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Research Article

Ultraviolet-Based Viral Inactivation: A Critical Examination of Current Research

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ABSTRACT

Ultraviolet (UV) radiation has emerged as a powerful, non-chemical disinfection method, gaining significant attention for its ability to inactivate pathogenic microorganisms, particularly viruses, amid global public health challenges such as the COVID-19 pandemic. This study provides a comprehensive analysis of UV-based viral inactivation technologies, with a focus on ultraviolet germicidal irradiation (UVGI) using the UV-C spectrum (200-280 nm). It explores the fundamental physical principles of UV radiation, the photochemical mechanisms disrupting microbial DNA and RNA, and the critical parameters influencing disinfection efficacy, including UV dose, irradiance, wavelength, exposure time, and environmental conditions. Theoretical frameworks are supported by calculations and experimental data to evaluate the impact of material properties, surface characteristics, and atmospheric factors on UV performance. The study critically assesses UVGI applications in diverse settings, such as healthcare facilities, public spaces, ventilation systems, and water treatment, while addressing safety considerations, technological limitations, and potential health risks associated with UV exposure. By synthesizing theoretical insights, experimental findings, and a detailed review of UV sensitivity across various pathogens, including SARS-CoV-2 and other coronaviruses, this work highlights the high susceptibility of viral pathogens to UV-C radiation. It also examines the implications of RNA mutations on UV efficacy and provides estimated inactivation doses for a range of microorganisms. These findings underscore the potential of UV-based technologies as a cornerstone of modern infection control strategies, offering insights into optimizing system design and implementation for effective microbial inactivation while ensuring safety and scalability in real-world applications.

1. Introduction

Coronaviruses (CoVs) constitute a large family of viruses capable of causing severe diseases in humans, including Middle East Respiratory Syndrome (MERS-CoV) and Severe Acute Respiratory Syndrome (SARS-CoV). The most recent outbreak, caused by the novel coronavirus SARS-CoV-2 and declared a global pandemic by the World Health Organization (WHO), has had profound implications not only for public health but also across regional, political, economic, and cultural domains [1]. COVID-19 is primarily transmitted via respiratory droplets and direct contact, targeting the human respiratory system. The continuous mutation of the virus further exacerbates its threat to global health [2]. Healthcare environments such as operating rooms and intensive care units are considered high-risk areas for nosocomial infections, particularly surgical site infections. These enclosed clinical settings often contain various contaminants, including microorganisms, dust particles, skin debris, hair, and respiratory droplets. Maintaining high air quality

standards in such critical hospital zones is essential to safeguard both patients and healthcare personnel from airborne chemical and microbiological agents. The microbial load in these environments is closely linked to the frequency and number of individuals entering and exiting the area [3]. Consequently, healthcare staff who are colonized with airborne pathogens may serve as vectors for surgical site infections, posing a significant risk to patient safety.

Ultraviolet (UV) radiation, particularly within the UV-C spectrum (200–280 nm), has gained renewed scientific attention due to its potential for pathogen inactivation in the context of global public health threats such as COVID-19. Coronaviruses—including SARS-CoV, MERS-CoV, and most recently SARS-CoV-2—have demonstrated the capacity to spread rapidly and cause widespread morbidity and mortality. Healthcare environments, especially surgical and intensive care units, are particularly vulnerable to airborne and surface-associated infections. In such settings, maintaining sterile conditions is essential, yet conventional chemical-based disinfection methods often fall short. UV Germicidal Irradiation (UVGI) has thus emerged as a viable, non-chemical alternative, targeting microbial DNA and RNA through photochemical disruption [4].

UVGI operates by disrupting the nucleic acids—ribonucleic acid (RNA) and deoxyribonucleic acid (DNA)—within microbial cells, thereby rendering them incapable of essential biological functions [5]. The use of UV radiation in medical applications dates back to the early 20th century, when it was employed in the treatment of tuberculosis and dermatological infections. However, the advent of antibiotics and pharmaceutical therapies in the mid-20th century led to a decline in the widespread use of UV radiation for therapeutic purposes [6]. Despite this, the UV disinfection technique—initially introduced in 1877 and further developed by 1906—has regained prominence in contemporary times due to renewed public and scientific interest [7].

In the context of the ongoing COVID-19 pandemic, researchers have turned to UV technologies, particularly UV-C light, which exhibits strong antimicrobial properties, as a means of mitigating viral transmission [8-9]. While biological and immunological studies of viral infections are often perceived as distinct from engineering disciplines, UV disinfection represents an inherently multidisciplinary field, integrating physics, engineering, and biomedical sciences to address global health challenges. Viral pathogens, which are commonly transmitted through water, food, and bodily fluids, continue to spread rapidly and contribute to significant morbidity and mortality worldwide [10]. In this regard, novel hypotheses and research initiatives utilizing UV technologies offer promising avenues for improving healthcare outcomes and public health resilience.

All electromagnetic waves, ranging from radio waves to gamma rays, are categorized within the electromagnetic spectrum. In the context of health sciences, electromagnetic radiation—primarily sourced from the sun—comprises gamma rays, X-rays, ultraviolet rays, visible light, infrared radiation, microwaves, and radio waves (see Figure 1).

