HUSKY UV	- Disinfects surfaces, floors and walls using UVC light (254 nm) - Fully autonomous or remotely operated mobile robot - Fast and complete disinfection (up to 99.99 % removal of viruses and bacteria) - Integrated air filtration and purification system - Optimized security through redundant and independent systems - Disinfection speed: 450 m^2/h - Autonomy: 3 h of disinfection	- Tame-Care and E-Cobot, France	(Medical Expo, 2023)
Techi	- Useful for the disinfection of hospitals, hotel lobbies, malls, narrow corridors, retail and airport	- Techmetics, California, United States	(Medical Expo, 2023)
Smart	- Micron level atomization, autonomous mobile, intelligent obstacle avoidance - Flexible use of UV lamp - Perform tasks independently to reduce the risk of personnel exposure to infection	- Shenzhen EAI Technology, China	(Medical Expo, 2023)

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Table 5 (*continued*)

UVC devices	Characteristics	Company/origin	References
DiSiRt	- UVC light eliminates up to 99.99 % of microorganisms in hospitals, clinics, patient rooms, offices, registrations, communication routes shops, shopping malls, warehouses, schools, kindergartens factories, offices, public transport: buses, metro, trains, planes, private apartments, and houses - The motion of the robot with UVC lamps eliminates shadow zones and increases the effectiveness of disinfection - Additional ozonizer activation allows for disinfection of spaces where the light does not reach	- ACCREA Engineering, Poland	(Medical Expo, 2023)
DR1001	- Has the function of microbial disinfection + purify air + improve air quality - Dry mist hydrogen peroxide + ultraviolet dual-mode disinfection - Pathogen removal efficiency can reach 99.99 % - Automatic space modeling with laser + vision system - Independent disinfection, no manual intervention required - Autonomy: 6 h	- Bioteke Corporation, China	(Medical Expo, 2023)
Laska UVD Robot and Yezhik Robot	- Effectiveness 99.99 %; 12 UV lamps 254 nm - UV lamps life cycle: 9000 h	- Aitheon, United States, Ukraine and India	(Aitheon, 2023)
UVC-PURGE	- For indoor environment disinfection - Reduction (90.9-95.33 %) of *S. epidermidis*, *S. aureus* and *S. saprophyticus* - Irradiation of 9.375 mJ·s/cm^2 to 6.82 mJ·s/cm^2 - Cost $800	- Institute of Science and Technology, Bangladesh + Department of Computer Science and Engineering, Bangladesh	(Zaman et al., 2022)
Su-01	- Autonomy: 6 h - The spores on the surface of environmental substances (smooth surface, rough, porous surface) and all kind of multidrug-resistant bacteria can be killed (99.9999 %) - The air will be clean in 150 min - Cost $10,000	- Wuhan Donglisheng mechanical and electrical technology Co., Ltd., China	(Wuhan Donglisheng ME Technol. Co., 2021)
