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Ultraviolet Light (UV-C): An Effective Tool to Mitigate Pandemic Spread- A Review

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***Abstract*— Ultraviolet light is mainly divided into three wavelength ranges UV-A (315-400nm), UV-B (280-315nm) and UV-C (100-280nm). Among these, the short- UV (UV-C) is found to have germicidal properties and at the same time is harmless to humans. UV-C light can be produced using tube-lights, smartphone flashlights, torches or any light source by incorporating a biochemical reaction using a fused amorphous silica (SiO_2) based dichroic mirror filter accompanied by Ultraviolet Germicidal Irradiation and Diffraction Grating splitting of white beams. This arrangement allows UV-C rays to pass while blocking other higher wavelengths. When such light falls on surfaces, it gets absorbed by nucleic acids of micro-organisms. The absorbed energy can result in defects like formation of pyrimidine dimers via a photochemical reaction. Dimerization prevents replication by forming covalent bonds between adjacent bases in the DNA, resulting in the inactivation of the organism. Such apparatus can be used to disinfect hands, groceries, electronic equipment, closed rooms and public places. This review work is intended to analyze this cutting-edge technology and its lucid implementation in everyday life, which is most relevant in today's time. This paper has also scrutinized its potency to eliminate bacteria and novel viruses like SARS CoV-2.**

Keywords— Biochemical Reaction; Photochemical Reaction; Ultraviolet Germicidal Irradiation and Diffraction; UV-C, 222nm and 254nm.

1. INTRODUCTION

Ultraviolet (UV) light is a form of electromagnetic radiation with wavelengths that range from 10nm (with a frequency of approximately 30 PHz) to 400nm (750 THz). UV has wavelengths shorter than visible light but are relatively longer than X-rays. Such rays are present in sunlight, and contribute to about a tenth of its total electromagnetic radiation output. Apart from the sun (which is its largest source) [1], it can be produced and emitted by tanning booths, black lights, curing lamps, germicidal lamps [2], or by heating a body to an incandescent temperature, as is the case with solar UV, or even by passing an electric current through a gas, usually vaporized mercury [3]. Some unique challenges and hazards may apply to all the different UV sources depending upon the range of wavelengths of the emitted radiation.

Ultraviolet (UV) radiation is undetectable by the human eye, although, when it falls on certain materials, it may cause them to fluoresce—i.e., emit electromagnetic radiation of lower energy, such as visible light. Unlike humans, many insects are able to see ultraviolet radiation [4].

Certain wavelengths of UV light can be harnessed which can be useful to eliminate pathogens such as viruses, bacteria and fungi which can be used against SARS CoV-2 currently in addition to the other medical techniques as a shield.

2. UV LIGHT AND ITS TYPES

Ultraviolet light is divided into four sub-categories. Of these, first three are the most widely used ones for practical, research and academic purposes (refer figure 1 [5]).

2.1 UV-A light (315-400nm)

UV-A light possesses the longest wavelength and is least harmful among all. It is colloquially known as "black light", and its ability to cause objects to emit fluorescence (a coloured glowing effect) is widely adapted in artistic and celebratory designs. Particular insects and birds can perceive this type of UV radiation visually, along with some humans having rare conditions such as Aphakia (missing optic lens) [6].

2.2 UV-B light (280-315nm)

This category of UV light leads to sunburns with prolonged exposure along with amplified risk of skin cancer and other vital cellular damage. However, it accounts for vitamin D and 95% of all UV-B light is absorbed by the ozone layer [6].

2.3 UV-C light (100-280nm)

This category of UV is very harmful, however, far UV-C (222 nm) is completely innocuous to humans. This light finds its application largely as a disinfectant to kill micro-organisms by destroying their cells' nucleic acids. Most part of it is absorbed by the ozone layer just like UV-B (refer figure 2) [6] [7].