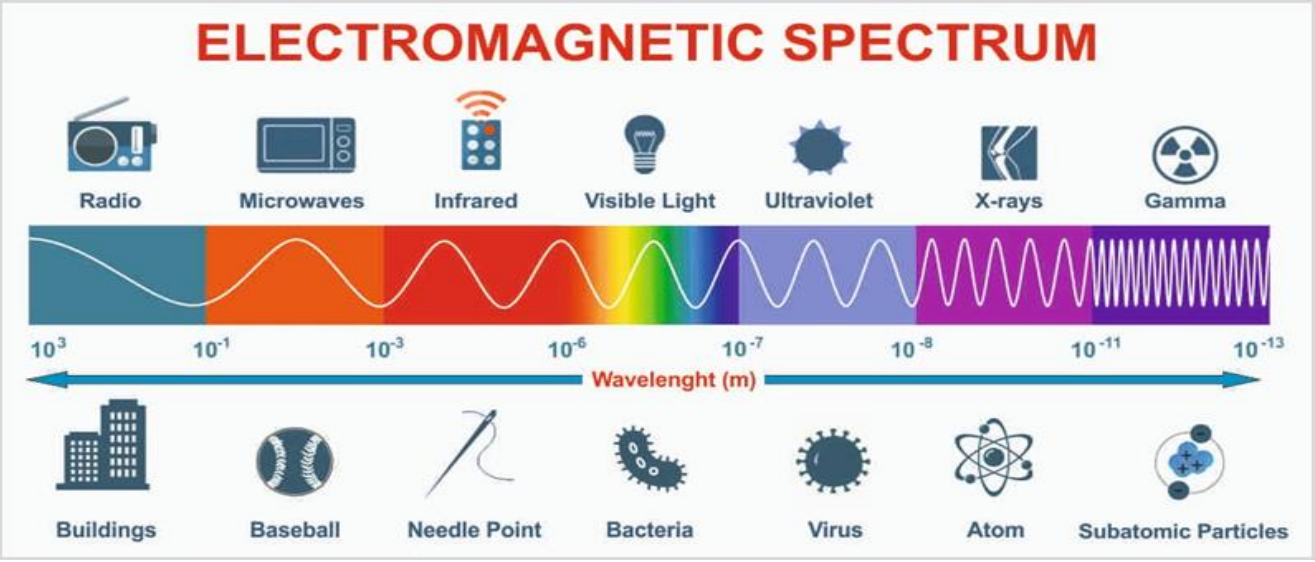

Figure 1: The electromagnetic spectrum encompasses various types of electromagnetic radiation, including radio waves, infrared rays, visible light, ultraviolet rays, X-rays, and gamma rays.

Several forms of this radiation, particularly those with shorter wavelengths and higher energy, are harmful to living organisms, including microorganisms [11].

Upon contact, these radiations transfer energy to cellular components, potentially resulting in cellular damage or death. Gamma rays, X-rays, and ultraviolet rays, which are classified as ionizing radiation, can ionize molecules by stripping away electrons. Due to their high energy and short wavelengths, these radiations are particularly detrimental to biological systems [12]. However, because of their scarcity in natural environments, such forms of radiation—including UV—are often generated artificially and applied in microbial control strategies. Their effectiveness in achieving sterilization without the application of heat makes them valuable tools in both clinical and industrial settings [13-15].

This study investigates the theoretical foundations of ultraviolet light, measurement methodologies for UV disinfection, its effects on microorganisms, and the performance of these methods in practical applications. In an effort to address critical questions concerning the required irradiation doses for the inactivation of SARS-CoV-2 and other microorganisms, the study reviews and analyzes inactivation data from a range of pathogens, including viruses, bacteria, and bacterial spores. Although the number of experimental studies directly examining the inactivation of SARS-CoV-2 by UV radiation remains limited, existing research on other coronaviruses indicates a high sensitivity of these microorganisms to UV-induced damage [16-17]. This article synthesizes findings from the literature and presents estimated UV sensitivity values for various pathogens. Furthermore, it provides an in-depth examination of the relationships between microbial susceptibility and observable biological characteristics, contributing to a more comprehensive understanding of UV disinfection efficacy.

2. Materials and Methods

The effectiveness of UV radiation in inactivating pathogens depends on several factors, including wavelength, dose, exposure time, and microorganism type. While ionizing forms of electromagnetic radiation, such as gamma rays and X-rays, have long been recognized for their biocidal properties, non-ionizing UV-C radiation offers a safer, more accessible approach for disinfection. However, UV radiation exposure also presents health risks, particularly in the form of skin damage, ocular injuries, and increased cancer risk [18]. Despite its disinfection benefits, excessive or uncontrolled exposure to UV radiation contributes to a measurable global disease burden, primarily through increased incidence of skin cancer, cataracts, and immunosuppression. This paper evaluates the dual nature of UV radiation—its potential as a disinfection technology and its role as an environmental health hazard—by synthesizing data on microbial inactivation thresholds, exposure risk assessments, and disease burden estimations across populations.

2.1. Sources of Ultraviolet Radiation

Ultraviolet (UV) radiation, with wavelengths ranging from 100 to 400 nanometers (nm), constitutes a segment of the electromagnetic spectrum situated between visible light and X-rays. The principal applications of radiation within this range involve its photobiological and photochemical effects on living organisms and chemical compounds [19]. Owing to its short wavelength and high energy, UV radiation is capable of inactivating a wide range of microorganisms, including bacteria, viruses, and unicellular organisms. Solar radiation encompasses both long-wavelength (infrared) and short-wavelength (UV) components, namely UV-A, UV-B, and UV-C. Wavelengths within the 200–300 nm range are particularly effective at disrupting the molecular structures of deoxyribonucleic acid (DNA) and ribonucleic acid (RNA), thereby impeding critical cellular processes such as protein synthesis. Among these, UV-B and UV-C bands demonstrate the most potent bactericidal activity. Notably, UV radiation at a wavelength of 253.7 nm has been widely recognized as optimal for achieving effective microbial disinfection [20-21].

When bacterial DNA is exposed to UV-C radiation, it absorbs the photonic energy, leading to molecular damage that impairs the cell's ability to replicate and infect host organisms. UV-C disinfection is typically administered by trained healthcare or technical personnel, with the disinfection duration varying according to room size; in most cases, a full cycle takes approximately 10 to 15 minutes. For safety reasons, no individuals should be present in the room during the UV-C exposure period, as the radiation poses significant risks to human health, particularly to the eyes and skin [22].

The ultraviolet spectrum is conventionally categorized into four regions (see Figure 2). Radiation within the 100–200 nm range is referred to as vacuum ultraviolet (VUV); however, its use in disinfection applications is limited due to strong absorption by atmospheric gases.

