Kaunas University of Technology

FACULTY OF MATHEMATICS AND NATURAL SCIENCES

Ultra-Violet-C light source investigation and application for healthcare premises disinfection

Master's Final Degree Project

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Summary

This study aimed to investigate the use of UV-C LED modules for creating a hybrid lighting-disinfection solution suitable for healthcare institutions. High-quality UV-C LED modules were constructed using specific 275 nm wavelength UV-C LED chips. The constructed UV-C radiation source was applied to the LED luminaire to create the hybrid solution. The photometric and photobiological properties of the LED luminaires and UV-C radiation sources were investigated. The luminaire "X" was found to have high efficiency, excellent 92.2 colour rendering index (CRI), and a suitable colour temperature (CCT) of almost 4000 K for work requiring concentration. A specific polymethylmethacrylate (PMMA) de-glaring micro-prismatic diffuser (DPRZ) with a matt light scattering layer was used for healthcare premises applications. The photobiological measurements of UV-C radiation sources were conducted to determine the optimal duration of premises disinfection required to avoid potential transmission of diseases outside of healthcare institutions. The results showed that 3 UV-C LEDs had the best sterilization abilities of all measured variations. For the SARS-Cov-2 virus or coronavirus, which requires a 50 J/m^2 dose for even 99% sterilization, the required time would only be 42 minutes assuming a distance of 2m between the UV-C light source and the objects in the healthcare premises. Other investigated microorganisms required higher doses and time for 90% sterilization, which were not suitable for safe surface disinfection. The outcome of the research provides valuable information about the properties and applications of recently invented UV-C LED sources. The hybrid solution created in this study has the potential to provide efficient and effective disinfection in healthcare premises, thereby reducing the risk of transmission of diseases.

Čeplikas Paulius, UV-C spinduliuotės šaltinių tyrimas ir taikymas sveikatos priežiūros patalpų dezinfekcijai. Magistro baigiamasis projektas / vadovas Prof. Giedrius Laukaitis; Kauno technologijos universitetas, Matematikos ir gamtos mokslų fakultetas.

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Reikšminiai žodžiai: Ultra Violetas, sveikatos priežiūra, mikroorganizmai.

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Santrauka

Šiuo tyrimu buvo siekiama ištirti UV-C LED modulių panaudojimą, kuriant hibridinį apšvietimo-dezinfekcijos sprendimą, tinkamą sveikatos priežiūros įstaigoms. Aukštos kokybės UV-C LED moduliai buvo sukonstruoti naudojant specifinius 275 nm bangos ilgio UV-C LED lustus. Sukonstruotas UV-C spinduliuotės šaltinis buvo pritaikytas LED šviestuvui, kuriant hibridinį sprendimą. Ištirtos LED šviestuvų ir UV-C spinduliuotės šaltinių fotometrinės ir fotobiologinės savybės. Nustatyta, kad šviestuvas „X“ pasižymi dideliu efektyvumu, puikiu 92,2 spalvų perteikimo indeksu (CRI), tinkama beveik 4000 K spalvų temperatūra (CCT) darbui, reikalaujančiam susikaupimo. Specialus polimetilmetakrilato (PMMA) akinimą mažinantis mikroprizminis difuzorius (DPRZ) su matiniu šviesą sklaidančiu sluoksniu buvo naudojamas sveikatos priežiūros patalpų pritaikymui. UV-C spinduliuotės šaltinių fotobiologiniai matavimai buvo atlikti siekiant nustatyti optimalią patalpų dezinfekcijos trukmę, reikalingą siekiant išvengti galimo ligų perdavimo už sveikatos priežiūros įstaigų ribų. Rezultatai parodė, kad 3 UV-C šviesos moduliai turėjo geriausias sterilizavimo savybes iš visų išmatuotų variacijų. SARS-Cov-2 virusui arba koronavirusui, kuriam reikalinga 50 J/m^2 dozė net 99% sterilizacijai, reikalingas laikas būtų tik 42 minutės, darant prielaidą, kad atstumas tarp UV-C spinduliuotės šaltinio ir objektų yra 2 m. Kiti tirti mikroorganizmai reikalavo didesnių dozių ir laiko 90% sterilizacijai, o tai netiko saugiai paviršių dezinfekcijai. Tyrimo rezultatai suteikia vertingos informacijos apie neseniai išrastų UV-C LED šaltinių savybes ir pritaikymą. Šiame tyrime sukurtas hibridinis sprendimas gali užtikrinti efektyvią dezinfekciją sveikatos priežiūros patalpose, taip sumažinant ligų perdavimo riziką.