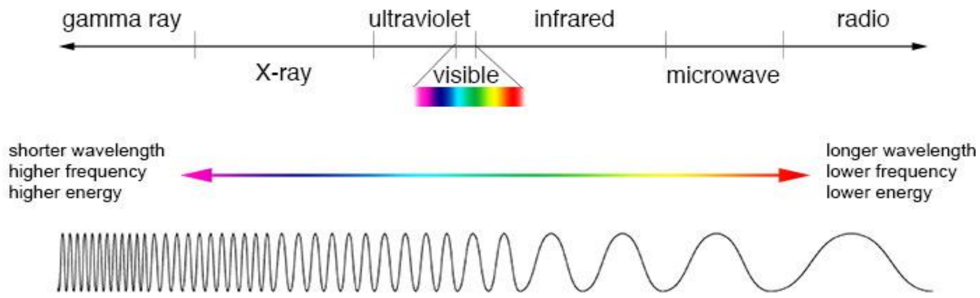

Figure 1: UV Spectrum

2.4 Extreme Ultraviolet (EUV) Light (10-100nm)

EUV light can only travel through a vacuum and is completely absorbed by the Earth's atmosphere. EUV radiation ionizes the upper atmosphere, leading to the formation of ionosphere. Additionally, Earth's thermosphere is mainly heated by the sun's EUV waves. EUV waves have to be measured using satellites, as they can't get past the atmosphere. However, due to its inability to travel through a medium, Extreme Ultraviolet Light is not much discussed [6].

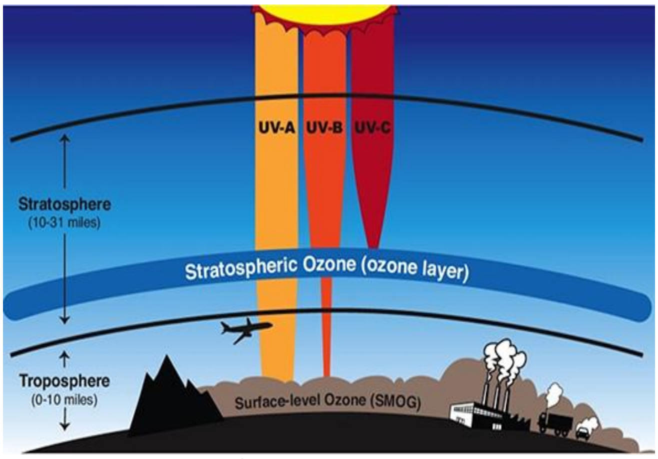

Figure 2: Interaction of various UV rays with the Ozone Layer

3. UV-C (254 nm and 222 nm)

Ultraviolet (UV) light exposure is a direct antimicrobial approach and its effectiveness against different strains of pathogens has been well-established. The most commonly employed type of UV light for germicidal applications is UV-C with a wavelength of around 254 nm [3].

UV-C is rarely observed in nature because it is absorbed completely by the atmosphere. Thus, the only possible way to produce UV-C radiation for disinfection is from an artificial source like a lamp or laser. Devices are designed to produce and emit UV-C light of the desired wavelength by means of doping or by using visible light. However, lamps using UV-C (254nm) can only be used to disinfect vacant spaces. This is because, such light penetrates up to the epidermis of the human skin which can cause corneal burns, commonly termed welders' flash, and snow blindness, a severe sunburn to the face on accidental over exposure. Moreover, it can damage the human eye too in the long run.

Off-late, far-UVC light (207 to 222nm) has been proven to be innocuous to humans and at the same time is as efficient as conventional germicidal UV light in killing microorganisms. The reason is that far-UVC light has a range of a few micrometers in biological material, and thus it cannot reach living human cells in the skin or eyes after being absorbed in the stratum corneum (dead skin layer) or the ocular tear layer (refer figure 3) [8]. As pathogens are extremely small, far-UVC light can still penetrate and kill them. Evidently, far UV-C (222nm) is as potent as conventional UV-C (254nm) and does not pose a health risk to humans as well [8].

4. UV GERMICIDAL IRRADIATION

Ultraviolet Germicidal Irradiation (UVGI) is based on electromagnetic radiation that impedes ability of microorganisms to reproduce by altering their nucleic acids via photochemical reactions. UV-C or far UV-C light is used for irradiation due to their germicidal properties. The germicidal effectiveness of UV-C peaks at about 260nm. This peak corresponds to the peak of UV absorption by bacterial DNA. The germicidal effectiveness of UV-C radiation can vary between species and the broader range wavelengths that include UV-B also make a miniscule contribution to inactivation [9].

