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Science of the Total Environment 792 (2021) 148548

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Review

UVC-based photoinactivation as an efficient tool to control the transmission of coronaviruses

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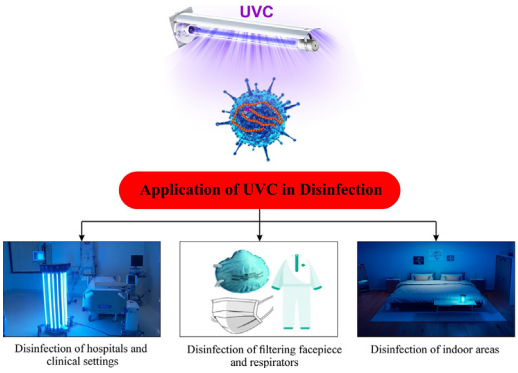
HIGHLIGHTS

- Ultra-violet radiation (UVC) effectively shows antiviral activity against viruses.
- Far UVC (222 nm) has the potential to efficiently inactivate coronaviruses.
- Various UVC-based commercial devices have been made available in recent years.
- Anti-viral efficacy of UVC is assessed against coronaviruses, including SARS-CoV-2.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 13 April 2021
Received in revised form 28 May 2021
Accepted 15 June 2021
Available online 16 June 2021

Editor: Ewa Korzeniewska

Keywords:
Coronaviruses
COVID-19
Disinfection
Irradiation
Photo-inactivation
UVC germicidal activity

ABSTRACT

The ongoing COVID-19 pandemic made us re-realize the importance of environmental disinfection and sanitation in indoor areas, hospitals, and clinical rooms. UVC irradiation of high energy and short wavelengths, especially in the 200–290-nm range possesses the great potential for germicidal disinfection. These properties of UVC allow to damage or destruct the nucleic acids (DNA/RNA) in diverse microbes (e.g., bacteria, fungi, and viruses). UVC light can hence be used as a promising tool for prevention and control of their infection or transmission. The present review offers insights into the historical perspective, mode of action, and recent advancements in the application of UVC-based antiviral therapy against coronaviruses (including SARS CoV-2). Moreover, the application of UVC lights in the sanitization of healthcare units, public places, medical instruments, respirators, and personal protective equipment (PPE) is also discussed. This article, therefore, is expected to deliver a new path for the developments of UVC-based viricidal approach.

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https://doi.org/10.1016/j.scitotenv.2021.148548
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1. Introduction

Virus transmission between individuals typically occurs through contaminated media (including air, water, and food) and inanimate surfaces called fomites (Kutter et al., 2018; Stephens et al., 2019). Airborne and water-borne pathogenic viruses are among the most important global risks faced by mankind. Such viruses can cause disease in human, animal, and plant systems (Artika et al., 2020; Matthews, 2019). These viruses have been the foremost players in causing the deadliest pandemics, as evidenced throughout history. Several viruses, including influenza, Ebola, Hepatitis, human immunodeficiency virus (HIV), and coronaviruses, have contributed to the development of dangerous disease outbreaks (CDCP, 2009; Jakhesara et al., 2014; Spengler et al., 2016). For the effective control of a pandemic, it is desirable to gain detailed information in various respects (e.g., the virus structure, the mechanism of infection in the host organism, and its epidemiology).

Inactivation of the viruses is one of the safest goals to prevent the spread of infections. Such inactivation makes viruses incapable of infection/multiplication by either altering their structural core (DNA/RNA) or by denaturing viral proteins (capsid) in the viral assembly (Guo et al., 2018; Majiya et al., 2018; Zhang et al., 2019a). Broadly, virus inactivation techniques are classified into physical and chemical methods. The former can be further divided into two types: thermal treatment (including pasteurization and dry heating) and non-thermal treatment (such as application of high pressure). The latter includes virus disinfection using detergents, solvents, acidic pH, ethanol, and sodium hypochlorite (WHO, 2004; Zhang et al., 2019b). Recently, the application of non-thermal plasma for viral inactivation is gaining attraction as a chemical-free technique (Pradeep and Chulkyoon, 2016; Xia et al., 2019). The inactivation or disinfection technique largely depends upon the virus composition, structure, and biological function as a better knowledge of these parameters can facilitate virus disinfection at the primary level (WHO, 2004; Wigginton and Kohn, 2012). For example, virus composition and structure data can help predict the reactivity of viral components treated with disinfectants. Moreover, the information about the biological function of viral domains, including virus-host cell interaction, virus assembly, etc. can play an important role in the identification of regions that should be targeted during virus inactivation strategies.

In recent years, several novel approaches have been developed for virus inactivation. These include light-based inactivation (UV/gamma rays), ozone gas treatment, and chemical disinfection using iodine, H_2O_2, cold plasma, etc. (Feng et al., 2011; Filipić et al., 2020; Hadi et al., 2020; Sunnen, 2003; Wolf et al., 2018). Ultra-violet (particularly UVC) irradiation has particularly attracted the researcher's attention as one of the most effective anti-viral strategies. UV light is capable of destroying a broad range of microbes, including bacteria, fungi, yeasts, and viruses. UV light has many other diverse applications (e.g., water disinfection, food sterilization, and surface decontamination) (Caillet-Fauquet et al., 2004; Dai et al., 2012; Kowalski, 2010; Narita et al., 2020; Weiss and Horzinek, 1986). UVC rays can disintegrate the genetic material (DNA/RNA) of microbes by dimerizing the pyrimidines (particularly thymine/uracil) present in the nucleic acids (as discussed further in Section 2.1) (Dai et al., 2012). With respect to viral inactivation, UV irradiation provides several advantages such as broader virus inactivation, manageable costs, and practical applicability. As such, UV irradiation is also applicable as a supplement to the existing techniques.

Across the complete UV spectrum, UVC wavelength at around 260 nm is the most effective for germicidal applications toward harmful viruses in the air, water, and on any kind of environmental surfaces. Likewise, low-pressure mercury vapor lamps also have a strong emission at 254 nm (UV_{254}) with a strong disinfection effect (Daryany et al., 2009; de Roda Husman et al., 2004). However, UVC radiation from the pulsed xenon lamps (around a 230-nm wavelength) can provide more instantaneous energy than conventional mercury lamps. Conventional mercury lamps used for UV emissions are now being replaced by UVC-LED, which has higher virus inactivation efficiency and germicidal wavelengths of 269–276 nm (Kim and Kang, 2020; Kim and Kang, 2018). The most important factors that must be considered before using UV irradiation are UV dose uniformity with respect to time and area, UV flow rate, and the nature of the material being treated (Araud et al., 2020; Welch et al., 2018; WHO, 2004). In the natural environment, viruses may be inactivated (including coronaviruses) simply after sunlight exposure (Fujioka and Yoneyama, 2002; Ratnesar-Shumate et al., 2020; Sagripanti and Lytle, 2020; Silverman et al., 2013). In contrast, ultraviolet germicidal irradiation (UVGI/UVC) can be employed for virus inactivation in public environments, such as healthcare settings, dentistry offices, and hospitals (Lindblad et al., 2019; McDevitt et al., 2008; Tseng and Li, 2007). The use of UVC light has already been accepted for use in water disinfection, medical sanitation, and the generation of sterile conditions. UVGI can be used to disinfect surfaces, air, rooms, and even liquids. It is preferred over heat sterilization and chemical disinfectants. However, the practical use of UV light in public settings has been quite limited, because UV light may pose hazards to human health as a carcinogen (Löfgren, 2017; Schulman and Fisher, 2009).