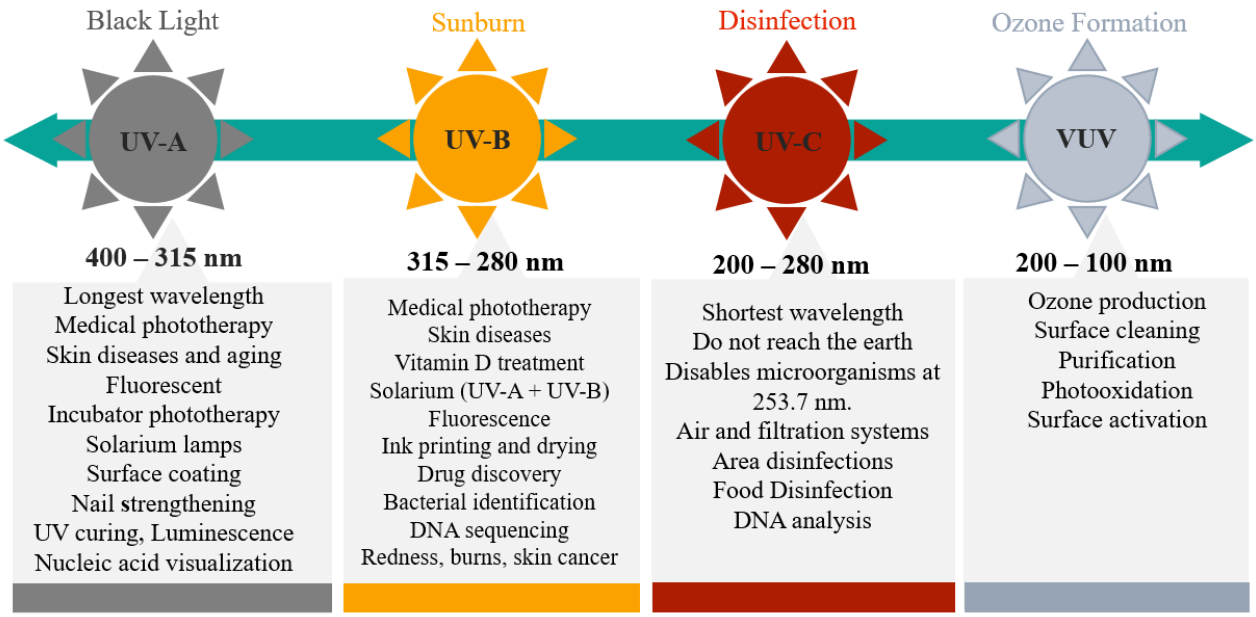

Figure 2: UV radiation spectrums and their interaction with matter: (1) UV-C is completely blocked, (2) UV-B is partially absorbed, and (3) UV-A mostly reaches the Earth's surface.

The more commonly employed regions for disinfection purposes include UV-C (200–280 nm), UV-B (280–315 nm), and UV-A (315–400 nm). Among these, UV-C exhibits the highest antimicrobial and antiviral efficacy [23]. In contrast, UV-A is the least effective for disinfection and is primarily associated with dermatological effects such as skin tanning. While UV-B can induce skin burns and DNA damage, its relatively low germicidal efficiency restricts its use in microbial control. UV-C, by directly damaging nucleic acids, offers the most effective germicidal action and is therefore the preferred range for ultraviolet disinfection technologies.

2.2. Applications of UV-C light sources

UV-C radiation at a wavelength of 253.7 nm, which lies within the ultraviolet portion of the natural solar spectrum, exhibits significant disinfectant properties against a wide range of microorganisms, including bacteria, viruses, yeasts, and molds [24]. The germicidal action of UV-C is primarily mediated through photochemical reactions such as photohydration, photo-thermal, photodissociation, photodimerization, and photo-physical effects, all of which contribute to cellular damage and the inhibition of replication processes [25]. The mechanism of microbial inactivation by UV-C light involves the destruction of nucleic acids. Specifically, the short wavelength and high-energy photons at 253.7 nm are absorbed by cellular RNA and DNA, leading to the formation of covalent bonds between adjacent nucleotides [26].

A well-documented photochemical event is the dimerization of adjacent uracil bases in RNA, which results in structural alterations that prevent normal replication and transcription. These uracil dimers, formed through covalent bonding induced by UV-C radiation, are among the earliest manifestations of UV-induced cellular damage. The accumulation of such dimers disrupts RNA secondary structure and hampers essential biological processes, including chromosomal replication and gene expression. This impairment ultimately inhibits microbial proliferation and pathogenic activity, as illustrated in Figure 3. Uracil dimerization likely enhances bacterial sterilization by forming cyclobutane pyrimidine dimers (CPDs), which introduce structural distortions in DNA. These lesions block replication and transcription, leading to lethal mutagenesis and irreversible inactivation of bacterial cells.

Exposure to UV-C radiation leads to irreversible molecular damage in the nucleic acids (DNA or RNA) of microorganisms. The energy absorbed within the 200–300 nm germicidal range causes the breakage of nucleic acid strands and the disruption of protein cross-linkages, resulting in cellular inactivation or death. Thus, UV-C irradiation effectively impairs the fundamental genetic mechanisms necessary for microbial survival and reproduction.

The required disinfection dose can vary depending on factors such as the material or medium to be disinfected, the concentration of microorganisms present, and the acceptable level of microbial contamination for the specific material or environment [27]. The dosage in disinfection is typically quantified by both the irradiation time and the radiation intensity. In all studies published to date,