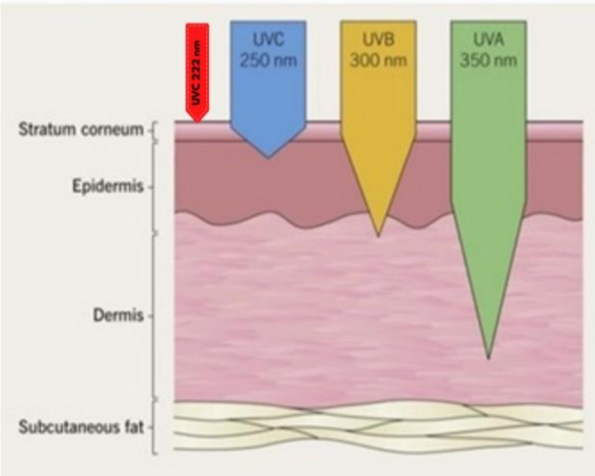

Figure 3: Penetration levels of different UV wavelengths in human skin

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4.1 DNA Structure (Background):

Deoxyribonucleic acid (DNA) is a macromolecule with high molecular mass, which comprises of elements called nucleotides. Each nucleotide element is made up of three parts:

1. deoxyribose
2. phosphate,
3. one of four nitrogenous bases (nucleic acid bases)-
    a. Thymine (T)
    b. Adenine (A)
    c. Cytosine (C)
    d. Guanine (G)

These four bases form base pairs where either thymine can be bonded to adenine or cytosine can be bonded to guanine. Since thymine and adenine pair up, there will be equal amounts of thymine and adenine always. Similarly, cytosine will always exist in same quantity as that of guanine. The particular sequences formed by these base pairs make up the genetic code that forms the chemical basis for heredity. The basic repeating unit of DNA are nucleotides and they are made up of nitrogenous bases called purines and pyrimidines. These bases are linked to pentoses to make nucleosides. The nucleosides are linked by phosphate groups to make the DNA chain [9].

The DNA double helix has two types of bonds, covalent and hydrogen (refer figure 4). Covalent bonds exist within each linear strand and strongly bond bases, sugars, and phosphate groups (both within each component and between components). Hydrogen bonds exist between the two strands and form between a base, from one strand and a base from the second strand in complementary pairing. These hydrogen bonds are individually weak but collectively quite strong [10].

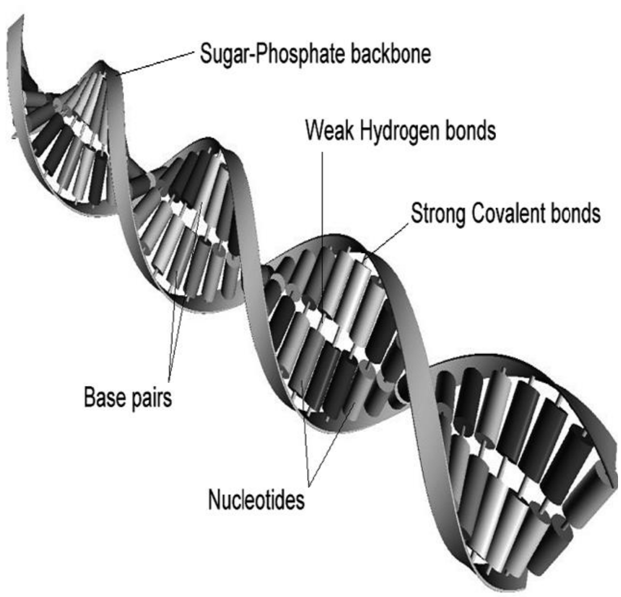

Figure 4: DNA Structure

5. PATHOGEN INACTIVATING ACTION OF UV-C

There exist two types of nucleic acids viz. ribonucleic acid (RNA) and deoxyribonucleic acid (DNA). During UV irradiation and inactivation, nucleic acids of microorganisms are the most sensitive target. RNA has D-ribose as its main constituent and adenine, cytosine, guanine, and uracil as bases. DNA has 2-deoxy-D-ribose as its main constituent and adenine, cytosine, guanine, and thymine as bases. Hydrogen bonds link the bases. Bacteria and fungi have DNA, while viruses may have either DNA or RNA. DNA and RNA are responsible for replication in microbes and alteration to these nucleic acids hinders reproduction [9].