At present, one of the most desirable applications of UV irradiation appears to be the inactivation of coronaviruses. Coronaviruses are positive-directional and enveloped single-stranded RNA (30–35 kb) viruses that belong to the family *Coronaviridae* (Ortiz-Prado et al., 2020;

Weiss and Leibowitz, 2011). Coronaviruses cause different diseases in humans and animals (Chen et al., 2020). The transmission of coronaviruses through contaminated surfaces and aerosols has proven to be of great significance in the outbreaks of severe acute respiratory syndrome (SARS) coronavirus, middle east respiratory syndrome (MERS) coronavirus, and the severe acute respiratory syndrome coronavirus 2 (SARS CoV-2) pandemic (Acter et al., 2020; Bradley and Bryan, 2019; Harapan et al., 2020; Liu et al., 2020a). Recently, the outbreak of coronavirus disease 2019 (COVID-19) has affected the entire world by causing nearly 3.5 million deaths worldwide. The outbreak of COVID-19, which is caused by a novel SARS CoV-2 strain, was declared to be a global pandemic by the WHO in early March 2020. Human to human transmission of SARS CoV-2 has been identified in hospitals, healthcare units, and personal households via respiratory droplets that are released during speaking, coughing, and sneezing. SARS CoV-2 has a high transmission rate, high reproduction number, and large incubation period. Therefore, the most urgent issue in controlling COVID-19 has been to prevent further infection in public places (Ortiz-Prado et al., 2020; Shereen et al., 2020).

UVC light exposure can be used as a highly effective direct antiviral approach against coronaviruses. To combat viral spread, UVC (290–200 nm) radiation can be effectively employed to decontaminate surfaces infected with coronaviruses. Prior studies have already evaluated the use of UVC light to inactivate enteric viruses, polioviruses, and noroviruses (Bosshard et al., 2013; Jean et al., 2011). In the last few decades, several reports have addressed the inactivation of coronavirus strains using UVC light. However, relatively little is known about the UVC sensitivity of the novel Cov-2 strain. All human coronaviruses have similar genomic sizes. Therefore, the CoV-2 strain is thought to be susceptible to UVC light just as are other coronaviruses. The present article describes the application of UVC light as an effective treatment option against coronaviruses, including the novel SARS CoV-2 virus. The motive behind this work is to estimate the SARS CoV-2 sensitivity toward UVC radiation and to identify the optimal wavelength to inactivate the SARS CoV-2 strain. We have compiled and reviewed the prior studies regarding the UVC-based inactivation of coronavirus (CoV). These results can be used in a primary database for researchers and scientists to develop an effective anti-viral strategy against the ongoing pandemic.

2. UVC irradiation

Ultraviolet (UV) rays make up a region of the electromagnetic spectrum (100–400 nm) that occurs between the extreme of the visible region and the X-ray bands. The UV region can be systematically divided into three different spectral regions according to their wavelength and energy: UVA region (315–400 nm), UVB region (280–315 nm), and UVC region (100–280 nm). Electromagnetic spectra for the three UV spectral regions are presented in Fig. 1.

2.1. Hazardous effects of UVC radiation on human health

Ultraviolet radiation makes up just 8% of the total solar radiation. The amount of UV radiations reaching the Earth's surface can vary widely around the globe with time. Natural UV exposure from sunlight depends upon many environmental factors, as follows: the position and height of the sun, aerosols, latitude, altitude, cloud coverage, haze formation, and the reflection of sunlight from surfaces (Turner et al., 2020). The natural UV forms a small proportion of sunlight although it is generally known to be strong enough to cause skin defects in humans. At the same time, many people are also exposed to artificial UV sources such as vapor lamps, halogen, and fluorescent lamps, tanning beds in the industry, commerce, and recreation.

UV rays (particularly UVB) present in the sunlight can stimulate the body to produce vitamin D_3, which is essential for bone health and normal metabolism (Wacker and Holick, 2013). In addition, moderate UV exposure in humans have beneficial effects, such as regulating endorphin levels; providing protection against sclerosis and melatonin biosynthesis; maintaining normal body rhythm; preventing many seasonal disorders; and reducing the risk of skin diseases such as scleroderma and dermatitis (Juzeniene and Moan, 2012; Kreuter et al., 2006). However, the over-exposure of humans to UVC light can also pose certain adverse implications for individuals and public health. The evidence of damage caused by UV light overexposure to humans has been investigated in some reports and documents (MacKie, 2000; SCHEER, 2017; Schulman and Fisher, 2009; Tenkate et al., 2019; WHO, 1994).

UVC radiation is a known cause of skin cancer, skin aging, and eye damage with a potential to affect the immune system. Human eyes are particularly sensitive to UVC light. Prolonged UVC exposure can cause temporary damage to the eyes and even corneal injuries

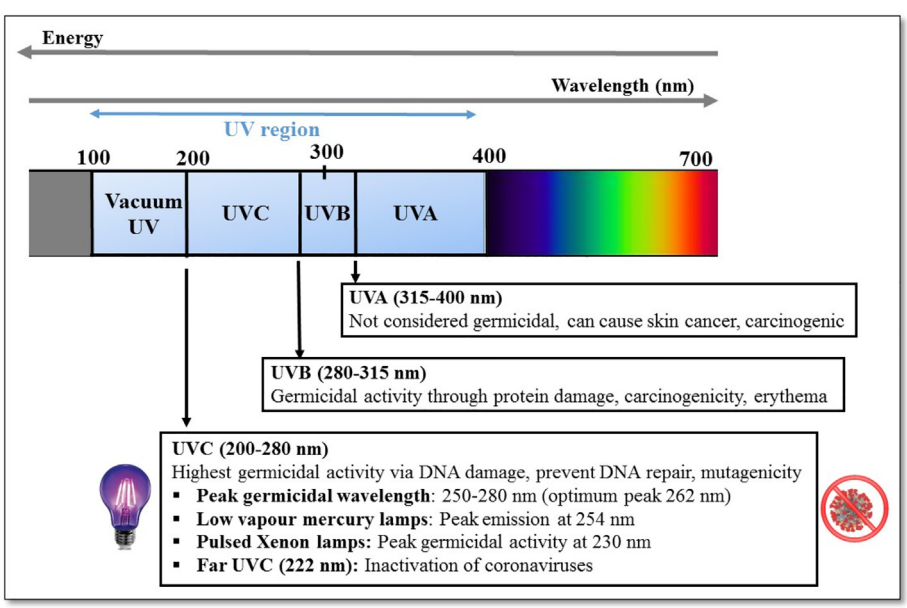

Fig. 1. A diagram showing the ultra-violet (UV) spectrum (100–400 nm), the corresponding wavelength ranges, their germicidal activity, and hazards for human health.

(Welch et al., 2018; Young, 2006). Examples of different eye disorders resulting from high UV exposure are flash burns, ground-glass eyeballs, welder's flash, and snow blindness depending upon the source of the UV light. Exposure to UVC light is common during welding operations at construction sites and workplaces. Ocular hazards experienced by welders include photo-phthalmia (welder's flash), conjunctivitis, photokeratitis, cataracts, and eye melanoma if exposed to UVR emitted from welding arcs.

There is a line of evidence that chronic exposure to high-intensity UV light can lead to the development of age-related macular degeneration of the retina and cortical cataracts (SCHEER, 2017; WHO, 2003). Apart from causing destructive effects on the eyes, short-term UVC exposure can pose high damage to human skin (e.g., skin burns, erythema (reddening of the skin), swelling, and skin darkening). On the other hand, prolonged and long-term exposure to UV light can induce skin cancers such as basal cell carcinomas, squamous cell carcinomas, and even malignant melanoma (Liu-Smith et al., 2017; Narayanan et al., 2010; Pfeifer and Besaratinia, 2012).