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Abbreviations:

Prof. – professor;

UV – ultraviolet;

UV-VIS - Ultraviolet–Visible;

DNA - deoxyribonucleic acid;

RNA - ribonucleic acid;

LED – light emitting diode;

PCB – printed circuit board;

CCT - correlated colour temperature;

CRI – colour rendering index;

COI – cyanosis observation index;

SMT – surface mounting technology;

UVGI – ultraviolet germicidal irradiation;

ROS – reactive oxygen species;

EPS - extracellular polymeric substance;

AC – altering current;

DC – direct current;

PMMA - polymethyl methacrylate;

DPRZ - de-glaring micro-prismatic diffuser.

Introduction

The COVID-19 pandemic has had a big impact on our daily lives and has made disinfection even more crucial to stopping the spread of infectious diseases. Disinfection, which is the process of bringing the number of microorganisms down to a safe level, is a crucial procedure in the medical field, the food industry, the water treatment industry, and other sectors. Traditional disinfection techniques like heat and chemical disinfectants have drawbacks like toxicity, environmental issues, and material damage. As a result, effective, secure, and environmentally friendly alternative disinfection technologies are required [1].

Since the early 1900s, ultraviolet (UV) light has been used to disinfect surfaces, and it has been shown to be effective against a range of microorganisms, including bacteria, viruses, and fungi. Microorganisms' DNA and RNA can be harmed by UV light, which prevents them from reproducing and spreading infection. However, there are some disadvantages to conventional UV-C lamps that use mercury vapour, including high energy consumption, protracted warm-up times, and the presence of toxic materials [2].

The advancement of UV-C LED technology in recent years has provided a promising disinfection solution. UV-C light from UV-C LED sources has a wavelength of 200–280 nm and is very effective at killing microorganisms. In comparison to conventional lamps, UV-C LED sources have several advantages, including low energy consumption, high efficiency, compact size, and long lifespan. They are also safe for the environment because they don't contain any hazardous materials, which makes them the best option for a variety of disinfection applications [3].

Aim of the research: To develop a UV-C LED light source optimized for healthcare institutions and investigate its irradiation properties based on standards.

Research tasks:

1. To construct a 275 nm wavelength UV-C LED module by applying UV-C LED chips on a PCB plate.
2. To apply constructed UV-C LED light source to the LED luminaire that would be applicable to healthcare premises and surface/air disinfection.
3. To investigate photometric, photobiological properties of constructed UV-C LED hybrid luminaire and theoretically evaluate its disinfection abilities.

1. Literature review

1.1. LED luminaire

The abbreviation LED meaning light emitting diode is one of the most important notations in this whole research work. It can be applied when using it together with other terms that include LED luminaire, LED chip, UV LED etc. LED luminaires are the most important electrical devices when it comes to premises illumination. It is rapidly changing the old, gas-containing tube light sources and offers a huge number of different applications and control possibilities.

LED luminaire is the same lighting device as it was for 20-40 years already, just a few changes have been made. The light source and its controlling component have changed. Tubes and electric discharge lamps were switched to more compact, less energy wasting and easier light distribution-controlled LED modules. It also contains a few more components that are very important such as reflectors, lenses, housing, shielding parts, LED drivers, emergency blocks to control light when there is no power and many other possible components that make the LED luminaire modern these days [4].

The principle defining the LED operation process is called electro-luminance. It is based on electron movement or in other words recombination with electron holes by jumping between p and n types of semiconductors which creates a p-n junction. When the right voltage is given to the leads the consequence of electron jumping is the released energy in the form of photons. Photons are the light that humans can see and their colour depends on the band gap energy [5].