UV-C inactivates microorganisms by causing the cross-links between constituent nucleic acids to form via a photochemical reaction. UV-C rays get absorbed and can result in the formation of intra-strand cyclobutyl-pyrimidine dimers in DNA, which in turn can either lead to mutations or even cell death.

Pyrimidines are molecular components in the biosynthesis process and include thymine and cytosine. Thymine and cytosine are two of the base pair components of DNA among others. The primary dimers formed in DNA by UV exposure are known as thymine dimers (refer figure 5). Their formation leads to structural defects in the genetic material and additional damage occurs upon the formation of cytosine dimers which is a lethal combination. Various other types of photoproducts are also formed that can contribute to cell death. Photohydration reactions can occur under UV irradiation in which the pyrimidines cytosine and uracil bond with elements of water molecules. However, the same reaction does not occur with thymine [9].

It has also been found that the photohydration yield is independent of wavelength which justifies the use of far UV-C (222nm) over conventional UV-C (254nm).

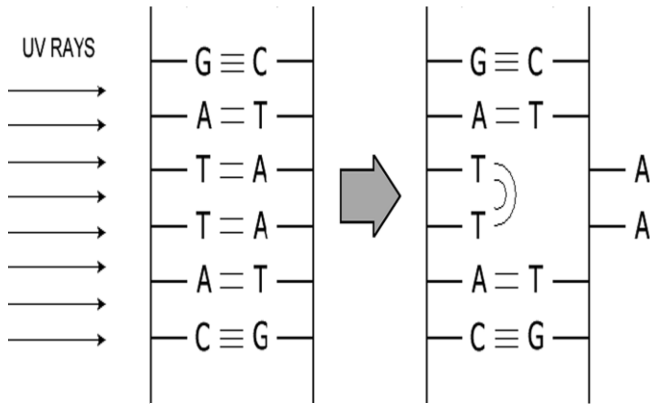

Figure 5: Formation of Thymine dimers

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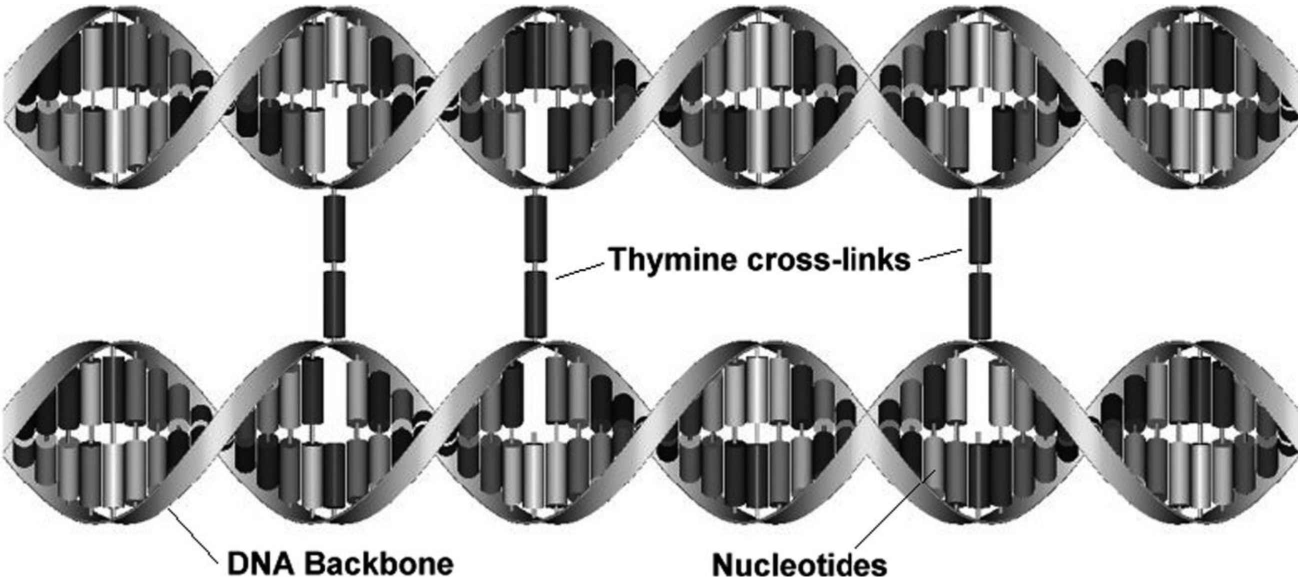

Figure 6: Cross-Linking

Apart from cross-links between adjacent thymines, UV-C may also induce cross-links (refer figure 6) between non-adjacent thymines. Cross-linking can also occur between the nucleotides and the proteins in the capsid (protein shell enclosing genetic material) of viruses, thereby permanently damaging the capsid of DNA viruses.