Helios	- Kills bacteria and other harmful microorganisms, with a disinfection rate of 99 % - Large working space - Unmanned operation - Cost $25,000	- UVC Light, United Kingdom	(UVC Light, 2020)
ZENZOE Easy, Pro, Plus	- 8 min to disinfect 25 m^2 - Inactivation of microorganisms up to 99.99 % - Useful to disinfect hospitals, commercial centers, and airports - Cost $90,000	- Development: ASTI Mobile Robotics and BOOS Technical Lighting - Distribution: Aura Light, Portugal	(Aura Light, 2023)
HERO21	- Achieves a level of disinfection of 99.99 % with a 360° coverage - Autonomy: 3.5 h - Disinfect 14 rooms (25 m^2) in 5-10 min - 8 UVC low-pressure mercury vapour discharge lamps; 130-W, 254 nm - 2.67 mJ·cm^{-2}·s^{-1} at 1 m and 0.29 mJ·cm^{-2}·s^{-1} at 3 m distances achieve 99 % inactivation of *B. subtilis* spores - 10-30 s with doses of 2 - 6 mJ·cm^{-2}·s^{-1} achieve 99 % inactivation of human coronavirus 229E - Cost $70,000	- ICA Group, Germany	(ICA Group, 2022)
HoST-UVC Disinfection Robot	- Disinfects 1000 m^2 area in 1 h - 360° disinfection of floor and surfaces from 8 UVC 254 nm lamps - Eradicate with 99.9 % confidence level of many pathogens including coronavirus - Useful for hospitals and nursing homes, retail malls, education institutions, gyms and fitness centers, hotels, commercial building, retail malls, factory plant floor	- Mobile Industrial Robots, Denmark	(Mobile Industrial Robots, 2023)
SAM's technology	- Deactivates up to 99.9999 % (log6) of bacteria, viruses and other pathogens - Autonomously drives around objects to eliminate shadows	- Loop Robots, Netherlands	(Loop Robots, 2022)
5G IoT UVC LED	- For hospital disinfection and sterilization - Certified by the Certified Medical Assistant - Satisfactory and constant ultraviolet dry spray particles within 10 μm - 99 % inactivation of microorganisms (virus, fungus, bacteria, protozoa) in the air - The irradiance of each lamp is 200 μW/cm^2	- Nigeria	(Matthew et al., 2022)
UV-360 Room Sanitizer	- Composed of 4 lamps that emit UVC light (254 nm) for a total energy of 325 W - Equipped with sensors that detect movement during operation and then switch off the lamps for security reasons if an obstacle is detected - UVC radiation reaches up to 2.4 m from the source - Certified by the US Environmental Protection Agency for safety on air pollutants - Disinfection of operating theatres: 72 % reduction of microorganisms after 5 min	- Ultraviolet Device, Inc., United States	(Bosco et al., 2022)
UVBot system	- 2D LiDAR: control the robot remotely, check the disinfection map, and add virtual walls to the map - SLAM algorithm generates a map of the space being disinfected - 99.9 % reduction of tulane virus at a UV dose of 45 mJ/cm^2 in 30 s	- Whiteside Area Career Center, United States	(Wang et al., 2022)