LED luminaire has one more very important component which is called LED driver. It is responsible to convert the net voltage to the one that is suitable for LED modules according to their operating voltage window. Each driver has its operating windows as well and it needs to be carefully selected when trying to compose with LED modules.

LEDs are utilized for the illumination of places and objects. Due to its small size, low energy consumption, long lifespan, and versatility in terms of use in many applications, it is applied everywhere. A few significant uses for LEDs include optical switching, burglar alarm systems, power ON/OFF indications, power level indicators etc. LEDs are also utilized in LED displays, vehicle lighting, TV and smartphone backlighting, as well as in dimming lights and LED displays [6].

LED luminaires have various photometric parameters that are important in general. Some of those would be correlated colour temperature (CCT), colour rendering index (CRI), luminous flux, glare control, cleanability, and cyanosis observation index (COI). Each of these parameters determines where certain LED luminaires should be applied, and it defines the quality of the light parameters.

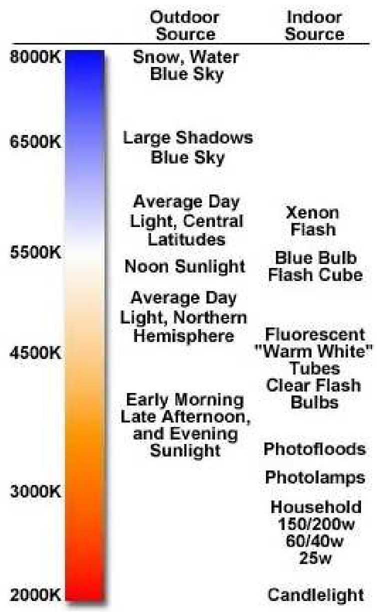

Fig. 1. The colour temperature chart [7].

The one parameter which can be easily distinguished by the naked eye is the CCT which defines light source colour from the comfortable yellow-white at 2000 K to the dazzling and intense blue-white 8000 K light. To take it simple it is separated into two divisions that would be warm and cold light and it is measured in Kelvin (K). An example of the different light sources relevance to the CCT is presented in **Fig. 1**. [7] [8]. CCT is a measure of the colour of light emitted by a light source. McCamy's approximation is a way to estimate the CCT of a light source based on its chromaticity coordinates. Chromaticity coordinates are two numbers that represent the colour of a light source in a standardized way. These coordinates are necessary for CCT calculations which can be obtained by measuring a light source with a light spectrometer. The chromaticity coordinates can be found on the CIE chromaticity diagram which is presented in **Fig. 2**.

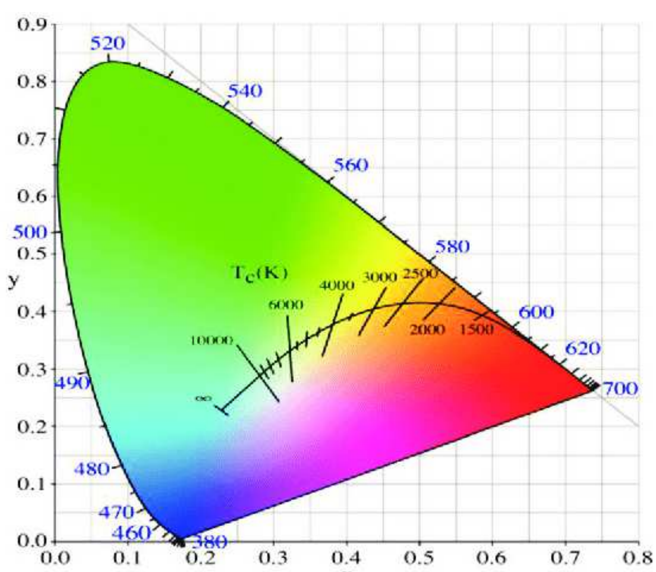

Fig. 2. CIE chromaticity diagram [9].