Cytosine and guanine can also undergo cross-linking, but three hydrogen bonds for thymine/adenine bonds makes it require high amount of energy and thus thymine dimers are in majority. Apart from cross-links with adjacent thymine nucleotides and with thymine in adjacent strands of DNA, thymine has the ability to also form links with proteins, including proteins in the capsid but in small amounts [9].

In RNA, for prokaryotic cells, eukaryotic cells and viruses, uracil takes the place of thymine. Thus, inactivation of RNA viruses involves cross-linking between the uracil nucleotides and the creation of uracil dimers. Uracil dimers can permanently damage the capsid of RNA viruses [9].

6. EFFECT OF GERMICIDAL IRRADIATION

A dose of 4.5 J/m^2 causes the formation of about 50,000 pyrimidine dimers per cell. It has been found that 100 J/m^2 induces approximately seven pyrimidine dimers per genome (complete set of nucleic acids in an organism) in SV40 (simian virus 40), which is sufficient to strongly inhibit viral DNA synthesis. Thymine dimers form within 1 picosecond of UV excitation, provided the bases are properly oriented at the instant of light absorption. Only a minute percent of the thymine doublets are likely to be favorably positioned for reaction and dimerization at the time of UV excitation [9].

The effect of 254 nm UV-C light on viruses, Sars CoV-2, bacteria and fungi has been given in tables 1,2,3 and 4 respectively.

TABLE 1. Summary of Ultraviolet dosage (254 nm) on Coronaviruses [11]

Microbe	D_{90} Dose (J/m^2)
Coronavirus	6.6
Berne virus (Coronaviridae)	7.2
Murine Coronavirus (MHV)	15
SARS Coronavirus (Frankfurt 1)	16.4
Canine Coronavirus (CCV)	28.5
Murine Coronavirus (MHV)	28.5
SARS Coronavirus (CoV-P9)	40
SARS Coronavirus (Hanoi)	133.9
SARS Coronavirus (Urbani)	2410

(D_{90} refers to the energy required to deactivate 90% of the microbe per unit area)

TABLE 2. Dosage and efficacy data of UV-C on SARS-CoV-2 [12]

Viral Inactivation(%)	Dose (mJ/cm^2)	Exposure Time (secs)
90	0.016	0.01
99	0.706	0.32
99.9	6.556	2.98
99.99	31.88	14.49
99.999	108.714	49.42

TABLE 3. Effect of UV-C (254nm) on bacteria [11]

Bacteria (Sr. no.)	D_{90} J/m^2	Survival (CFU) at exposure time (seconds)					
		0	5	15	30	60	90
1	26	1500	400	0			
2	40	8200	1900	0			
3	26	18000	1000	10	0		
4	120	1800	800	100	0		
5	52	7200	2100	28	4	0	
6	18	4200	1900	38	10	0	
7	13	2800	2600	1000	20	100	10

Bacteria:

1. Multidrug resistant pseudomonas aeruginosa
2. Methicillin resistant Staphylococcus aureus
3. ESBL- producing Escherichia Coli
4. Vancomycin-resistant Enterococcus Faecium
5. Carbapenem-resistant klebsiella pneumoniae
6. Acinetobacter baumannii
7. Clostridium difficile

TABLE 4. Effect of UV-C (254nm) on fungi [11]

Fungi	D_{90} J/m^2	Survival (CFU) at exposure time (seconds)					
		0	5	15	30	60	90
Candida parapsilosis	98	2300	300	11	0		
Fusarium Solani	313	1700	1100	300	0		
Candida Albicans	374	3000	2800	700	32	0	
Aspergillus fumigatus	560	2700	2700	2200	1200	100	10

7. USING WHITE LIGHT TO PRODUCE UV-C

White light emanating from any source viz. tube lights, smartphone flashlights, Light Emitting Diode (LED) bulbs or torches can be used to produce UV-C light. This technology is made available by incorporating a biochemical reaction using a fused amorphous silica (SiO_2) based dichroic mirror filter [13] accompanied by Diffraction Grating splitting of white beams and Ultraviolet Germicidal Irradiation.
The above mechanism is housed in a thin sheet known as a biofilm coupled with a Bandpass/Dichroic Mirror Filter.