There are certain guidelines framed by the World Health Organisation (WHO) or Occupational Safety and Health Association (OSHA) related to the environmental safety and health aspects of UVC radiation. To protect the humans from harmful effects of UV light, ISO 15858, 2016 guidelines specify minimum human safety requirements for the use of UVC lamp devices with the maximum limit of exposure limit value (ELV) as 60 J/m^2 at 254 nm for 8 h in a day. Note that this guideline complies of the ones recommended by the National Institute of Occupational Safety and Health (NIOSH). The European Commission health agency has framed several guidelines regarding the biological effects of UV-A, B, and C used in the cosmetics industry. In addition, the European Commission (Directive 2006/25/EC) has set the exposure limit of UVC irradiation for workers to be 30 J m^{-2} as ELV for 8 h a day. The "American Conference of Governmental Industrial Hygienists" (ACGIH) has issued guidelines to protect the skin and eyes from UVC exposure by setting certain limits. The threshold value for UVC (UV_{254}) exposure cannot exceed 6 mJ cm^{-2} for 8 h, while the upper limit of UVC irradiation is set at 0.2 μW cm^{-2} (Nardell et al., 2008). As discussed above, UVC light can be a potential health hazard due to its destructive and carcinogenic effects. Consequently, the application of UVC light in public settings is a highly controversial issue.

2.2. Effectiveness of UVC on virus inactivation

Among the three UV spectral regions, the UVC bandwidth exhibits high potential in inactivating microorganisms due to its strong antiviral properties (Kowalski, 2010; Reed, 2010; Yin et al., 2013). The main mechanism behind UVC toxicity to microbes lies in its ability to damage the genetic material present in the cell nucleus. The wavelength range of 250–270 nm is considered to be one of the most lethal ranges because its energy is intensely absorbed by nucleic acids (DNA/RNA) in microbial cells and viruses (Gurzadyan et al., 1995; Wang et al., 2019). DNA/RNA usually absorbs wavelengths ranging from 200 to 300 nm, with a peak absorbance at 260 nm. Genetic damage occurs due to the photodimerization (formation of dimers) between the pyrimidine nucleotide molecules (uracil dimers) in the DNA/RNA strands (Fig. 2). Subsequently, the formation of cyclobutane pyrimidine dimers (CPDs) results in DNA disassembly and ultimately disrupts cellular replication and other cellular functions (Chevremont et al., 2012a; Chevremont et al., 2012b). The prevention of cell replication may lead to cell death and prevention of viral reproduction/infection (González-Ramírez et al., 2011; Mouret et al., 2006). Further, the UVC light denatures enzymes that are required during DNA repair via a photo-reactivation mechanism (Horikawa et al., 2013). Thus, the UVC induced photolysis in viruses produces different photoproducts (i.e. CPDs) and some other non-toxic byproducts. These mutagenic DNA lesions are the most common and abundant damage products caused by UV photolysis (Sinha and Häder, 2002).

Several research teams have discussed the application of UVC light against various animal and human viruses such as HIV, chikungunya virus, parvovirus, human enteric virus, human papilloma virus, SARS coronavirus, hemorrhagic fever virus, pancreas necrosis virus, and erythrovirus B-19 (Caillet-Fauquet et al., 2004; Eickmann et al., 2020; Keil et al., 2020; Kim et al., 2017; Marx et al., 1996; Mathew et al., 2018; Meyers et al., 2017; Øye and Rimstad, 2001; Sugawara et al., 2001). Also, UVC radiation has been reported to successfully inactivate non-enveloped viruses such as hepatitis A virus, feline calicivirus, porcine circovirus type 2 (PCV-2), and Senecavirus A (SVA) in biological samples such as platelets and animal plasma (Blázquez et al., 2019; Gravemann et al., 2018). The key factors that must be taken into consideration for virus inactivation with UVC irradiation are the wavelength, the UV dosage, and the virus inactivation factor (k) (summarized in Table 1). The UVC effectiveness varies across different viruses because they require different irradiation doses for complete inactivation of the microorganism. The UV sensitivity of viruses can be described by inactivation kinetics. Applying the first order Chick Watson model, virus disinfection mechanisms by UVC light can be expressed as follows (Hijnen et al., 2006):

$$\mathrm{Log}\left(\frac{N}{N_0}\right) = k{*}\mathrm{UV\ dose}$$

where N/N_0 indicates the ratio between the number of microbes (viruses) after and before UVC irradiation. K indicates the virus inactivation rate constant (cm^2/mJ) to describe inactivation. UV dose (D) indicates the radiant exposure per unit area or fluence (mJ cm^{-2}) at a particular wavelength (λ). The inactivation kinetics can be used to measure the

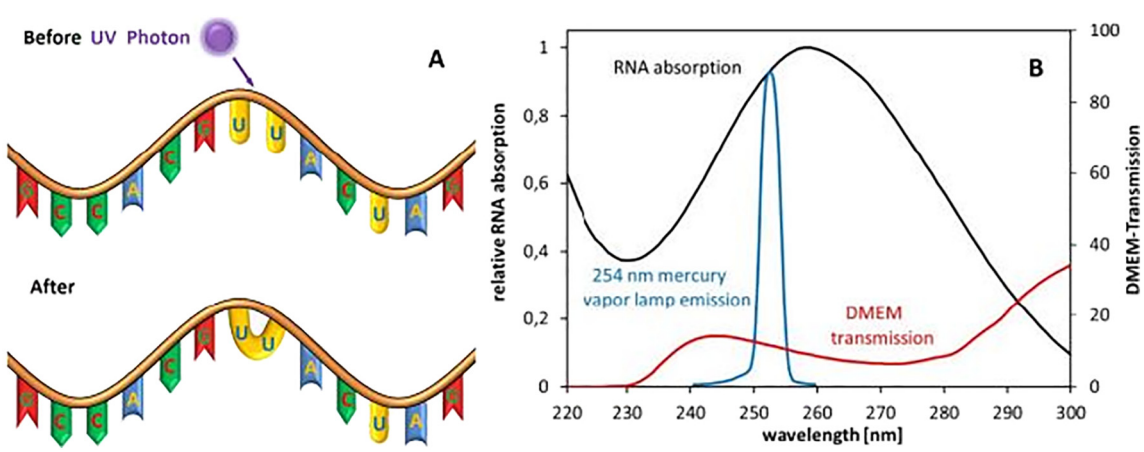

Fig. 2. Schematic of the RNA damage mechanism through the formation of a dimer with UVC light. Relative absorption spectra of RNA, relative emission spectrum of a low-pressure mercury vapor lamp, and transmission of a typical (Eagle) cell culture medium (Heßling et al., 2020).

Table 1
Various parameters influencing the inactivation of a virus in a UVC irradiated process.