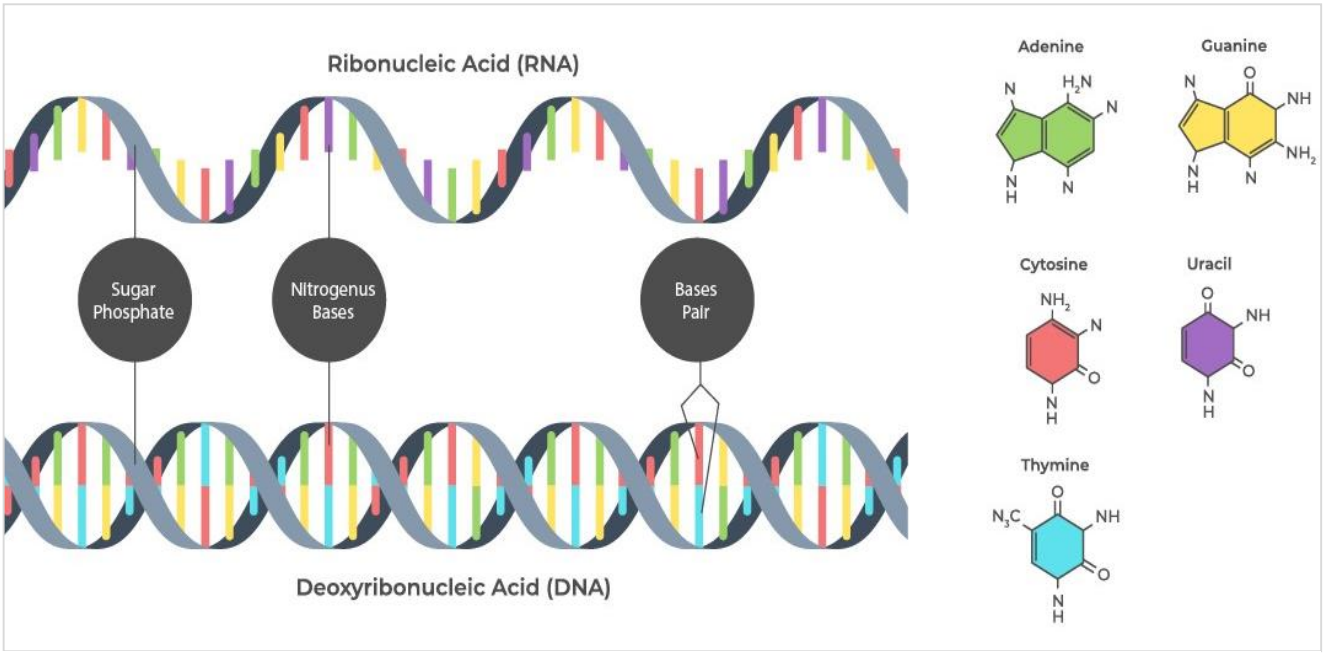

Figure 3: UV radiation in the 200–300 nm germicidal range is absorbed by RNA, leading to damage through pyrimidine dimer formation, such as uracil dimers. The figure shows this UV-induced RNA damage mechanism.

UV-C radiation has proven effective against all known coronaviruses. In our research, these findings have been compared with studies conducted on various coronaviruses, leading to the conclusion that UV-C radiation is effective not only against SARS-CoV-2 but also against potential future mutations of the virus.

RNA mutations have the potential to significantly alter the pathogenicity of a virus, and the antiviral action of UV-C radiation is primarily attributed to the absorption properties of RNA. Given this, it can be concluded that current UV-C disinfection systems are well-suited for combating all viral strains, including SARS-CoV-2. In this study, the necessary irradiation doses for the inactivation of SARS-CoV-2 and other coronaviruses were evaluated by reviewing and analyzing recent findings related to the photo-inactivation of the current coronavirus strains.

Step 1: Calculate Dosage

Ultraviolet radiation dosage quantifies the total energy delivered per unit area over a given exposure period. This metric is critical in a range of applications, including phototherapy, solar radiation studies, and UV-based sterilization or disinfection systems. For surface disinfection applications, the UV dose depends on the irradiation and exposure time(seconds). In equation 1, Distance, UV intensity and exposure time are important factors to accurately forecast the rate of UV dose [28, 29].

$$UV\ Dose\ \left(\frac{mJ}{cm^2}\right) = UV\ Intensity\ \left(\frac{mW}{cm^2}\right) x\ Exposure\ Time \quad (1)$$

or

$$UV\ Dose\ \left(\frac{\mu W.s}{cm^2}\right) = UV\ Intensity\ \left(\frac{\mu W}{cm^2}\right) x\ Exposure\ Time \quad (2)$$

Example Calculation: If a UV-C lamp emits radiation at an intensity of 2 mW/cm^2 and the surface is exposed for 30 seconds:

$$\text{Dose} = 2\ \text{mW/cm}^2 \times 30\ \text{s} = 60\ \text{mJ/cm}^2$$

This dose is often sufficient for microbial inactivation in surface sterilization procedures. Common applications for types of ultraviolet radiation are shown in Table 1.

Table 1: Typical dosage ranges by UV type

UV Type	Wavelength Range (nm)	Common Application	Typical Dose
UV-A	315–400	Dermatology, photobiology	>10 J/cm²
UV-B	280–315	Phototherapy, psoriasis	0.1–2 J/cm²
UV-C	200–280	Disinfection, sterilization	1–100 mJ/cm²

Step 2: Calculate Irradiance

Radiation is defined as the power per unit area and surface at a specific distance. In equation 3, UV irradiance decreases with the square of the distance from the source:

$$E \propto \frac{1}{r^2} \quad (3)$$

Hence, the positioning of the UV source significantly influences dosage. Factors such as surface

reflectivity, humidity, air particulates, and material transparency may attenuate the effective dose. The biological effect of UV radiation is wavelength-dependent; hence, action spectra are often applied to weight the dose according to biological effectiveness. After obtaining the dose requirement and calculated irradiance, the time required for the disinfection target is determined [30]. At certain wavelengths, UV light destroys the organism by breaking the molecular bonds in DNA. The effectiveness of UV irradiation is determined by various factors, including location and operational parameters, such as density, exposure duration, and lamp placement

Step 3: Calculate Time

Exposure time is a critical parameter in determining the total ultraviolet (UV) radiation dose delivered to a surface, medium, or biological target. In controlled applications, such as UV disinfection, phototherapy, and materials testing, accurate calculation of the exposure duration is essential for ensuring efficacy and safety.

To determine the time required to eradicate all microorganisms, including bacteria, viruses, spores and fungi, the following conditions should be met: (1) the specific dose of the required wavelength, (2) the number, location / distance of the LEDs, and (3) the minimum irradiation point on the surface. While these studies have demonstrated a significant reduction in bacterial levels within clinical settings, there has been limited investigation into patient outcomes or the practical applicability of UV-C use in healthcare environments.