Table 5 (*continued*)

UVC devices	Characteristics	Company/origin	References
	- 360° disinfection coverage - Autonomy: 2.5 h - Only used without the presence of people - Cost < $1000		
TMiRob	- Application for hospitals, to help reset surgery rooms and intensive care units - UV lamp + ultra-dry mist hydrogen peroxide nozzle	- TMI Robotics Technology, China	(Mobile Robot Guide, 2020)
DECIMATOR	- Kill rate of 99.9 % in 10 min - Autonomous navigation system - Integrate 2D LiDAR and a 3D depth camera - Can operate for up to 4 h after 30 min of charging	- Addverb Technologies, worldwide	(Addverb Technologies, 2023)
Smart Guard UV	- UV Pulsed Xenon system - Autonomy: 8 h after 4 h of charging - 99.9 % effective against Coronavirus, Norovirus, *Salmonella*, *E. coli*, *C. auris*, and MRSA - Autonomous navigation system - Integrate 2D LiDAR and a 3D depth camera - Cost: $157,000	- Smart Guard, United States	(SmartGuardUV, 2021)
ASSUM (autonomous sanitary sterilization ultraviolet machine)	- UVC dose between 200 and 500 mJ/cm^2 inactivates SARS-CoV-2 by ≥99.91 % to ≥99.99 % for 12 min at a minimum distance of 100 cm - 4 UVC Phillips lamps of 254 nm in 360° (600 × 900 × 1500 mm each)	- MTS Tech, Barcelona	(Lorca-Oró et al., 2022)
Germicidal Robot (G-robot)	- Far-UVC (222 nm) - Automation - By using a manipulator for UV disinfection, high-touch surfaces and areas that are cluttered and shadowed can be disinfected more effectively - LiDAR and SLAM system	- Toronto Metropolitan University, United States	(Mehta et al., 2022)
ROBUV-SUR and ROBUV-AIR	- ROBUV-SUR: Cleaning surfaces, rooms and corridors - ROBUV-AIR: Operates alongside people traversing corridors and hallways while cleaning air - Intel RealSense cameras with LIDAR laser sensors generating distance field image - 22 mJ/cm^2 reduces the number of viruses by 99.9999 % in 25 s	- University of Technology, Poland	(Dzierżek et al., 2022)
UV Disinfection Robot	- Sterilization of surfaces - Uses 2 24 V UVC LED lamps; Arduino uno; motor driver; ultrasonic sensor; bluetooth driver; 12 V batteries, PIR sensor - 50 s for the inactivation of coronavirus present on the surface - Disinfection is done as it programmed without human intervention - Able to move around the room and on detecting humans or animals with the help of PIR motion sensor, it turns OFF the UV lights automatically - Avoid obstacles by measuring collision distance with the help of ultrasonic sensor	- Department Of Computer Science and Engineering, Nagpur Institute Of Technology, India	(Golange et al., 2022)
UV LED Robot	- Terminal decontamination of SARS-CoV-2 patient rooms - 100 % inactivation of SARS-CoV-2 in airborne infection isolation rooms - 92.4 % inactivation of SARS-CoV-2 in isolation rooms	- Korea University Medical Center, Korea	(Seok et al., 2022)
ARIS-K2 SEIT-UV	- Anti-virus robot that disinfects 1000 m^2 in 150 min - Accredited by universities, research labs and hospitals that it kills 99.99 % of germs - Mapping-based navigation - Uniform disinfection - Robots communicate with doors and elevators and can move across floors - Motion detection: 2D LiDAR, 3D Camera - Automatic charging - Disinfects 25 m^2 in 10 min - Autonomy: 3 h	- Youibot, China - -Milvus Robotics, Turkey	(WAKU Robotics GmbH, 2023) (Milvus Robotics, 2020)
Multifunctional Disinfection Robot	- Combined disinfection: Philips UV germicidal lamp (15 W, 253.7 nm) ➔ kills 99.99 % of bacteria on surfaces; spray nozzles located at a height of 400 mm ➔ simultaneous combined treatment of rooms with equipment and furniture, including high-quality processing of the lower surfaces of tables, chairs and beds; air filtration mode ➔ safe air disinfection is ensured in the presence of a person	- Department of Mechanics Al-Farabi Kazakh National University, Republic of Kazakhstan	(Tuleshov et al., 2022)
Cleanse® Portal	- First-ever human-safe far-UVC (222 nm) technology - Sanitises clothing and personal belongings: make a slow 360° turn for 20 s	- Healthe, New York	(Healhté By Lighting Science, 2020)
Disinfection Robot	- Disinfects public transport using UVC rays - Can climb small ladders with Tri-star wheels, composed of three 130 mm onmiwheels - IR and thermal sensors for the detection of obstacles and people, respectively	- School of Mechatronics Engineering at Ricardo Palma University, Peru	(Hurtado et al., 2022)
UVC1 multipurpose robot	- 8 UVC lights 254 nm, 36 watt - Remotely controllable in a range of 2 km - Atmega128 microcontroller is utilized to navigate the robot and send the operator's commands to the system	- Faculty of Mechanical and Energy Engineering, Shahid Beheshti University, Tehran, Iran	(Sedaghat et al., 2022)

(continued on next page)

Table 5 (*continued*)