After obtaining the chromaticity coordinated McCamy's approximation can be used for CCT calculations with the following formula:

$$CCT = -449n^3 + 3525n^2 - 6823.3n + 5520.33 , \quad (1)$$

The formula involves the use of "n" which is a number that is derived from the chromaticity coordinates of a given light source. To determine the value of "n" the distance between the chromaticity coordinates and a reference point on the CIE chromaticity diagram must first be determined. This distance is then divided by a constant value that is dependent on the chosen reference point [10].

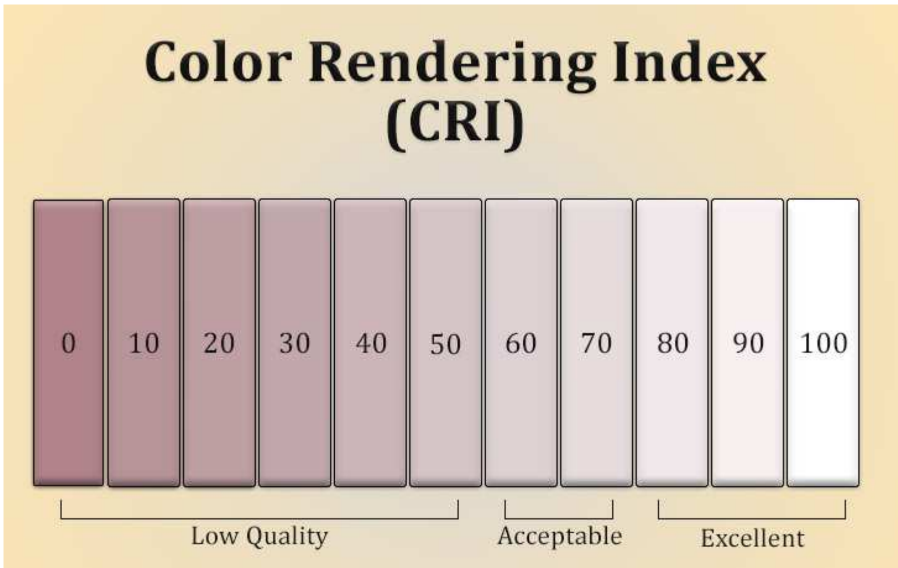

Fig. 3. Colour rendering index scale [11].

All of the mentioned parameters are important, but the most significant, besides the CCT, are CRI and COI. In comparison to a natural or conventional light source, a light source's capacity to faithfully portray the colours of various objects is measured quantitatively by the colour rendering index CRI. It is a comparison value that can be used to assess how a light source appears to be coloured. The scale goes from 0 to 100, with 100 being the finest possible ability to display colour and 0 being the least (**Fig. 3**.) [11]. The CRI is then calculated by taking the average of the individual colour rendering indexes (R1-R8) weighted by their importance to general colour rendering. ΔE is a measure of the colour difference between the test light source and the reference light source for a given colour. In other words, the Euclidean distance (ΔE) is a measure between the two-colour points in the colour space, which is a 3D colour space that takes into account the way humans perceive colour. It helps to obtain the important variable R_i (individual colour rendering index) which is necessary for total CRI calculation. The formula for CRI calculation is:

$$CRI = (\frac{1}{R_a}) \sum R_i , \quad (2)$$

where R_a is the average of the first eight colour rendering indexes (R1-R8) and R_i is the individual colour rendering index for each of the eight colours [12].