Order	Factor affecting virus inactivation	Characteristics/Remarks	References
1.	UVC sources and wavelength	• Low and medium pressure mercury UV lamps:254 nm • UV light-emitting diodes (UV-LEDs): Varying wavelengths • Far-UVC (200–240 nm) radiating excimer lamps: safer to use • Micro plasma lamps.	(Barnard et al., 2020; Buonanno et al., 2020; Eickmann et al., 2020; Kitagawa et al., 2021; Welch et al., 2018)
2.	Applied UVC dose (E)	• Definition: Delivered irradiance or fluence rate to microbial cells (mW cm^{-2}) multiplied by the exposure time (s). • Varies with the total energy dose/fluence rate • A large value of radiant flux will generate a higher UV dose that will provide a more efficient virus inactivation process. • At close distances, the radiation produces a higher destructive effect.	(Chevrefils et al., 2006; Heßling et al., 2020; Malayeri et al., 2016)
3.	Inactivation rate constant (k)	• A higher value of k displays the increased sensitivity of the virus at a particular wavelength. • k value varies with the wavelength used for inactivation. • Viruses must be reduced by 4 log inactivation (99.99%) in the environment matrices (water/air) to reach safe levels.	(Rattanakul and Oguma, 2018; Rattanakul et al., 2014)
4.	Inherent viral characteristics	• Non-enveloped viruses more UVC resistant than enveloped viruses, • Proteins and lipids of the envelope viruses broken more easily than other viral parts • Physical size, molecular weight, surface hydrophilicity, and presence of repair mechanism	(Raeiszadeh and Adeli, 2020; Wang et al., 2020)

anti-viral efficiency of the UVC irradiation process. Virus inactivation is usually defined in the terms of 'log inactivation,' which basically reflects the number of reductions expressed in the order of magnitude of virus concentration (Kane, 2018; Song et al., 2016). A log inactivation of 1 means that 90% of the desired viruses are inactivated, while a log inactivation of 2 implies that 99% of viruses are inactivated. Similarly, a log inactivation of 3 means that 99.9% of viruses are inactivated by UVC irradiation. A higher value of k displays the increased sensitivity of the virus at a particular wavelength. For example, a high value of k (0.045 cm^2/mJ) was obtained with 260-nm UVC LEDs for human adenovirus C (Beck et al., 2017). In another report, k of MS2 was measured as 0.066 cm^2/mJ in 260-nm UVC LEDs, while a combination of UVC LEDs of 260 and 280 nm yielded a k value of 0.61 cm^2/mJ (Rattanakul et al., 2014).

The UV wavelength is also considered to be the most influential factor in anti-viral disinfection in the UVC irradiation process since the nucleic acids (DNA) have the largest absorbance at 262 nm and strong inactivation efficiency between 250 and 280 nm. Studies have confirmed that a wavelength of 254 nm is considered the most effective for the maximum germicidal activity for viruses (Bolton and Cotton, 2011). Also, other UV wavelengths such as 255 nm, 275 nm, and 280 nm have been reported for the inactivation of viruses (Bowker et al., 2011; Rattanakul and Oguma, 2018).

The efficacy of shorter wavelengths (UVC_{255}) has also been assessed for virus inactivation relative to longer wavelengths (UVC_{280}) on bacteriophages. Currently, far UVC wavelengths (222 nm) are considered the most effective for inactivating air-borne viruses, including coronaviruses. The far-UVC light being strongly absorbed by the proteins in peptide bonds generally show limited penetration depth in biological materials as compared to conventional UVGI. However, this limited penetration is sufficient enough (in terms of depth) to inactivate the viruses and bacteria which are still smaller than the penetration size. Hence, far-UVC light is found to be as efficient in killing the pathogens as conventional germicidal UV light. Far-UVC is considered to be safer than other UVC ranges and is therefore unlikely to cause any harm to eyes and skin as well (Buonanno et al., 2020; Welch et al., 2018). It was reported that 222-nm far-UVC light (between 1.7 and 1.2 mJ/cm^2) could inactivate 99.9% of aerosolized human coronaviruses such as alpha HCoV-229E and beta HCoV (Buonanno et al., 2020). The effect of far-UVC light was also tested in public places at the exposure limit of ~3 mJ/cm^2/h to show 90% viral inactivation in 8 min and 99.9% inactivation in ~25 min. Recently, far UVC was reported to result in 88.5 and 99.7% reduction of viable SARS-CoV-2 based on the $TCID_{50}$ assay for 10 and 30 s, respectively (Kitagawa et al., 2021).

The UV dose is also a significant factor in UVC irradiation-based virus inactivation. The UV dose (E) is determined by the radiant energy falling per unit area. It can be calculated as the product of UV radiant flux (I) and contact time (Bolton et al., 2015; Wigginton et al., 2012). The UV radiant flux (radiant power) is the radiant energy passing in a particular unit of time (t). The equation for the UV dose can be expressed as follows:

$$E\ (\mathrm{mJ\ cm^{-2}}) = I\ (\mathrm{W\ m^{-2}}) \times \mathrm{time}\ (\mathrm{s})$$

A large value of radiant flux will generate a higher UV dose that will provide a more efficient virus inactivation process. The optimal UV dose range for 4 log inactivation (99.99% reduction) varies with the type of virus (LeChevallier and Au, 2004). For example, rotaviruses need approx. 25 mJ/cm^2 dose of UVC (254 nm: mercury lamp) for a log inactivation of 3 (Kowalski, 2010). In contrast, for the same amount of log inactivation, adenoviruses require 140 mJ/cm^2 of UVC irradiation (Malayeri et al., 2016). The relationship between the incremental log inactivation of various pathogens (including viruses) and UV irradiation doses using different UVC sources was also studied (Chevrefils et al., 2006).

3. Importance of UVC during COVID-19 pandemic

UVC exposure is a direct anti-viral approach with proven efficiency against various airborne and other viruses (Zhang et al., 2019a). The importance of UVC radiation in the current pandemic is therefore recognized because UVC irradiation has already been used for the prevention of airborne virus transmission and infection (Budowsky et al., 1981; Hijnen et al., 2006). Based on earlier studies regarding the inactivation of coronaviruses using UVC, it is possible to predict the reactivity and susceptibility of the SARS CoV-2 virus to UVC irradiation (Blázquez et al., 2019; Heßling et al., 2020; Shirbandi et al., 2020). However, little is known regarding the UVC dose required to inactivate SARS CoV-2. This section is therefore organized to emphasize the efficiency of UVC light against coronavirus transmission and to establish a primary database for its effectiveness against SARS CoV-2.

3.1. COVID-19 pandemic

COVID-19 is an ongoing infectious disease outbreak that was declared a global pandemic by the WHO in March 2020 (Sohrabi et al., 2020). The pandemic has caused more than 3.5 million deaths and more than 169 million confirmed cases in over 200 countries since its first report in Wuhan, China in December 2019 (WHO Coronavirus

dashboard accessed on 28 May 2021). The causative agent of COVID-19 is an enveloped positive-sense RNA virus (SARS CoV-2) that belongs to the coronavirus family. Among its diverse family, several coronaviruses have previously caused pandemics. These include severe acute respiratory syndrome coronavirus (SARS CoV-1) in 2003, and the Middle East respiratory syndrome coronavirus (MERS CoV) in 2012 (Lu et al., 2020; Oboho et al., 2015; Zhong et al., 2003). The SARS CoV-2 virus transmits between individuals in close contact through respiratory droplets that are produced through talking, coughing, and sneezing, or through contaminated surfaces/aerosols (Lai et al., 2020; Van Doremalen et al., 2020). Recently, the WHO reported that there is a high probability of airborne transmission of SARS CoV-2 through fine aerosol forms, which can be suspended in the air for a long period of time and over large distances (Morawska and Cao, 2020).