UVC devices	Characteristics	Company/origin	References
Ultraviolet-C Healthcare Surface Disinfection Robot	- Inactivation of 80 % of the microbes (SARS and Ebola viruses, and *E. coli*) in hospital environment - Autonomy: 2 h after 5 h plugged - Autonomy software with 3 modular subsystems: Augmented Monte Carlo Localization based localization; Rapidly Exploring Random Tree* based path planning; and Spanning Tree Coverage based coverage path planning - Sterilization of 53.82–77.55 % out of all surfaces in 11.57–20.56 s/m^2 - ROBOTIS TurtleBot3 model Waffle Pi - 2D LiDAR and a magnetic, angular rate, and gravity (MARG) sensor	- School of Electrical Engineering and Informatics Institut Teknologi Bandung	(Kurniawan and Adiprawita, 2021)
Automated UVC Light Mobile Robot (AUMR)	- 8 UVC-C lamps (60 watts each) - Can be operated automatically as it has a magnetic line sensor and employs a fuzzy inference system algorithm for its movement - Sterilization and disinfection of the air (aerosol) in isolation or other medical rooms but also of the floors in rooms or hallways - Disinfection method: 10 min; 36 W × 6 lamps	- School of Electrical Engineering, Telkom University, Indonesia	(Rusdinar et al., 2021)
Artificial Intelligence Disinfection roBOT (AIDBOT)	- 5 RGB-D cameras, 3 laser sensors (2D LiDAR sensors SICK TiM551) and SLAM - 99.9 % sterilization effect: 11 s for *S. aureus*, 15 s for *P. aeruginosa*, and 19 s for *E. coli* at a distance of 1 m (UVC doses 15 to 28 J/m^2)	- Artificial Intelligence and Robotics Institute, Korea - Institute of Science and Technology, Seoul 02792, Korea	(Hong et al., 2021)
UltraBot	- Fully autonomous and safe for people robot for UVC disinfection of warehouses, shopping malls, open office spaces, campuses, hospitals - LiDAR and SLAM systems:10 ultrasonic sensors and 4 Intel RealSense RGB-D cameras to collision detection and obstacle avoidance	- Skolkovo Institute of Science and Technology Moscow, Russia	(Mikhailovskiy et al., 2021)
Arborea Intellbird	- Robot 1: filter glass 40 W UVC at 245–256 nm light - Robot 2: quartz glass 450 W UVC at 185–254 nm light + ozone generation at 185 nm	- Arborea Intellbird, Salamanca, Spain	(Martínez de Alba et al., 2021)
MUVi-UVC	- Composed of an enclosed booth with 3 UVC lights at 240 nm each with 4 bulbs - Developed for disinfecting mobile medical equipment - 99.999 % inactivation of *S. aureus* and MRSA, *P. aeruginosa* and resistant *P. aeruginosa* (PA219), *C. auris*, SARS-CoV-2, *E. coli* and *S. enterica typhi* for 5 min - 99.999 % inactivation of spores of *A. niger* after 30 min	- Mobile UV Innovations Pty Ltd., Australia	(Khan et al., 2022)

Legend: *A. niger – Aspergillus niger*; BPV – Bovine papillomavirus; *C. auris - Candida auris*; *C. difficile - Clostridium difficile*; CCHFV - Crimean–Congo haemorrhagic fever virus; CPV – Canine Parvovirus; *E. coli – Escherichia coli*; EMC – Encephalomyocarditis Virus; HAV – Hepatitis A; HSV-1 - herpes simplex virus type 1; *L. monocytogenes – Listeria monocytogenes*; LiDAR - light detection and ranging; MERS-CoV - Middle East respiratory syndrome coronavirus; MRSA - methicillin-resistant *Staphylococcus aureus*; NiV - Nipah virus; *P. aeruginosa – Pseudomonas aeruginosa*; *S. albus - Staphylococcus albus*; *S. aureus - Staphylococcus aureus*; *S. enterica Typhimurium - Salmonella enterica Typhimurium*; *S. epidermidis - Staphylococcus epidermidis*; *S. saprophyticus - Staphylococcus saprophyticus*; SARS-CoV-1 - Severe acute respiratory syndrome coronavirus 1; SARS-CoV-2 - Severe acute respiratory syndrome coronavirus 2; SLAM - Simultaneous localization and mapping; SV40 - Simian virus 40; VRE - Vancomycin-resistant Enterococci.