7.1 Light activated anti-microbial surfaces (Biofilms)

Biofilms or light activated anti-microbial surfaces in this particular case of converting white light to UV-C, are made up of lanthanide-doped up conversion luminescent nano-crystalline and micro-crystalline Y_2SiO_5 (yttrium orthosilicate), methylene blue with or without gold nanoparticles [14] or photosensitizer-containing cellulose acetate film [15]. Unlike photocatalytic surfaces, which convert light energy into reactive chemical species, these specially designed surfaces inactivate microorganisms through purely optical mechanisms, wherein incident visible light is partially converted into UV-C thereby causing germicidal irradiation. This sheet, in addition to up conversion phosphors which utilize a Pr(3+) activator are synthesized for light conversion and the results are cross checked with photoluminescence spectroscopy (for experimental purposes) [16].

7.2 Dichroic Mirror Filter/ Bandpass filter (BFP)

In combination with the light activated anti-microbial surfaces, dichroic mirror filters help block the unwanted wavelengths of light. They separate a broad spectrum of light into two components: a reflected component and a transmitted component. They provide the ability to select different bands from a spectrum and direct those bands to where they can either be used or discarded.

This filter comprises of alternating layers of optical coatings with different refractive indices are built up upon a glass substrate. The interfaces between the layers of different refractive index produce phased reflections, selectively reinforcing certain wavelengths of light and interfering with other wavelengths (refer figure 7).

The layers are usually added by vacuum deposition. By controlling the thickness and number of the layers, the frequency of the passband of the filter can be tuned and made as wide or narrow as desired. As unwanted wavelengths are reflected rather than absorbed, dichroic filters do not absorb this unwanted energy during operation and thus do not heat up.

They are often labeled with two numbers (e.g., 450/50). That means that the filter will detect the wavelengths of the first number within 50nm, here between 425-475nm [17].

For germicidal irradiation, i.e. UV-C generation and emission, Sputtered or ion-assisted PVD oxide-based band

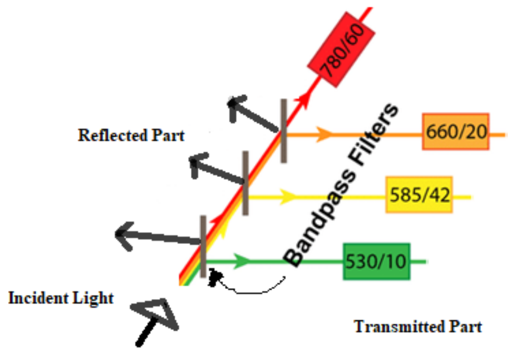

Figure 7: Bandpass Filters

passed filters are used transmit about 80% of the desired UV-C rays.

8. ADVANTAGES OF USING UV-C AS A METHOD OF DISINFECTION

8.1 For surface disinfection (for airborne pandemic causing pathogen)

One of the most significant advantages of deploying UV radiation in disinfection protocols is that it is non-toxic. Chemical disinfection is purely based on substances which may be harmful if consumed (for e.g., Sodium Hypochlorite and other chlorine compounds, Formaldehyde, Glutaraldehyde, Hydrogen peroxide), or even be corrosive to unprotected skin – and human-led chemical disinfection and cleaning processes carry the inherent risk of contaminating surfaces and, where relevant, food preparation utensils. Though extreme doses of UV light can be harmful, novel UV technologies implemented in public places and healthy environments are specifically designed to minimize the risk of overexposure for staff and patients [18].

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UV light has been shown to destroy or neutralize a wide array of pathogens, bacteria, spores and fungi: in order to destroy the same range of harmful organisms through chemical means, either multiple substances must be used or a single concentrated cleaning chemical must be deployed, with potential risks posed by residue and fumes. Manual chemical cleaning carries the additional fear of leaving surfaces damp and internal spaces humid, an atmosphere which fosters the growth of fungi and moulds.