According to the AS/NZS 1680.2.5:2018 standard, the Cyanosis Observation Index (COI) is a parameter that assesses a light source's suitability for visual cyanosis detection which includes LED light sources. A spreadsheet calculator and the Spectral Power Distribution (SPD) data of a luminaire can be used to determine its COI. Skin and mucous membrane cyanosis, a bluish hue, is a sign of inadequate blood flow or low oxygen levels in the red blood cells. Because it makes cyanosis detection more precise, COI is significant in medical settings [13]. The COI is calculated based on the change in colour appearance of fully oxygenated blood (100% oxygen saturation) and oxygen-reduced blood (cyanosed blood at 50% oxygen saturation) when illuminated by the light source in question compared with a 4000K reference light source. The spectral reflectance of oxygenated and cyanosed blood is multiplied by the spectral distribution of the light source being considered over the spectral range 380-780nm, in steps of 5nm. The resulting colour is then calculated in a specific colour space and compared with a 4000K reference illuminant to determine the COI value. The lower the COI value, the smaller the shift in colour appearance under illumination by the light source being considered. The COI is a measure of how much the chromaticity coordinates of the light source deviate from the chromaticity coordinates of a Planckian radiator with the same CCT. The higher the COI, the more the light source will affect the perception of cyanosis. The COI is calculated using the following formula:

$$COI = (X_S - X_{50})^2 + (Y_S - Y_{50})^2 + (Z_S - Z_{50})^2, \qquad (3)$$

where X_S, Y_S, and Z_S are the chromaticity coordinates of the light source, and X_{50}, Y_{50}, and Z_{50} are the chromaticity coordinates of the Planckian radiator with the same CCT as the light source [14].

1.1.1. LED modules

In the previous section, there was a lot of information about LED luminaires and here the most significant component of the LED luminaire will be explained, it is called the LED module or the LED light source. The main principle of LED module operation was clarified in the previous section. Therefore, its advantages and disadvantages compared with conventional light sources will be defined in this chapter.

Advantages start with the most obvious fact, that LED modules are very small and compact, they can fit in the smaller housing of the luminaire and yet provide the same or even better illumination. Compared to traditional lighting solutions, LEDs require very low voltage and current settings and have extremely fast response times. LEDs do not need any warm p time to provide their best performance. There is one more advantage of this type of light source, it would be a lifetime, which can reach up to 20 years while no other lighting solutions can not provide any better option.

Despite all the positive things, LEDs also have some drawbacks. Even though it does not require high electrical resources, the minimal excess of current or voltage may damage the LED permanently. Some of the high-power LEDs tend to heat over time and require additional cooling devices like little radiators, or aluminium plates covered with thermal conductivity supporting materials. If an LED is overheated its light output may differ from the original at standard conditions [15].

LED modules can be used in a variety of applications, including lighting fixtures like recessed luminaires, various metal housing luminaires, wall or surface luminaires, emergency lighting, high bays, floodlights, and park and street luminaires. Due to their size and shape LEDs can be applied to any type of housing and provide high-quality illumination over the chosen are whether it may be inside or outside [16].

1.1.2. LED chips

An LED module typically requires two main components, which would be a printed circuit board (PCB) and LED chips that are a thin layer of semiconductors made of gallium nitride (GaN) or indium gallium nitride (InGaN) inserted between a few layers of other semiconductor material. This combination of semiconducting materials is responsible for the lighting of the LED module when the voltage is applied. An example of an LED chip is presented in **Fig. 4**.

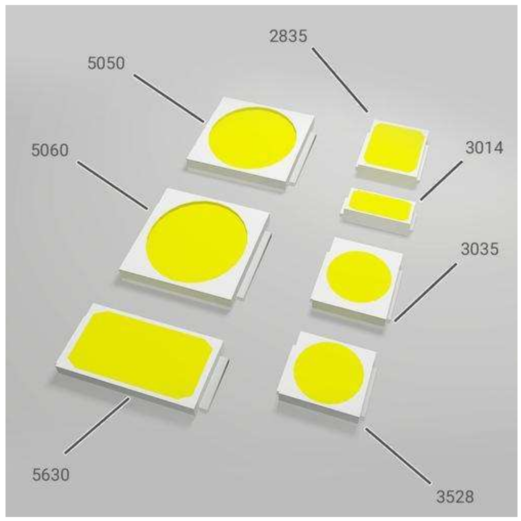

Fig. 4. Different sizes LED chip examples [17].

The special qualities that enable them to emit light when a current is run through them are the reasons that the semiconductor materials used in LED chips are chosen. In order to maximize the movement of electrons and holes (positively charged carriers) through the LED chip, which allows the semiconductor material to generate light, the layers of the LED chip are meticulously designed and constructed [16].