The average incubation period of COVID-19 is approximately 2–12 days (Guo et al., 2020; Li et al., 2020). Since the basic R_0 number of SARS CoV-2 is between 2.4 and 3.3. On average, a person can infect 2–3 other people after the onset of infection (Kucharski et al., 2020; Liu et al., 2020b). COVID-19 causes flu-like symptoms (fever, cough, throat pain, etc.), mild respiratory disorders, and lethargy in humans. Its genomic structure is quite similar to all other human coronaviruses, which includes viral RNA that is enclosed by crown-like glycoprotein spikes on its surface (McIntosh et al., 2020). Although only a few vaccines for COVID-19 are available, their efficacy is not yet validated to the full extent. Moreover, the ongoing mutations in the COVID-19 virus further pose a challenge to the vaccination program. Therefore, it has become a highly global threat to humankind. The next section will provide a detailed review of reports to date regarding the inactivation and control of human coronaviruses using UVC irradiation.

3.2. UVC irradiation for coronavirus inactivation

In order to contain coronavirus multiplication and transmission in the environment, UVC has been suggested as one of the most cost-effective germicidal solutions for the ongoing COVID-19 pandemic (Derraik et al., 2020; Heimbuch and Harnish, 2019; Ianevski et al., 2020; Li et al., 2020). After the SARS outbreak in 2002–3, some studies focused on the germicidal activity of UV light against SARS CoV-1 (Ansaldi et al., 2004; Rabenau et al., 2005). Animal models of coronaviruses have also been studied to predict the susceptibility of human coronaviruses to UVC (Pratelli, 2008; Saknimit et al., 1988; Walker and Ko, 2007). The virucidal action of UVC irradiation has been explored with respect to the stability of human coronaviruses in cell cultures, aerosols, and even biological fluids. Besides the transmission of coronaviruses through direct contact and respiratory droplets, there is an increasing concerns on the transmission of SARS CoV-2 via water, wastewater, and aerosols. This section discusses the tests conducted on UVC sensitivity against three human coronaviruses (SARS CoV-1, MERS CoV, and SARS CoV-2), as summarized in Table 2. The complete information on the relationship between applied UV dosage and the log inactivation of coronaviruses is also evaluated, along with the inactivation efficiency of UVC sterilization. Despite the lack of uniformity in the research methods for human coronavirus inactivation studies, the critical review of all prior reports are discussed and compared in the following sections.

3.2.1. Severe acute respiratory syndrome coronavirus (SARS CoV-1)

SARS CoV-1 was the infectious agent responsible for the SARS outbreak in 2003. This disease was transmissible from person to person and causes clusters of disease in healthcare workers (Peiris et al., 2004; Zhong et al., 2003). Studies showed that UVC treatment of SARS CoV-1 in culture medium was able to eliminate the viral infectivity. The stability of the SARS CoV-1 strain subjected to UVC irradiation was investigated in Vero-E6 cell lines (Dong, 2003). When irradiated with UVC light, the virus-infected cells were inactivated within 60 min, and their viral infectivity reached an undetectable limit as tested by the cytopathic effect (CPE). A year later, another study reported the inactivation of SARS CoV-1 by employing UVC irradiation of 254 nm (Darnell et al., 2004). Inactivation of SARS CoV-1 was observed within 15 min of irradiation, while UVA irradiation was unable to show any effect on virus viability. In this study, a quick increase in viral inactivation was observed (15 min), which may be attributed to a high dosage due to close proximity (3 cm) of the UV light to the viral aliquots. The same group of

Table 2
A compilation of different published studies and reports regarding the photo-inactivation of coronaviruses using UVC irradiation.

Order	UVC exposure wavelength	UVC light intensity/irradiance	Distance from UVC source/illumination	Inactivation time/conditions	Sample/media	Reference
(a) SARS CoV-1						
1.	260 nm	90 μW cm^{-2}	80 cm	60 min	Vero-E6 cells	Dong, 2003
2.	254 nm	4016 μW cm^{-2}	3 cm	15 min	Vero-E6 cells	Darnell et al., 2004
3.	254 nm	4016 μW cm^{-2}	3 cm	40 min	Non-cellular blood products PBS solution, BSA protein solutions	Darnell and Taylor, 2006
4.	254 nm	200 mJ cm^{-2}	–	Log reduction factor of ≥3.1	Platelets concentrates/ plasma	Eickmann et al., 2020
5.	222 nm	3 mJ cm^{-2}	22 cm	25 min (99.9% inactivation)	Aerosols	Buonanno et al., 2020
(b) MERS CoV						
6.	254 nm	–	1.22 m	5 min	Platelets concentrates/ plasma	Bedell et al., 2016
7.	254 nm	200 mJ cm^{-2}	–	Log reduction factor of ≥3.7	Platelets concentrates/ plasma	Eickmann et al., 2018
(c) SARS CoV-2						
8.	265 nm	6.2 J/m^2	75 × 45 × 50 cm UVC chamber	log reduction of ≥3.4	Platelets concentrates/ plasma	Keil et al., 2020
9.	280 ± 5 nm	3.75 mW cm^{-2}	2 cm	1–60 s	Aerosols	Inagaki et al., 2020
10.	254 nm	70 mJ cm^{-2} (estimated)	–	1 log inactivation (estimated)	Aerosols	Sagripanti and Lytle, 2020
11.	254 nm	3.7 mJ cm^{-2}	–	3 log inactivation for low virus concentration.	Vero-E6 cells	Bianco et al., 2020
12.	254 nm	1940 mW cm^{-2}	3 cm	Complete inactivation in 9 min	Liquid suspension	(Heilingloh et al., 2020)
13.	222 nm	0.1 mW cm^{-2}	24 cm	2.51 log reduction (Undetectable levels) in 30 s	Liquid suspension	(Kitagawa et al., 2021)
14.	254 nm	2.2 mW cm^{-2}	30 cm	Inactivation, by lethal dose (viral inactivation 99.999%)	Liquid suspension	(Sabino et al., 2020)
15.	PX-UV robot model PXUV4D	–	1 m	99.992% reduction in 5 min	Liquid suspension and dried samples	(Simmons et al., 2021)
16.	254 nm	1.082 mW cm^{-2}	–	more than 3-log inactivation and inhibition of SARS CoV-2 replication	Vero-E6 cells	(Biasin et al., 2021)

researchers successfully examined the inactivation efficiency of UVC light on SARS CoV-1 in blood and plasma products (Darnell and Taylor, 2006). This group found that the UVC treatment could inactivate SARS CoV-1 to the limit of detection ($TCID_{50}$ at 1 log/ml) after 40 min of exposure in PBS solution. Recently, a group of researchers conducted a study on the UVC based inactivation of emerging SARS CoV viruses in plasma concentrates (Eickmann et al., 2020). The plasma concentrates spiked with viruses were exposed to UVC irradiation. The $TCID_{50}$ assay was used to assess viral infectivity before and after UVC treatment. The infectivity assays suggested that a UVC dose of even 100 mJ cm^{-2} was able to inactivate SARS CoV-1 to an undetectable level. A similar experiment was performed to demonstrate the treatment efficiency of blood plasma and platelets by employing UVC light in combination with methylene blue (Eickmann et al., 2020). The results indicated 3.4 log reduction of SARS CoV (in plasma concentrates) at UVC dose of 200 mJ cm^{-2}. Accordingly, UVC treatment was demonstrated as an effective option for reducing virus infectivity in blood products.