Additionally, chemical disinfection leads to by-product residue formation. However, as UV disinfection doesn't involve chemicals, the question of by-product formation doesn't arise [19]. Over a period of time, disease pathogens become immune to chemical treatment which renders the disinfection method ineffective. The use of UV-C radiation to kill pathogens eliminates the possibility of immunity and helps curb the spread of pathogens at a faster rate.

While considering logistical terms, operators in settings where UV disinfection technology has been implemented have spoken positively about the ease of installation and use. These systems, once implemented, have to be rarely moved nor they have to be adjusted every time before use, many of which can be operated remotely. Another striking feature of UV-C disinfection is that it is extremely economical as compared to other methods. It hardly requires maintenance and lasts long.

8.2 For water disinfection (for waterborne pandemic causing pathogens)

UV-C disinfection offers numerous significant advantages in comparison to other methods such as chlorination, filtration and oxidization.

In particular there are no harmful by-products, toxic or non-toxic waste produced by the disinfection process, harmful side effects, negative environmental effects, or changes to the water chemistry. As it is a physical method of disinfection, there is no danger of overdosing or over-exposure of the water, air or surface to UV irradiation. Most importantly, no organism is immune to UV-C irradiation and thus cannot acquire any resistance.

Furthermore, the process requires very little contact time for disinfection in comparison to other processes, does not affect the smell or taste of the treated water, and can be simultaneously combined with a variety of other disinfection and treatment processes [19].

In addition to its negligible impact on the environment, UV-C disinfection reduces the dependence on other costlier and environmentally-harmful methods of disinfection, increases economy due to low investments and maintenance costs, and guarantees reliability and safety due to sophisticated sensors (refer figure 8).

However, UV-C disinfection is undermined by contaminated pipe networks and without regular sanitation and cleaning of the pipe network the lasting protective effect is mitigated; nonetheless such obstacles are easily overcome by combining UV-C disinfection with complementary methods.

SODIUM HYPOCHLORITE	UV DISINFECTION
Annual Cost = $166,900	Annual Cost = $58,100
• Sodium Hypochlorite • De-chlorination (SO2 or Bisulfite) • Hazardous Chemical Handling Charge • Fuel Delivery Surcharge • Laboratory Chlorine Testing • Electrical Cost • Chlorine Residual Probe • Hypochlorite Tank • Hypochlorite Containment • Hypochlorite Feed System • De-chlorination Feed Equipment • Personal Protective Equipment • Annual Equipment Maintenance (including de-scaling) • Spill Kit	• Lamp Replacement • Electrical Requirements • Equipment Maintenance • Indicator Organism Testing • Wiper Seals, solution, parts • Ballasts Replacement (if required)

Figure 8: Factors affecting cost

[The (figure 9) compares the environmental aspects of different disinfection methods [18].

a. 1 and 3 compare water disinfection methods
b. 2 and 3 compare surface disinfection methods]

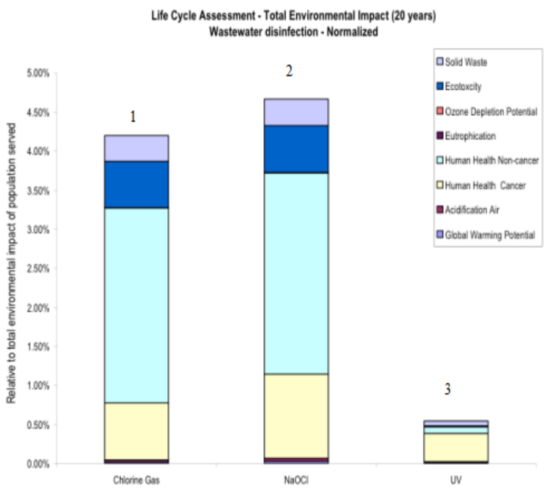

Figure 9: Environmental Impact of various disinfection methods

9. POTENTIAL APPLICATIONS OF UV-C DISINFECTION SYSTEMS TO CURB THE COVID-19 PANDEMIC

Currently, as the world and especially India battles the lurking pandemic, it is imperative to find a solution that keeps the virus at bay and at the same time is harmless to humans. The most apt solution to this question is the use of UV-C disinfection systems. As proved earlier, far UV-C (254nm and 222nm) is totally lethal against all pathogens including SARS CoV-2, UV-C (222nm) can even be put to use in human occupied spaces.