While some microorganisms exhibit high sensitivity to UV-C radiation and can be effectively inactivated with a relatively low dose, significantly higher energy is required to eliminate more resilient organisms, such as fungi and spores. Therefore, the efficacy of UV-C in microbial inactivation is directly dependent on the dose administered. It is well established that UV-C radiation at a wavelength of 253.7 nm achieves a 99.9% inactivation rate for bacteria and viruses under optimal conditions. The determination of the appropriate number of UV-C lamps and their radiative power must be based on the dimensions of the environment to be disinfected. For example, in a room or office with an average size of 3x4x5 meters, a 15-watt UV-C lamp achieves a disinfection rate of 90%. To attain a 99% disinfection efficiency, the power of the lamp must be doubled. As the size of the room or office increases, both the power and the number of lamps should be proportionally increased. However, it is important to note that prolonged and intense exposure to UV-C radiation can cause skin reddening and, in the long term, may contribute to the development of skin cancer. Additionally, direct exposure to UV-C light can cause severe damage to the retina. Due to these health risks, UV-C radiation should be used cautiously, especially in disinfection and sterilization procedures. Beyond the effectiveness of disinfection systems, the potential negative effects on human health must also be carefully considered [31].

2.3. UVGI Disinfection Performance

Ultraviolet Germicidal Irradiation (UVGI) is a disinfection method that employs short-wavelength UV-C radiation (typically 254 nm) to inactivate microorganisms by damaging their nucleic acids. The effectiveness of UVGI depends primarily on the delivered UV dose, which is a function of irradiance and exposure time. When UV-C photons are absorbed by microbial DNA or RNA, they induce photochemical reactions such as the formation of thymine dimers, disrupting replication and leading to loss of viability. Factors influencing performance include the pathogen type, UV dose, surface characteristics, and environmental conditions such as humidity and airflow. Uniform irradiance distribution and appropriate exposure time are critical to ensure reliable microbial inactivation across the target area.

Radiation disinfection represents an alternative inactivation strategy for microorganisms and viruses, offering certain advantages over ultraviolet radiation, liquid disinfectants, and heat sterilization. Published reports in the literature have demonstrated that high doses of UV-C radiation are sufficient to inactivate SARS-CoV-2 or SARS-CoV in virus culture media [32-33]. However, there is a lack of data regarding the viral susceptibility to UV-C in UV-permeable fluids or in the absence of preservatives, which hinders accurate estimations of UV-C sensitivity in such conditions.

The results obtained from various studies are summarized and analyzed in Table 2, which categorizes the findings based on the type of irradiated sample (aerosol, surface, or liquid), the type of light source (including its peak emission wavelength), the inactivation effect, and the applied irradiation dose. The UV literature review presented in Table 2 provides valuable predictions regarding SARS-CoV-2 inactivation, as well as the inactivation of almost all other microorganisms through sun exposure. Given the established UV sensitivity of SARS-CoV-2, the data presented in this study support the conclusion that UV light is likely to have a

comparable effect on the transmission of coronaviruses as it has on other microorganisms. This review extensively analyzes studies that focus on the application of UV-C irradiation for the inactivation of various microorganisms, including viruses, bacteria, and spores.

Table 2: In the literature review, UV-C irradiation studies for inactivation of viruses / bacteria / spores

Main Group	Group	Type	Viral Inactivation Dose mJ/cm^2				Ref.
			D90	D99	D99.9	D99.99	
Viruses	Adenovirus	Adenovirus, type 1 (PLC/PRF/5 & HeLa cell line)	35	69	103	138	[34]
		Adenovirus, type 2 (PLC/PRF/5)	40	78	119	160	[35]
		Adenovirus, type 2 (human lung cell line)	35	55	75	100	[36]
		Adenovirus, type 2 (A549 cell line, CCL-185)	26	100	135	168	[37]
		Adenovirus, type 4 ATCC VR1572 (PLC/PRF/5 ATCC CRL8024)	10	34	69	116	[38]
		Adenovirus, type 6 (PLC/PRF/5 & HeLa cell line)	39	77	115	154	[34]
		Adenovirus, type 40 (HEK293)	35	70	105	139	[39]
		Adenovirus, type 41 (HEK293)	45	91	136	182	
	Coronavirus	Coronavirus	0,7	1,3	2	2,6	[40]
		Coronaviridae (Bernevirus)	0,7	1,4	2,2	2,9	[41]
		Coronavirus (Murine, MHV)	1,5	3	4,5	6	[42]
		Coronavirus (SARS, Cov-P9)	4	8	12	16	[43]
		Coronavirus (SARS, Hanoi)	13,4	26,8	40,2	53,5	[44]
	Coronavirus-2	HCoV-229E	0,56	1,1	1,7	-	[45]
		HCoV-OC43	0,39	0,78	1,2	-	
		SARS-CoV-2	0,016	0,71	6,556	31,88	[46]
	Coxsackievirus	Coxsackievirus, B3 (BGM cell line)	8	16	25	33	[35]
		Coxsackievirus, B4 (BGM cell line)	7	13	18	24	[47]
		Coxsackievirus, B5 (BGM cell line)	9,5	18	27	36	[35]
	Echovirus	Echovirus I (BGM cell line)	8	17	25	33	
		EchovirusII (BGM cell line)	7	14	21	28	
	Hepatitis A	Hepatitis A HM175 (FRhK-4 cell)	5,4	15	25	35	[48]
	Influenza	Influenza	3,4	6,8	10,2	13,6	[49]
		Influenza A (H1N1)	1,3	2,6	3,8	-	[45]
	Myoviridae	Myoviridae (E, coliC)	1,8	3,6	5,1	6,7	[47]
	Picornaviridae	Picornaviridae aphthovirus AS1 (BHK-21)	31	63	94	125	[50]
	Poliovirus	Poliovirus, type 1 (BGM cell line)	8	16	23	31	[35]
	Rotavirus	Rotavirus SA-11 (MA 104 cell line)	9	19	26	36	[48]
	Siphoviridae	Siphoviridae (E, coli C)	1,8	3,6	5,7	7,5	[47]
	Group Average		13,36	28,44	42,63	64,56	
Bacteria	Aeromonas	Aeromonas hydrophila (ATCC7966)	1,1	2,5	4	5,5	[48]
		Aeromonas salmonicida (AL 2017)	1,5	2,7	3,1	5,9	[51]
	Burkholderia	Burkholderia mallei (M13)	1,2	2,7	4,1	5,5	[52]
		Burkholderia pseudomallei (ATCC 11688)	1,7	3,5	5,5	7,4	
	Brucella	Brucella melitensis (ATCC23456)	2,8	5,3	7,8	10,3	
		Brucella suis (KS528)	2,7	5,3	7,9	10,5	
	Faecal	Faecal coliforms	6	9	13	22	[53]
		Faecal streptococci	9	14	22	30	
	Klebsiella	Klebsiella pneumoniae	5	7	10	12	[54]
		Klebsiella terrigena (ATCC 33257)	3,6	6,4	9,3	12	[48]