Far UVC light (wavelength range 207–222 nm) commonly produced by excimer lamps has also gained attention in the place of conventional 254-nm UVC light (Narita et al., 2020). One of the most important characteristics of far UVC light is its viral disinfection without causing any harm to human tissues, such as mammalian skin (Barnard et al., 2020; Buonanno et al., 2017; Buonanno et al., 2013). Far UVC light (222 nm) has been shown to produce 95% inactivation of aerosolized influenza virus (H1N1) at a low dose of just 2 mJ cm^{-2} (Welch et al., 2018). Recently, far UVC light was also studied for its activity against two airborne coronaviruses strains of SARS CoV-1 (HCoV-229E and HCoV-OC43) (Buonanno et al., 2020). The viral infectivity was measured using a 50% tissue culture infectious dose assay $TCID_{50}$ assay. A low UV intensity of 3 mJ cm^{-2} resulted in 1 log inactivation in 8 min, 2 log inactivation in 16 min, and 3 log inactivation in 25 min (Fig. 3a). Far-UVC light-based fiber optics have been proposed in the direct and selective treatment of COVID-19 patients, while far-UVC excimer lamps replace conventional overhead lamps (Haider et al., 2020). Therefore, UVC irradiation treatment may be a tool to treat aerosols and blood-related products (e.g. plasma concentrates, plasma, etc.). Still, the effect of far-UVC on human health is not fully elucidated.

3.2.2. Middle east respiratory syndrome coronavirus (MERS CoV)

UVC treatment was also used to treat surfaces to inactivate MERS coronaviruses. For example, one study proposed using UVC radiation to disinfect entire rooms (Bedell et al., 2016). The disinfection setup consisted of a sensor controlling three UVC emitters in a biosafety level-3 (BSL-3) facility. The virus samples (MERS CoV) were loaded on glass slips and then exposed to UVC. Next, their infectivity was evaluated by incubating the slips in Vero E6 cell lines. UVC treatment for only 5 min resulted in 2.71 log inactivation of the virus, with a 6 log inactivation after 30 min (Bedell et al., 2016). UVC irradiation may also be used as an effective strategy to disinfect blood-related products (such as plasma, plasma concentrates, and platelets units) to prevent virus transmission during blood transfusion (Terpstra et al., 2008). In this context, the inactivation of MERS CoV was described by varying doses of UVC (using THERAFLEX UV-Platelets system) (Eickmann et al., 2018). The platelet concentrates were spiked with MERS CoV titers extracted

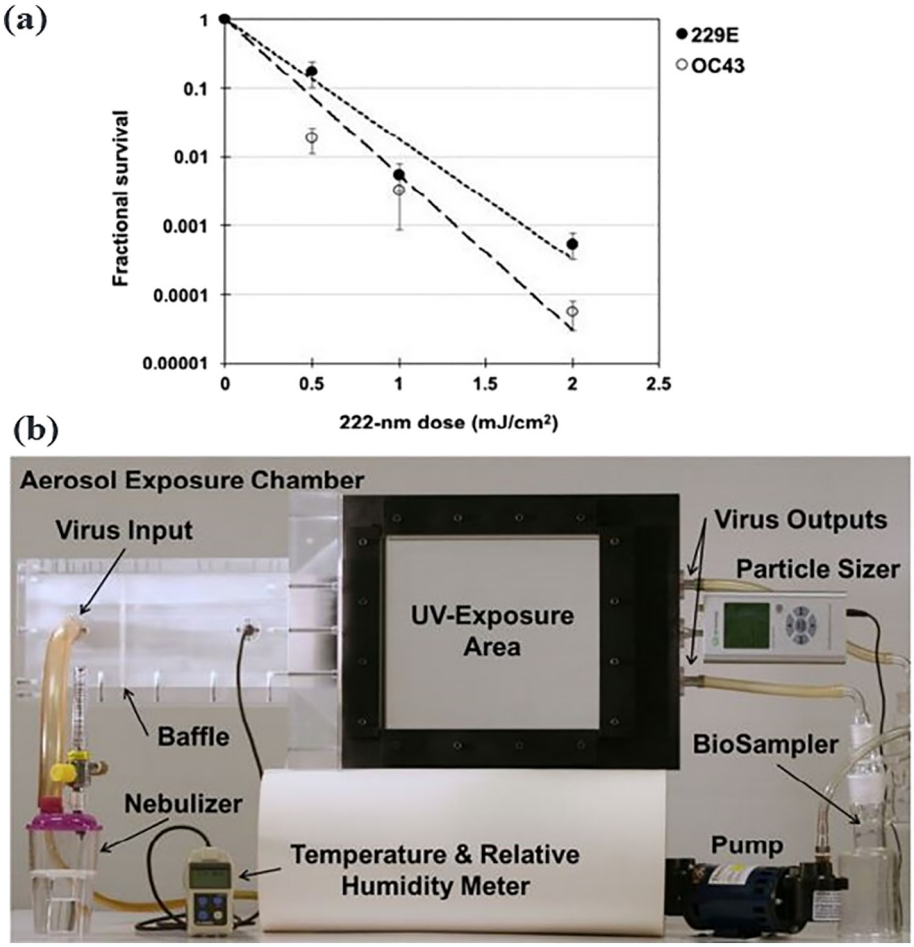

Fig. 3. A chamber system built for UV irradiation testing of the survival of coronaviruses: (a) The survival of two coronaviruses HCoV-229E and HCoV-OC43 as a function of far-UVC (222 nm) dose. The inactivation rate constant (k) was found to be 4.1 cm^2/mJ and 5.9 cm^2/mJ for both strains, respectively (Buonanno et al., 2020). (b) Photograph of the custom UV irradiation chamber (Welch et al., 2018).

from cell cultures. According to the infectivity assays ($TCID_{50}$), MERS CoV was inactivated using UVC irradiation in a dose-dependent relationship. A UV dosage of 150 mJ cm^{-2} reduced the infectivity level of the virus to a non-detectable range. The high virus inactivation constant (k) (> 3.7) obtained after the assay indicated that the radiation was sufficient to lower the risk of infection through blood products.

3.2.3. Severe acute respiratory syndrome coronavirus (SARS CoV-2)

The novel SARS CoV-2 has caused a deadly pandemic in 2020 (Guo et al., 2020; Harapan et al., 2020). In some recent studies, the high susceptibility of the SARS CoV-2 virus to UVC light has been demonstrated (Heilingloh et al., 2020; Simmons et al., 2021). Efforts have also been made to inactivate SARS CoV-2 in the blood (plasma/platelet units) by means of UVC irradiation and riboflavin treatment (Keil et al., 2020). SARS CoV-2 cultured in monolayer Vero-E6 cell lines were inoculated into plasma/platelets units. The plasma or platelets units were suspended in illumination (storage bags) and mixed with riboflavin solution to make a final product. After the units were spiked with the virus, they were subjected to UVC treatment using a Mirasol illuminator under biosafety level-3. The infectious titers of SARS CoV-2 were determined using a plaque assay of Vero-E6 cells. The UVC dose resulted in ≥3.4 log reduction of the average viral titer of 4.62 PFU/ml. A similar setup consisting of deep-UV LEDs (280 ± 5 nm) was displayed for SARS CoV-2 inactivation in aerosols and contaminated surfaces (Inagaki et al., 2020). The viral aliquots containing virus-infected Vero-E6 cell lines were irradiated from a short distance of 2 cm, after which the infectivity assay was determined using CPE. These authors were able to achieve 87.4% of SARS CoV-2 inactivation within 1 s, while 3 log inactivation was achieved after 10 s of UV exposure. (Inagaki et al., 2020). In a separate set of studies, the UVC sensitivity of the novel SARS CoV-2 strain was evaluated (Sagripanti and Lytle, 2020). The UVC_{254} sensitivity and genomic characteristics of SARS CoV-2 were compared with that of other ssRNA coronaviruses (e.g. SARS CoV-1 and MERS CoV) and the influenza virus. The virus survival of 37% (D_{37s}) was calculated during testing. Therefore, a UVC fluence of 70 mJ cm^{-2} was estimated for SARS CoV-2 inactivation corresponding to 1 log inactivation.