A p-type layer, an n-type layer, and an active layer are frequently found in an LED chip's construction. The photons are produced when the electrons and holes unite in the active layer (light). Electrodes that respectively inject electrons and holes into the active layer are the p-type and n-type layers. Typically, LED chips have a size of less than a square millimetre. To help with heat transfer and safeguard the delicate semiconductor material, they are frequently put atop a metal or ceramic substrate [16][18].

Besides the usual LED chips, there are recently released UV-C LED chips, specifically designed for microorganism sterilization or disinfection and the aim of such devices is to change the currently existing germicidal lamps. UV-C LED chips are a form of LED that emits UV-C light with a wavelength of 200 to 280 nanometers (nm). UV-C radiation is extremely powerful at killing viruses, bacteria, and other microorganisms, but it requires to be used very carefully to preserve human health. In order to kill microbes and inhibit their reproduction, UV-C LED chips emit photons with enough energy to sever the molecular bonds in their DNA and RNA. UV-C LED chips have an average lifespan of up to 10,000 hours or even more and are incredibly effective, way ahead of currently used

UV-C lamps. UV-C LEDs are safer to use because they do not contain any hazardous gas and their radiation direction can be easily manipulated by using silicon-based lenses. Also, they use less energy than conventional UV-C lamps, which makes them perfect for battery- and portable-powered applications [19].

1.1.3. Surface mounting technology

Several Light Emitting Diodes placed on a printed circuit board make up a self-contained LED module. Resistors, capacitors, and inductors are common electrical components found on PCBs that are used to control the voltage and current sent to LEDs. Printed circuit boards frequently have LED chips mounted using surface-mount technology (SMT). The PCB is covered in solder paste, and the LED chips are inserted there before being placed in a reflow oven to melt the solder and affix the LED chips to the Board. For the LED module to last a long time and have strong electrical contact, this technique is essential. An LED module is a ready-to-use lighting system made up of LED chips, a driver, and a heat-dissipating enclosure. The main element of an LED module is an LED chip, and the semiconductor is what emits the light. There are various other ways of soldering LED chips on the PCBs, however, the explained one is the most common. If talking about a concrete example, a PC-white LED package is shown in **Fig. 5.** and includes several components, including an LED chip (also known as an LED die), phosphors, an encapsulant, bonding wire, die-attach, a lead frame, and housing. The epi-layer, current-spreading layer, chip substrate, chip electrodes, etc. are among the layers that further split the LED chip. The main task of converting the blue LED light into a yellow and red spectrum is carried out by the phosphors combined with an encapsulant. The housing serves as a sturdy shell to shield the pc-white LED from mechanical harm. The interior surface of the housing is always coated with reflecting materials, such as silver, in order to improve the light extraction efficiency of the pc-white LED. To connect the LED chip with the external circuit via bonding wires for electricity conductivity, the lead frame is embedded inside the housing. In addition to serving as a heat flow path between the LED chip and the lead frame, the die attaches layer with solder paste is used to fix the LED chip to the lead frame [20].

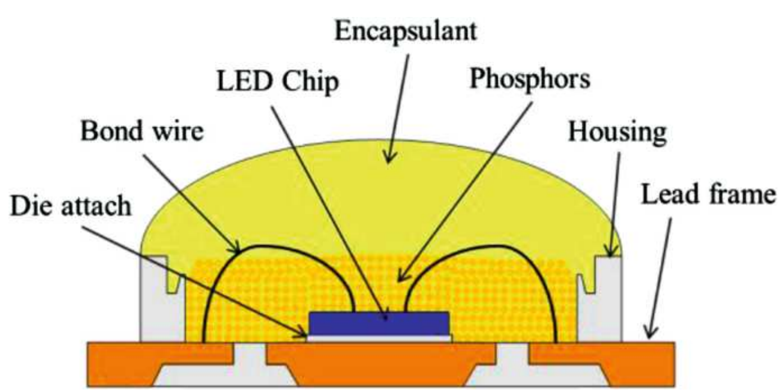

Fig. 5. Example of LED chip structure [21].