	Legionella	Legionella longbeachae (ATCC 33462)	1,4	3	4,7	6,3	[55]
		Legionella pneumophila (ATCC 43660)	3	5	7,2	9,3	[48]
	Mycobacterium	Mycobacterium avium (D55A01)	6,4	9,4	12	15	[56]
		Mycobacterium intracellulare (ATCC13950)	7,4	11	15	19	
		Mycobacterium avium hominissuis (HMC02, WT)	7,7	12	17	22	[57]
	Salmonella	Salmonella spp	1,8	2	3,5	7	[58]
		Salmonella typhimurium (ATCC 6539)	2,6	4,5	5,8	7	[59]
	Shewanella	Shewanella algae	0,9	1,7	2,4	3,2	[60]
		Shewanella oneidensis (MR4)	0,7	1,4	2,1	2,8	
		Shewanella putrefaciens (200)	0,5	0,8	1,1	1,4	
	Shigella	Shigella dysenteriae (ATCC 29027)	0,1	1	1,9	2,8	[48]
		Shigella sonnei (ATCC9290)	3,2	4,9	6,5	8,2	[59]
	Staphylococcus	Staphylococcus albus	1,1	3,2	4	4,8	[61]
		Staphylococcus aureus (ATCC BAA-1556)	4,5	7,2	8,8	10	[62]
	Vibrio	Vibrio anguillarum	0,5	1,2	1,5	2	[51]
		Vibrio cholerae (classical OGAWA 154)	0,8	1,4	2,3	3,9	[63]
	Yersinia	Yersinia enterocolitica (ATCC 27729)	1,6	2,7	4	5,1	[48]
		Yersinia pestis(A1122)	1,4	2,6	3,7	4,9	[52]
	Group Average		2,86	4,76	6,79	9,14	
Spores	Aspergillus	Aspergillus brasiliensis	122	226	293	-	[64]
	Bacillus	Bacillus anthracis (Sterne)	28	37	52	-	[65]
		Bacillus cereus (ATCC 11778)	52	93	140	-	[66]
		Bacillus atrophaeus (ATCC 9372)	22	38	55	71	[67]
		Bacillus pumilus (ATCC 27142)	68	138	204	272	[37]
		Bacillus subtilis (ATCC 6633)	36	48	59	77	[59]
	Cylindrospermum	Cylindrospermum (spores)	14	26	43	-	[68]
	Encephalitozoon	Encephalitozoon intestinalis	2,8	5,6	8,4	-	[69]
	Clostridium	Clostridium pasteurianum (ATCC 6013)	3,4	5,3	6,7	8,4	[66]
	Penicillium	Penicillium expansum (ATCC 36200)	11	38	49	65	
	Streptomyces	Streptomyces griseus (10137)	8,5	13	15	18	
	Thermoactinomyces	Thermoactinomyces vulgaris (ATCC 43649)	55	90	115	140	
	Group Average		35,23	63,16	86,68	93,06	

2.4. UV-C Dose Sensitivity Analysis

UV rays show the greatest antimicrobial activity, especially in the 253.7 nm wavelength region [70-72]. This wavelength is the most effectively value absorbed by DNA. UV radiation energy absorbed by cellular RNAs produces uracil dimers taking the responsibility for the primary mechanism of cellular UV damage. Another antimicrobial action mechanism of UV radiation is the addition of hydroxyl groups to the nucleotide bases. In this way, RNA replication, transcription and expression of genes are impaired before cell division. During sterilization processes, viruses, mycoplasma, bacteria, and fungi become inactive when exposed to UV rays. Although UV-C radiation is known to have an inactivating effect on all microorganisms, different UV-C irradiation doses are required for successful inactivation in all pathogens. Table 2 summarizes the specific species indicated by the results of studies performed on viruses, bacteria, and spores when exposed to ultraviolet light.

Disinfection level is typically expressed either as a percentage reduction of viable microorganisms or as a logarithmic reduction value (log reduction), both of which serve as standardized metrics to assess the efficacy of disinfection processes. These measures provide critical insights into the extent of microbial inactivation achieved by a given treatment, enabling quantitative comparison across different methods and conditions. Log reduction is a metric used to quantify

the reduction in the number of viable microorganisms following a disinfection or sterilization procedure. It is calculated by using the formula (4):

$$\text{Log Reduction} = \log_{10}\left(\frac{N_0}{N}\right) \quad (4)$$

Disinfection level is measured as percentage of disinfection or log reduction, and these values are displayed as Log 1 = 90%, Log 2 = 99%, Log 3 = 99.9%, and Log 4 = 99.99%. The D90 value indicates the ultraviolet dose for 90% inactivation. The D90 value range for Coronavirus-1 (SARS-CoV-1) is 0.7-13.4, the average ultraviolet inactivation sensitivity is 4.06, and the average ultraviolet inactivation sensitivity of the SARS-CoV-2 virus is 0.322. Most experts consider SARS-Cov-1 to be the closest relative to SARS-Cov-2 and therefore offer the best comparison for estimated inactivation dose rates. If we compare viruses, bacteria, and spores, it seems that viruses are generally affected by a lower dose of UV-C. In viruses, it is also obvious that coronaviruses are sterilized by UV-C rays in a short time. Although bacteria are larger than viruses and smaller than spores, it is seen that they are the weakest microorganisms against UV-C rays. While the 99.99% extinction dose of viruses under UV-C effect is about 64,56 mJ/cm^2, it is 9,14 mJ/cm^2 for bacteria and 93,06 mJ/cm^2 for spores, as seen in Figure 4. The UV radiation energy absorbed by cellular RNAs produces uracil dimers, which are responsible for the primary mechanism of cellular UV damage. We believe that uracil dimerization may be the main reason for better sterilization in bacteria. As can be seen from figure 4, the low-enough energy level for electronic transition in bacteria compared to spores supports this view. Looking at figure 4, it is generally seen that viruses are sterilized with fewer doses. On the other hand, spores are also sterilized with the highest dose of UV-C.