focused on hardware development to create autonomous algorithms to maximize the performance and efficiency of disinfection (Mehta et al., 2023). It is already possible to program the mobility of robots using Bluetooth devices without the need for ongoing human presence at the disinfection site (Guettari et al., 2021). Some authors suggest building a roadmap for planning the trajectory of automated robots to optimize the dose of UVC irradiation and achieve an optimal, faster, and cheaper disinfection treatment (Guettari et al., 2021; Marques et al., 2021). Marques et al. (2021) implemented a two-stage solver that uses a Linear Program to achieve dwell times and a Travelling Salesman Problem to program the robot movement without collisions. The maximum speed of the robot end-effectors tested was 0.5 m/s. For dosage planning, they considered the visibility and exposure of each surface to UV light by calculating an irradiance matrix using a Graphics Processing Unit (GPU) (Marques et al., 2021). The results of that work showed that the surfaces tested required a minimum disinfection fluence of 280 J/cm^2 and a constant radiant flux power of 80 W to achieve a 3 log reduction of SARS-CoV-2 (Marques et al., 2021).

Some UVC robots have simultaneous localization and mapping (SLAM) systems and LiDAR sensors, such as UVD Robot, developed by Blue ocean robotics (Robots, 2021), UVBot system (Wang et al., 2022), DECIMATOR (Addverb Technologies, 2023), Smart Guard UV (SmartGuardUV, 2021), AIDBOT (Hong et al., 2021) and UltraBot (Mikhailovskiy et al., 2021). These systems allow a safe service and navigation of the disinfecting robot with distance sensors and cameras, measuring the angles and distances of obstacles (Wang et al., 2022). Another robot (i-Robot) uses different systems of ultrasound and infrared sensors to measure distances, avoid obstacles, and detect motion. For instance, if people are detected around, it turns off the UVC lamps (Guettari et al., 2021).

UVC Robots (named Handsfree UVC decontamination devices) can automatically calculate the amount of UVC energy necessary to apply in each region (UVC cleaning systems Inc., 2021). The algorithm used ensures that all the areas in the environment receive adequate UV dosage (Mehta et al., 2023). Nevertheless, the use of computational fluid dynamics can be a very useful tool to estimate the UV dose for disinfection considering the area to disinfect, the target pathogens, and the regulatory aspects to be considered (Srivastava et al., 2021). The i-Robot UVC carries software to plan the disinfectant time considering the area to be disinfected, the temperature, and the humidity rate (Guettari et al., 2021).

6.2. Are UVC robots safe for humans?

Most of the studies that utilize UVC devices use pulsed xenon-UV technology followed by low-pressure mercury lamps and far-UVC. Therefore, UVC robots available in the market are often not suitable to operate in the simultaneous presence of humans. Only far-UVC devices with wavelengths of 222 nm have been suggested as viable for use in occupied rooms, as this wavelength might have more limited health effects (Graeffe et al., 2023). However, this safety aspect remains dubious (Graeffe et al., 2023).

Care222™ using a 222 nm UVC-emitting KrCl excimer lamp module was found to be an alternative disinfection system for intermittently occupied spaces such as public toilets, being less harmful to humans (Kitagawa et al., 2021b). The CFU of aerobic bacteria collected from bathroom surfaces (e.g. toilet seat, a control panel of the electric toilet seat, and the top of the toilet paper holder) were reduced by 50 % when compared to non-treated surfaces after 18 h of exposure to UVC (Kitagawa et al., 2021b). Mehta et al. (2022) recently developed an advantageous far-UVC robot (G-Robot) over commercially available UVC robots, including its ability to be used in a context of human presence, and its improved disinfection effectiveness for cluttered and shadowed spaces (Mehta et al., 2022). Cleanse® Portal, developed by Healthé, was the first-ever human-safe far-UVC technology, disinfecting clothing and personal belongings in 20 s while covering 360° (Healhté By Lighting Science, 2020).