1.2. Ultraviolet radiation

A form of electromagnetic radiation with a shorter wavelength (**Fig. 6**.) and more energy than visible light is ultraviolet (UV) radiation. The main source of UV radiation is sunlight, but it may also be created artificially by lamps and other sources like the recently mentioned UV-C LED modules. There are four known regions of UV spectra: UV-A, UV-B, UV-C and V-UV [22]. UV radiation is known for more than 200 years, and it was discovered in 1801 by Johann Wilhelm Ritter. The beginning of UV investigation was at the end of the nineteenth century and some of the results are still used duo to its accuracy [23].

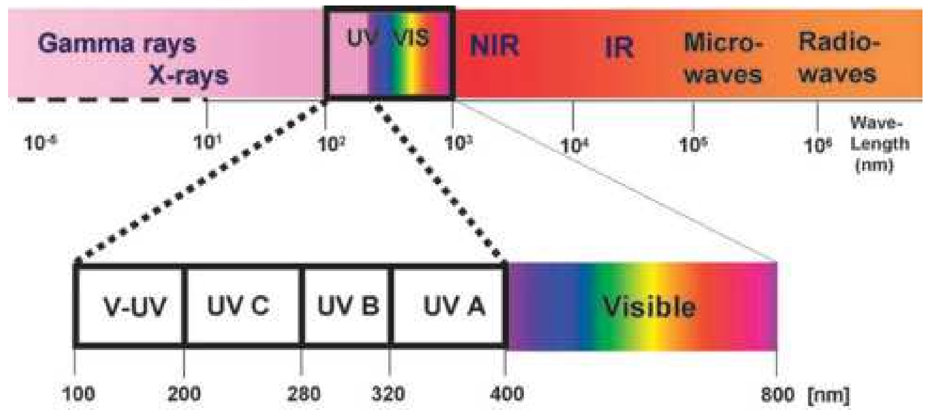

Fig. 6. Ultraviolet spectra distribution [22].

- The longest-wavelength and least energetic form of UV light is UV-A (320–400 nm). It causes tanning and skin ageing and is a component of sunshine.
- The middle-wavelength and more intense kind of UV light is known as UV-B (280–320 nm). It causes skin cancer and sunburn and is also a component of sunlight.
- The shortest wavelength and most intense form of UV light is UV-C (200-280 nm). While it cannot reach the Earth's surface due to the Earth's atmosphere, it may be created artificially for sterilization and disinfection reasons.
- An even shorter wavelength is V-UV, which can only travel freely in a vacuum (100-200 nm) [22][24].

Live organisms can be harmed by excessive UV radiation exposure, which can result in eye damage, skin damage, and a higher chance of developing skin cancer. Wearing protective clothes, using sunscreen, and limiting exposure to the sun and other UV radiation sources are all significant ways to protect oneself from UV radiation [24].

1.2.1. UV-A

Ultraviolet (UV) radiation, which has a shorter wavelength than visible light but a longer wavelength than X-rays, is one of the forms of electromagnetic radiation that is invisible to the human eye. Long-wave or black light UV, which has a wavelength range of 315 to 400 nm, is another name for UV-A radiation. Since UV-A radiation is less absorbed by the ozone layer than UV-B or UV-C radiation, it is the most common type of UV radiation to reach the Earth's surface (**Fig. 7.**). However, because UV-A radiation may penetrate the skin and the eyes more deeply than other forms of UV radiation and harm DNA, collagen, elastin, and other cellular components, it can also pose major health hazards to people and other living things. Premature ageing, wrinkles, skin cancer, cataracts, retinal degeneration, and other illnesses may occur from interaction with UV-A radiation. Contrarily, UV-A radiation also has some beneficial applications, including causing fluorescence in some materials and substances, helping with forensic analyses and phototherapy treatments, promoting the production of melanin in tanning beds, and eliminating germs and viruses in sterilization equipment.