Our work has laid the groundwork for the eradication of the SARS-CoV-2 virus and its variants, demonstrating that we are on the right track. UV-C rays are a method used in the health and food industry to purify hospitals, health equipment, and agricultural products from bacteria and viruses. In the studies conducted, it has been determined that UV-C rays destroy organisms such as viruses, bacteria, and spores in a short time in the surface, air, liquid, etc. UV technologies have become extremely useful for disinfection, especially in the fight against the COVID-19 outbreak, in hospitals, pools, drinking water facilities, food, agriculture, and animal husbandry (greenhouses, fertilized waters, fishing, etc.). Considering the general features of UV, some points should be taken into consideration in the use of UV for disinfection. Preventing direct contact of people with UV light is the primary focus. Also, as the dust and dirt layer prevents UV transmission, the UV lamp should be cleaned frequently.

N_0 is the initial concentration of microorganisms (before treatment), and N is the concentration of microorganisms after treatment.

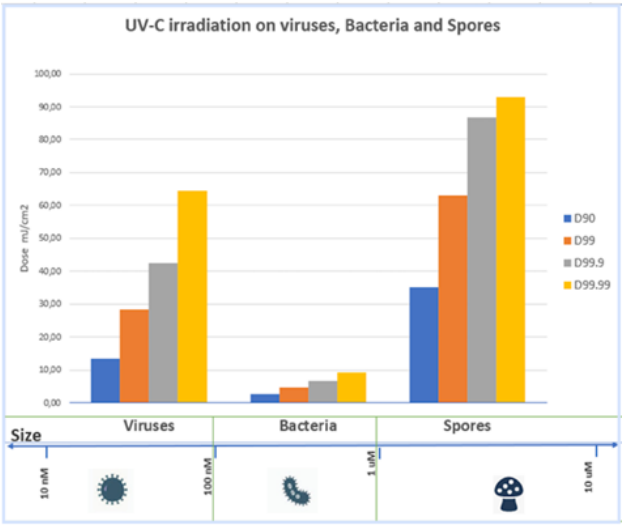

Figure 4: It is the required dosage chart for UV-C irradiation to destroy viruses, bacteria, and spores (90%, 99%, 99.9%, and 99.99%).

High-energy UV-C light is highly effective against a broad spectrum of microorganisms. Viruses, which contain RNA or DNA, are particularly sensitive to this radiation. Similarly, bacteria and fungi, as DNA-containing organisms, are also susceptible to the effects of UV light. It is also sensitive to UV lights in spores. Information on dosages required to inactivate different microorganisms with long-term UV use for disinfection is given in table 1. Bacteria are often easier to inactivate than viruses, fungi, and spores. The average dose for D90 in viruses is 13.36 mJ/cm^2, and it is 2.86 mJ/cm^2 for bacteria and 35.23 mJ/cm^2 for spores, as presented in figure 5. Adenovirus and picomavirade appear to be more resistant to UV-C rays than other types of viruses. As can be understood from these values, the new CoV-2 virus is very weak against UV-C rays. A small amount of UV-C for coronavirus is sufficient for sterilization. As a reason for this, it can be said that UV electronic transitions are effective in viruses, especially in the coronavirus family. Small amount UV-C rapidly affects the RNA of coronavirus and then uracil dimerization occurs. When uracil dimerization occurs, we can say that the structure of the virus deteriorates and loses its effect.

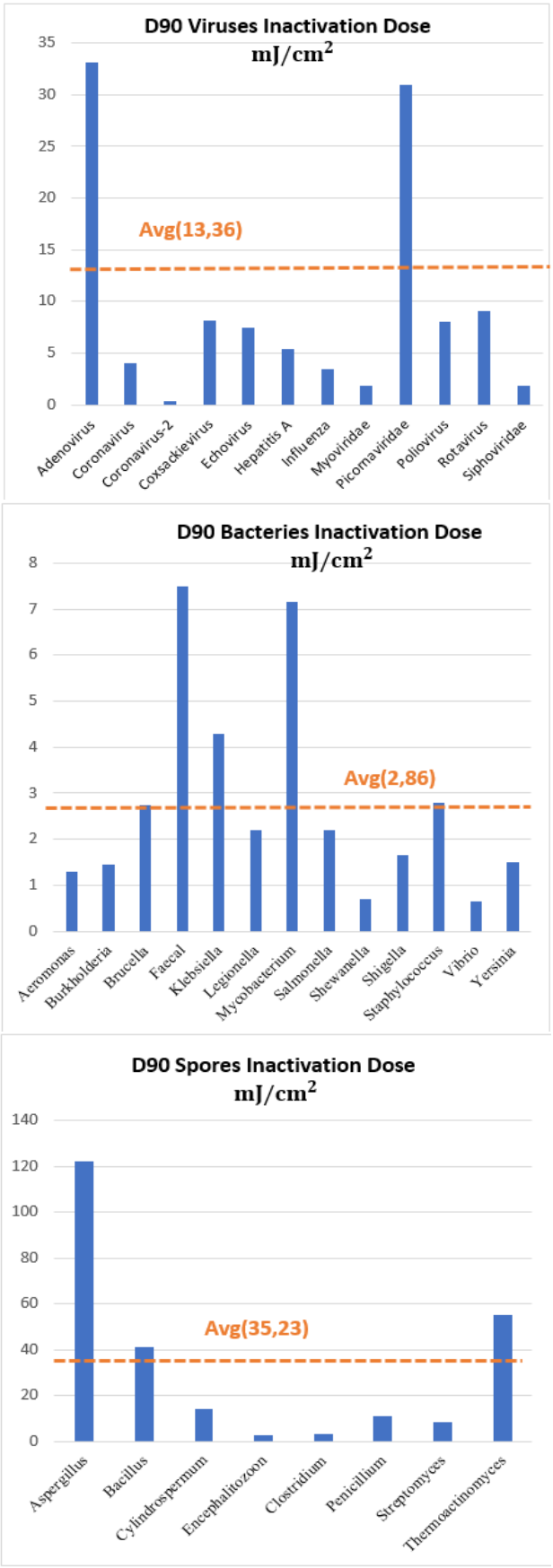

Figure 5: The 90% extinction dose rates for viruses, bacteria, and spores under UV-C irradiation at 254 nm wavelength are shown in the graphs.