6.3. Limitations of UVC technological devices

6.3.1. Operational issues

UVC devices are increasingly advocated as a simple solution for the immediate disinfection of rooms and spaces in one process and are also attractive due to automation and apparent cost savings by reducing disinfection staff efforts. Despite offering a non-touch technology, UVC disinfection robots do not remove the biologically contaminated material (Diab-El Schahawi et al., 2021). Thus, UVC disinfection is typically complemented by manual cleaning and the application of chemical disinfectants (Astrid et al., 2021). Moreover, UVC disinfection does not offer the persistence of some chemical disinfectants and has limitations in penetrating organic and inorganic materials, reinforcing the relevance of a pre-cleaning process and complementary chemical-based disinfection (Astrid et al., 2021). Elgujja et al. (2020) listed several limitations to existing applications of UV surface decontamination, with the key finding being that shadowed areas remain difficult to disinfect. A solution for shadowing limitations includes the use of a reflective chamber or reflective surfaces (Demeersseman et al., 2023).

Further technological development in sensing and smart aspects would allow a higher reproducibility, quality assurance and efficacy of the disinfection process while ensuring reduced maintenance costs. Analysis of the capital and operating costs of UVC robots for disinfection remains to be done. It is acceptable that UVC robots are more expensive than traditional chemical disinfectants. However, the return on investment will largely depend on the acquisition and energy costs.

6.3.2. Environmental and health safety issues

The environmental and health safety risks from using UVC irradiation vary with the UVC light source used. If UVC mercury lamps are used, environmental and health concerns from mercury use can be highlighted (Nyangaresi et al., 2018). Some UVC sources may generate ozone and other harmful gases, which may have respiratory implications (Claus, 2021). The Environmental Protection Agency (EPA) advises that UVC lamps that emit ozone should not be used in closed premises without ventilation (Environmental Protection Agency - EPA, 2014). Another impact of UVC on atmospheric chemistry is the dramatic increase of pollutant microparticles and gas phase compounds, which affect indoor air quality (Graeffe et al., 2023).

Most of the existing UVC robots suffer from the inability to be used if a person is presented in a disinfecting environment, due to the potential risks of damaging skin and eyes, and even possible carcinogenic effects (Garciá De Abajo et al., 2020). However, these risks can be prevented by using a UVC disinfection system that does not require human intervention or using protective equipment against UVC light (Demeersseman et al., 2023). Only far-UVC devices have been accepted to be used in the presence of people (Kitagawa et al., 2021a). Most of the safety requirements regarding UVC exposure are based on the guidelines of The International Commission on Non-Ionizing Radiation Protection (2004). Since the hazardous effects of UVC depend on the wavelength, the maximum exposure limit for radiation with a wavelength of 270 nm is 3 mJ/cm^2 and for 254 nm is 6 mJ/cm^2. Naturally, for the lower radiation wavelength of 222 nm (far-UVC), the maximum amount of light to which humans can be safely exposed is higher (23 mJ/cm^2; for 8 h) (International Commission on Non-Ionizing Radiation Protection, 2004).

7. Conclusions and perspectives

The SARS-CoV-2 pandemic led to an exponential interest in developing UVC-based devices for indoor space disinfection in addition to conventional preventive measures and the use of traditional disinfectants. UVC is a well-known and well-understood technology that could successfully inactivate pathogens, including viruses and bacteria. Therefore, an increased use of UVC-based devices has the potential to reduce the risks of airborne diseases and the dissemination of pathogens on surfaces of public spaces. These systems could not only be a powerful strategy to mitigate disinfection issues on hospital surfaces but are also promising for the food and water industry.

Automated UVC disinfecting solutions, such as UVC robots using advanced technologies emerged in the market, reducing the need for manual work. Contrary to most of the traditional disinfection approaches, UVC robots are recognized for not producing (eco)toxic disinfection by-products, carrying an environmentally friendly status. However, the absence of established protocols and guidelines to validate commercial UVC-based devices towards different pathogens and potential safety issues limit the use of this technology simultaneously with human presence. While some researchers propose that at the wavelength of 222 nm (far-UVC), UVC-based devices efficiently inactivate pathogens without harm to humans, others refer to this wavelength as potentially harmful for unprotected human exposure. Therefore, it is clear that UVC-based technologies are promising for the disinfection of microorganisms present in the air, liquids matrices and on surfaces. However, validation of environmental and public health risks even if potentially reduced, remains elusive.

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CRediT authorship contribution statement

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Data availability

No data was used for the research described in the article.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported.

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