The potential effect of UVC radiation on the viricidal properties of SARS CoV-2 was tested using different irradiation doses and viral concentrations (Bianco et al., 2020). UVC was generated using low vapor mercury lamps for uniform illumination. Three concentrations of SARS CoV-2 were prepared. Their viability post UVC exposure was determined using RT-PCR and CPE. The UVC treatment inhibited viral replication at lower concentrations of virus (multiplicity of infection - 0.5) for the first two days. However, the complete inhibition of replication was observed after 6 days at a dose of 3.7 mJ cm^{-2}. The virus inhibition was observed as a function of both UVC intensity and viral concentration (Bianco et al., 2020).

Among all studies of human coronavirus inactivation, log inactivation studies have been considered to be important tools for measurements of viral infectivity. Many studies on UVC treatment for SARS CoV-2 have achieved log inactivation constants of greater than 3 (Bianco et al., 2020; Keil et al., 2020). It may be inferred that the existing UVC disinfection methods and procedures should be sufficient to inactivate human coronaviruses, including SARS-CoV-2. The exposure of UVC to humans limits its practical applications, while there is a need for more research on far UVC for future applications.

3.3. Disinfection of N95 respiratory masks and clinical settings

A global pandemic such as COVID-19 poses an extensive concern for community and medical health. Healthcare workers are at the largest risk of infection given their particular exposure. COVID-19 response measures include the disinfection of filtering facemasks respirators (FFRs). These FFRs can filter the viral burden in air droplets, and prevent viral transmission. Numerous techniques, such as the use of heat, steam, microwaves, chemicals (e.g., H_2O_2 and bleach), and gases, have been evaluated for respiratory mask decontamination (Lindsley et al.,

Table 3
A summary of newspaper reports, articles and various independent researchers that tested the UVC inactivation of coronaviruses.

Order	Title	Source
1.	Evidence based approach: Effect of far UVC light on coronaviruses in aerosols: A step-wise summary.	https://in.dental-tribune.com/news/evidence-based-approach-effect-of-far-uvc-light-on-coronaviruses-in-aerosols-a-step-wise-summary/
2.	Breakthrough ultraviolet light development could help kill COVID-19 virus	https://www.healtheuropa.eu/breakthrough-ultraviolet-light-development-could-help-kill-covid-19-virus/100409/
3.	MIT Designs Robot That Eliminates Coronavirus with UV Light	https://www.extremetech.com/extreme/312198-mit-designs-robot-that-eliminates-coronavirus-with-uv-light
4.	Light Kills Coronavirus. Here's How It Could Help Beat Covid-19	https://www.forbes.com/sites/jvchamary/2020/06/29/light-coronavirus/#7315bfb75853
5.	Ontario company claims their ultraviolet light system can kill COVID-19	https://toronto.ctvnews.ca/ontario-company-claims-their-ultraviolet-light-system-can-kill-covid-19-1.5006546
6.	Killing coronavirus with handheld ultraviolet light device may be feasible	https://www.sciencedaily.com/releases/2020/06/200601194140.htm
7.	Can you kill coronavirus with UV light?	https://www.bbc.com/future/article/20200327-can-you-kill-coronavirus-with-uv-light
8.	Can UV Light Kill or Prevent Coronavirus?	https://www.medicinenet.com/can_uv_light_kill_or_prevent_coronavirus-news.htm
9.	Using UV light to kill coronavirus: The benefits and risks	https://www.cnet.com/health/how-to-use-uv-light-to-kill-the-coronavirus/
10.	UVC LAMPS AND SARS-COV-2	https://www.icnirp.org/en/activities/news/news-article/sars-cov-2-and-uvc-lamps.html
11.	Coronavirus Puts UV in the Disinfectant Spotlight	https://www.webmd.com/lung/news/20200519/coronavirus-puts-uv-in-the-disinfectant-spotlight
12.	COVID-19: This UV light disinfection robot can sanitise entire room in just 4 min	https://timesofindia.indiatimes.com/videos/city/bengaluru/covid-19-this-uv-light-disinfection-robot-can-sanitise-entire-room-in-just-4-minutes/videoshow/75718682.cms
13.	UV-light sterilization: A formidable weapon in the war on Covid-19?	https://www.business-standard.com/article/technology/uv-light-sterilisation-a-formidable-weapon-in-the-war-on-covid-19-120061600681_1.html
14.	UV light is an efficient way to deactivate the COVID-19 causing SARS-CoV-2 virus, reducing transmission	https://www.firstpost.com/health/uv-light-is-an-efficient-way-to-deactivate-the-covid-19-causing-sars-cov-2-virus-reducing-transmission-8527651.html
15.	COVID-19 UV light treatment is being studied – not yet in use – in Los Angeles	https://www.usatoday.com/story/news/factcheck/2020/05/02/fact-check-covid-19-uv-light-treatment-research-underway-los-angeles/3053177001/

2015). Accordingly, the UVC disinfection of respiratory masks and face pieces has been considered to be the best studied and effective method for germicidal control. Several studies have addressed the germicidal properties of UVC radiation in the decontamination of N95 respirators (EloiseáTorres, 2020; Fisher and Shaffer, 2011; Hamzavi et al., 2020). For instance, a UVC dose of 1 J cm^{-2} was enough to eliminate six strains of viruses, including SARS CoV and MERS CoV, from facepiece respirators (Heimbuch and Harnish, 2020). Likewise, the complete decontamination of N95 respirators infected with influenza H1N1 virus was achieved at a UVC_{254} dose of nearly 1 J cm^{-2} (Fisher and Shaffer, 2011; Mills et al., 2018). It is important to stress that a minimum UVC dose of 1 J cm^{-2} is required for the decontamination of respirators to ensure the safety of healthcare workers (Narla et al., 2020).

It is important to use valid dosimetry not only to provide effective decontamination but also to prevent any impairment in the mask's efficacy and safety (Liao et al., 2020; O'Hearn et al., 2020). High and inappropriate doses of UVC irradiation were reported to lower the efficiency and structural integrity of face pieces and N95 respiratory masks (Huber et al., 2020). For example, the treatment of germicidal UVC (950 J cm^{-2}) was able to increase virus penetration through the masks (Lindsley et al., 2015). In the same report, the UVC irradiation of 2360 J cm^{-2} reduced the breaking strength of materials (used in making respiratory masks) by approximately 51%. The maximum number of decontamination cycles for FFRs for reuse primarily depends on the model of the respiratory face piece and the UVC dose intensity to inactivate viruses (Lindsley et al., 2015). In addition to these studies, UVC irradiation has been used as a novel technology

Table 4
Commercial instruments and devices developed for UVC inactivation of coronaviruses during the COVID-19 pandemic.