Germicidal irradiation can either be conducted through UV-C generating bulbs or via a bio film arrangement as discussed earlier in this paper.

Application 1- Hospitals

UV-C disinfection (refer figure: 10 [ ]) can help reduce COVID-19 spread by bringing down Hospital-Acquired Infections (HAIs). These are infections that patients contract while in the hospital that were neither present nor developing at the time of admission. Nursing Homes, Clinics or hospitals can procure such disinfection systems to disinfect PPE kits, hand-gloves, clothes and surgical instruments. These can be also used to clean pantry items like groceries, packed food and utensils due to their non-toxic behavior.

Application 2: Hotels and restaurants

UVC-222nm germicidal irradiation can be used in hotels and restaurants. Inside restaurants, it can be used in kitchens, storage rooms, dining areas and waiting areas continuously without any harm in presence of humans. This will lead to easy disinfection and faster service.

Hotels can incorporate this system in every room, reception area, banquet hall and on cutlery sets. Sensors can be installed which enables the system to work after guests leave hotel rooms for UV-C (254nm).

Application 3: Schools and Colleges

Currently, educational institutes have not been asked to start operating. But once they are, UV-C can be instrumental to secure each and every student, teacher and non-teaching staff. Such systems can be installed in classrooms, toilets, laboratories, recreational areas and staff rooms.

Application 4: Public Transport

Public transport is one such case where maintaining social distancing could be challenging, especially in metropolitan cities like Mumbai. There have been numerous crowding incidents in local trains and buses in the recent times which can create havoc as far as the community transmission of COVID-19 is concerned. Thus, using UV-C (222nm) disinfection can be the best solution to stop the spread of COVID-19 without exercising strict social distancing. UV radiating devices can be fixed at regular intervals in train coaches or buses after considering their output power and strength.

Application 5: Theatres

As the theatres reopen in the coming days, each cinema hall can also incorporate UV-C (222nm) disinfection before every screening and ensure customers have a safe cinema experience.

Application 6: Shopping Markets and malls

Each shop can be fitted with such disinfection systems (222nm) so that businesses can run unhindered on full capacity.

Application 7: Ultraviolet Disinfection Tunnels

Analogous to X-ray tunnels used to scan baggage at various public places, UV-disinfection tunnel can be used to disinfect a wide range of objects at airports, malls, bus and train stations. As human interference in this process would be nil, UV-C (254nm) could be also used.

Application 8: Airports and flights

UV-C (222nm) disinfection devices can be used extensively at airports. Apart from UV tunnels, they can be used at lounges, shops, food-courts and toilets without any hassle.
Specialized systems with two arms (UV-C 254nm) (each for one column in an airplane) can be used to disinfect the cabin after every flight in a vacant condition or UV-C (222nm) radiating devices can be kept at regular intervals to disinfect the air and surfaces continuously in human presence.

Application 9: Groceries and other household items

UV-C (254nm and 222nm) handheld torches can be moved over such concerned objects for prescribed amounts of time to ensure the inactivation of viruses over their surface and not causing harm to the object at the same time.

10. CONCLUSION

The COVID-19 pandemic has brought the world virtually to a standstill and researchers are still in the race to find a concrete deterrence for the transmittal of the SARS CoV-2 as infections are being reported in individuals in spite of getting inoculated. Not disputing the significance of vaccines, according to the data presented in this paper, UV-C light can be used in combination with them and other medical therapies to curb the contagion of SARS CoV-2. UV-C rays (of wavelengths 254 nm and 222 nm) have been found to be extremely efficacious against a plethora of viruses, bacteria and fungi. However, the 222 nm UV-C rays have an edge over the 254 nm wavelength due to an important aspect of being harmless to human skin which makes them apt for use in public places without hindering the movement of humans. Also, UV-C disinfection is more effective than conventional techniques for both surface and water disinfection. Additionally, UV-C rays are environment friendly and

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economical which give them an upper hand over other methods from the point of views of sustainability and affordability. Also, as water can be disinfected using UV-C rays, governments over the world can even be prepared to tackle water-borne pandemics in the future using this cutting-edge technology. However, the human skin is susceptible to UV-C (254 nm) which is its major drawback. Prolonged exposures to the same could cause serious skin hazards which makes it utmost important to regulate and monitor the usage and sale of such devices.

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