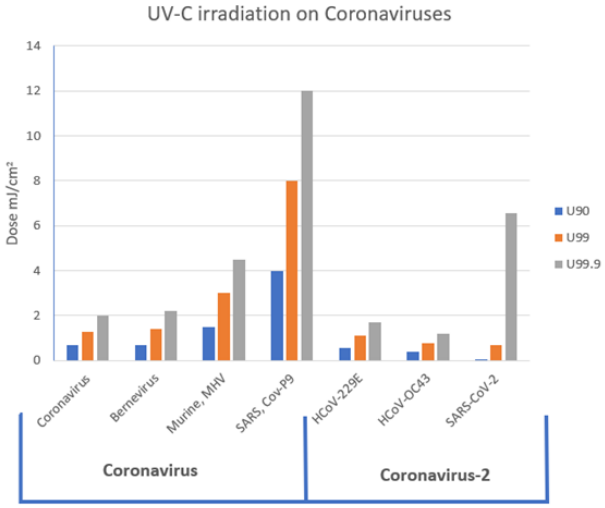

Figure 6: The required dosages of UV-C irradiation to achieve effective inactivation of coronaviruses are categorized based on the desired reduction levels: U90, U99, and U99.9.

Using the UV-C irradiation dosage data obtained from the past studies in table 1, the average dose required to destroy coronaviruses was calculated, and it was found to be 1.12 mJ/cm² for the U90 level, 2.32 mJ/cm² for the U99 level, and 4.3 mJ/cm² for the U99.9 level in Figure 6, except for Coronavirus (SARS, Hanoi). When the results obtained from the studies are narrowed down within the scope of the COVID-19 epidemic and the averages are examined again, it is seen that it is 0.32 mJ/cm² for the U90 level, 0.86 mJ/cm² for the U99, and 3.15 mJ/cm² for the U99.9 level. The results show that UV-C rays are more destructive at a lower dose rate in coronavirus-2 types than other coronavirus types. A close agreement was obtained between the predicted UV-C values in eradicating viruses. These results suggest that the methodology used here for estimating the UV susceptibility of SARS-CoV-2 virus from data obtained for members of the same family may have some accuracy.

3. Results and Discussion

The performance of ultraviolet germicidal irradiation systems in disinfection relies on several critical parameters, including wavelength, dosage, surface characteristics, and environmental conditions. The optimal inactivation of microorganisms occurs at a wavelength of 254 nm, aligning with the peak germicidal effectiveness of UV-C radiation. Dosage, a crucial determinant of disinfection efficiency, is calculated as the product of irradiance and exposure time, typically expressed in mJ/cm². Higher irradiance levels and prolonged exposure times result

in increased dosages, enhancing microbial inactivation.

Surface characteristics, such as material reflectivity and texture, play a significant role in UV penetration and distribution, influencing the uniformity of disinfection. Environmental conditions, including humidity and particulate matter, can attenuate UV effectiveness by scattering or absorbing radiation, reducing the dose delivered to the target. These factors collectively dictate the efficacy of UVGI applications, which are widely employed in air purification, water treatment, and surface sterilization in healthcare and public spaces. The interplay of these parameters underscores the importance of system design and environmental control in optimizing UVGI performance for diverse disinfection scenarios.

Ultraviolet radiation has a significant antiviral effect, but so far there have been very few studies of radiation dose measurements required to inactivate SARS-CoV-2. Inactivation studies with ultraviolet light are a key factor to decide the UV radiation dose required to reduce or destroy the virus. Using a structure designed by the inactivation of viruses in the sun, it was predicted that artificial UV-C ultraviolet radiation would neutralize the virus outbreak. In this study, it is to predict the sensitivity of viruses to inactivation with germicidal UV-C. Here, estimating the time required for the inactivation of infectious viruses and the amount of dose is useful for evaluating the persistence of viruses in areas exposed to radiation. Studies have reported that changes in humidity and ambient temperature have a very limited effect on environmental virus survival and disease transmission. The methodology employed in this study was used to estimate the UV-C susceptibility of related viruses or microorganisms.

4. Conclusion

Ultraviolet light technology has emerged as a significant area of research due to its broad spectrum of industrial applications and its potent antimicrobial properties, which enable the rapid inactivation of microorganisms under specific conditions. The effectiveness of UV radiation increases as the distance between the target and the light source decreases, making it crucial to minimize this distance for optimal exposure. Furthermore, the antimicrobial efficacy of UV light is directly influenced by the intensity and duration of exposure. Therefore, parameters such as lamp size, the number of lamps, and application time must be carefully determined based on the type of target microorganism (e.g., bacterial spores, viruses) and the size of the area to be treated.

In recent years, UV light has gained considerable attention for its potential in the early detection of viral infections, owing to its high selectivity, sensitivity, broad dynamic range, ease of fabrication, and rapid analysis capabilities. This review aims to summarize recent advancements in the fabrication and application of UV-based technologies for virus detection. Compared to conventional diagnostic methods, UV light-based systems offer several advantages, including simplicity, miniaturization, disposability, rapid response, and real-time analytical capabilities. Moreover, the integration of nanomaterials—such as gold and magnetic nanoparticles—into UV devices has enhanced both sensitivity and stability. In addition, the use of microarrays combined with microfluidic platforms allows for cost-effective production and simultaneous detection of multiple viral agents.

The findings discussed in this study are based on research involving various coronaviruses, including SARS-CoV, MERS-CoV, and SARS-CoV-2. Given the structural similarities among these viruses, it is highly probable that SARS-CoV-2 and its potential future mutations will remain susceptible to UV radiation. UV-C irradiation, in particular, has been shown to effectively inactivate bacteria, spores, and viruses by inducing damage to their nucleic acids. The dosage required for inactivation depends on the microorganism's resistance. RNA mutations, which may alter a virus's pathogenicity, can also affect the UV absorption characteristics of the RNA, thereby influencing the virus's vulnerability to UV exposure. These structural changes are a key factor underlying the antiviral efficacy of UV radiation. The insights presented in this study have important implications for environmental disinfection and sterilization strategies, contributing to the prevention of microbial transmission.

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