Order	Product	Developer	Product specifications	Source/company website
1.	UVC disinfection chamber	Skytron technologies	• Highest single emitter UVC dose • Field Balance and PowerBoost UV Technology • Correct dose of germicidal energy every time. • Lightweight and easy to move • Removable emitter for use in small spaces	https://www.skytron.com/products/infection-prevention/uvc-light-disinfection-robots/
2.	THOR UVC™	Finsen technologies	• Inactivation of 6 log reduction of bacteria and viruses (99.9999%) achieved through Thor UVC • Can be installed in hospitals and prevent viral spread • Automatic scanning and cleaning with optimum UVC dose • Fully portable, light, easy to operate, and easy to move from one area to another in a hospital	https://www.finsentech.com/uvc-disinfection-robots
3.	Connor UVC disinfection robot	RobotLAB technologies	• Specifically developed to prevent viral transmission indoors • Equipped with UV germicidal lamps, automatic disinfectant spray module, sensor technology, and battery life of up to 8 h • It is currently used to fight against Coronavirus (COVID-19)	https://www.robotlab.com/store/connor-uvc-disinfection-robot
4.	ChargeMax and UV-C Wand Sterilizer	Cetrix Technologies Ltd.	• A different range of products based on UVC disinfection • Safe and durable with transparent doors • ChargeMax's UVC lights efficiently destroy any bacteria or virus, especially the large COVID-19 virus that lives on the outer surfaces of objects • Safe for usage in hospitals, classrooms, and different work environments	https://www.cetrixtablets.com/coronavirus/
5.	DONTICS UVC towerTM	Dr. Ajay Bajaj, Bombay Dental, Mumbai	• Quick disinfection of rooms within 5 min • Easy to stack it in a corner • A delayed timer to avoid any human exposure • Variable Timer for various needs • Particularly manufactured for dental clinics	https://in.dental-tribune.com/news/how-to-use-ultraviolet-light-uvc-to-fight-covid-19-effectively-in-dental-clinics-dr-ajay-bajaj/
6.	UVC disinfection robotTM	UVD robots technology	• Preventing spread of infectious viruses and bacteria • User friendly and is designed to be operated by everyday cleaning staff. • App based working • Can be used in hospitals and nursing homes	http://www.uvd-robots.com/
7.	UVC Scanz Plus sanitizing machine	Eurotek Environmental Private Limited	• An ultraviolet scanning machine capable of disinfecting objects in 360° • Can measure the temperature of humans • Can be used in airports, malls, super markets, and apartments for 99.9% protection from viruses • Equipped with camera and scanner to capture photos	https://eurotekindia.com/
8.	Handsfree UVC decontamination device	UVC cleaning systems Inc.	• Intelligent sensing technology • Decontamination of large volumes of area in a small--time from distance • An automatic, calculated dose of UVC energy to the treatment area • Easy to use with remote control.	https://www.uvccleaningsystems.com/
9.	UV air sanitizers and germicidal UV lamps	Atlantic ultraviolet corporation	• Irradiates air and exposed surfaces • For use in unoccupied rooms • Portable, compact and lightweight • Rooms as large as 3500 sq. ft. can be treated with one fixture • More intense ultraviolet radiation in a limited space	https://ultraviolet.com/
10.	UV room disinfection system	ICROCHEM laboratories	• Efficiency checked with controlled laboratory trials • Can be effective used in hospitals and indoor areas • Equipped with modern technologies such as sensors	http://microchemlab.com/test/uv-room-disinfection-devices

for inactivating airborne coronaviruses in healthcare places, hospitals, nursing homes, laboratories, and personal households (Botta et al., 2020; Gurzawska-Comis et al., 2020; Lindblad et al., 2019; Memarzadeh et al., 2010).

4. Perspectives and technology evaluation

In this review, a comprehensive survey was conducted to evaluate the scientific investigations made on the photo-inactivation of different coronaviruses using UVC radiation. Because the high energy of UVC radiation is strongly absorbed by organic molecules (including viral DNA/RNA), it has become an important tool in germicidal and disinfection applications. Recently, in a number of news reporting and scientific articles, the application of UVC technology has been recommended for the disinfection of coronaviruses (Table 3). Most studies investigated in this survey employed germicidal UVC_{254} radiation for virus inactivation because 254 nm radiation is near the absorption band of RNA present in ssRNA viral genomes such as coronaviruses. UVC radiation at 254 nm is able to inactivate all types of coronaviruses in almost all examined studies. However, exposure to UVC_{254} can also cause harm to mammalian skin and eyes. Therefore, its direct applications in indoor and outdoor environments are highly discouraged. Instead of conventional UVC light, far UVC (222 nm) is proving to be useful in coronavirus inactivation without causing any harm to human health. Most prior studies have employed a low intensity of UVC radiant energy (between 2 and 200 mJ cm^{-2}) to efficiently inactivate coronaviruses. The determined upper limit for the log-reduction median dose for inactivating coronaviruses is estimated to be 10.6 mJ cm^{-2} (Heßling et al., 2020). These estimations are primarily based on studies of different coronaviruses, including SARS and MERS CoV. The ongoing COVID-19 pandemic and threat to FFRs safety have led to the development of UVC-based devices and instruments by certain manufacturers. Here, some of the commercialized devices and for disinfection of laboratories and FFRs are summarized in Table 4. The disinfection of indoor places, including hospitals, healthcare rooms, and clinical settings, has been already achieved using such devices. However, the large-scale application of UVC-based filtration devices in various public domains (like airports and bus stations) is limited until operation cost and human health safety issues are convincingly addressed and resolved. Some commercial devices manufactured for UVC disinfection of coronaviruses in healthcare areas and FFRs are shown in Fig. 4.

5. Conclusion

We recognize the importance of response measures for the effective control of coronaviruses under the unprecedented situation of

Fig. 4. Pictures of several germicidal devices that are based on UVC radiation for deployment in indoor places and respiratory masks (a) A UVC-disinfection based trolley prototype developed by Mekins Industries, Hyderabad, India for the rapid disinfection of hospitals (b) UV-C device working developed for disinfection of rooms (Bentancor and Vidal, 2018) (c) A portable UVC disinfection lamp developed for daily sterilization of essential items, toys, electronics and small areas. (d) UV device developed by Daavlin International for decontaminating respirators and other essential items (Hamzavi et al., 2020).

the COVID-19 pandemic. To treat diverse forms of coronaviruses, multiple strategies have been employed, such as dry heating, chemical disinfection, and microwave irradiation. Among such options, UVC-based irradiation has proven to be a potential agent against coronaviruses such as MERS CoV, SARS CoV-1, and SARS CoV-2. However, the application of UVC light for the routine disinfection of airborne viruses has technical challenges. Virus inactivation kinetics across different environmental conditions (such as temperature and humidity) have not been fully investigated. The UVC exposure doses must be quantified in relation to the virus inactivation kinetics. Moreover, the delivery of uniform UVC illumination doses over large volumes of air is a challenging task. UVC irradiation has been employed successfully to treat blood and plasma products to prevent virus transmission during a blood transfusion. Recently, far-UVC was explored as a potential alternative to conventional UVC germicidal wavelengths. The potential utility of UVC-based inactivation approaches has been validated in many case studies (including disinfection of surgical instruments, respiratory masks, and indoor environments like healthcare facilities and clinical settings). The utility of UVC has been gained attention for the disinfection of microbes in water systems and food products over the past few years. However, it has not been shown to be sufficient in the treatment of airborne viral transmission. Therefore, this technology requires more development and investigation before it is used widely. The main challenge with aerosols is the provision of sufficient UVC irradiation doses to disinfect large quantities of air under different environmental parameters such as temperature and relative humidity. The routine use of UVC for virus inactivation may eventually be used to target viruses such as SARS CoV-2.

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 in this paper.

Acknowledgements

SKB and JB are thankful to DBT-CIAB (Department of Biotechnology-Centre of Innovative and Applied Bioprocessing). Neha Bhardwaj acknowledges DST (Department of Science and Technology) for the INSPIRE FACULTY grant (Reg. no. IFA18-LSPA 127) for this research. MK is thankful to Wellcome trust/DBT IA for their early career fellowship. KHK acknowledges support from a grant from the National Research Foundation of Korea (NRF) funded by the Ministry of Science, ICT, & Future Planning (Grant No: 2016R1E1A1A01940995).

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