Additionally, some creatures with a different visual spectrum than humans, such as bumblebees, can perceive UV-A radiation and use it to find flowers and nectar sources. Thus, UV-A radiation is a fascinating and complex phenomenon that affects matter and life in both beneficial and detrimental ways [25].

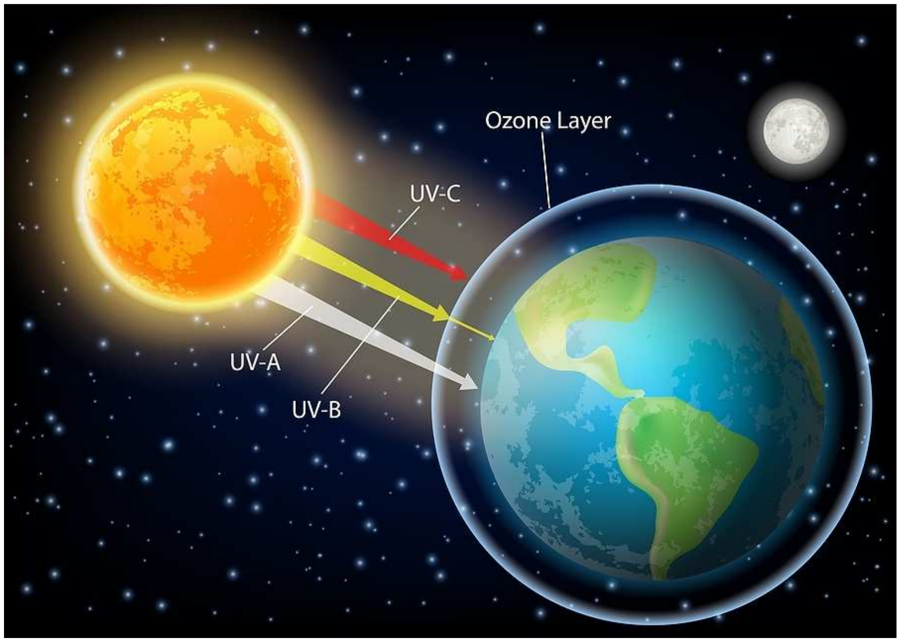

Fig. 7. Demonstration of UV radiation types' differences when interacting with the ozone layer [26].

1.2.2. UV-B

The second type of ultraviolet radiation is called UV-B and it has a wavelength variating from 280 to 315 nanometres, which makes it the middle band of UV light spectra. Figure 6 illustrates how much of each ultraviolet type can penetrate through the ozone layer, it is clearly seen that even if a major part of UV-B is stopped, a fraction of it still reaches the surface of the earth, especially in higher altitude areas. Of course, the penetration of the UV-B is not constant, it changes depending on season, time of the day and northern latitudes. For example, during the winter season in the north most of the radiation is stopped and attenuated, but in the southern regions in the summer more UV-B passes than usual. UV-B is not known for its ability to disinfect and sterilize various microorganisms like UV-C radiation, but it still has some effect on the skin cells and human DNA during its interaction. UV-B radiation is to blame for roughly 65% of occurrences of melanoma, the deadliest type of skin cancer. However, UV-B radiation can also encourage the skin's natural production of vitamin D, which is vital for strong bones and a healthy immune system. Lower COVID-19 death rates are linked to higher levels of UV-B exposure, probably because vitamin D1 has a protective effect. Additionally, UV-B radiation has medical applications, including the treatment of eczema, vitiligo, psoriasis, and other skin conditions [27][28].

1.2.3. UV-C

With a wavelength range of 200 to 280 nanometres, UV-C light is the shortest wavelength band of UV radiation. Additionally known as germicidal UV. Natural UV-C radiation does not naturally reach the Earth's surface since it is primarily absorbed by the ozone layer and the atmosphere. However, lamps and other sources of UV-C light can create it intentionally. Because it can damage the DNA and RNA of microorganisms like bacteria, viruses, fungi, and parasites, UV-C radiation has the potential to have potent disinfectant properties. This can stop them from procreating and spreading disease to people and other living things. Human coronaviruses and their viral proxies, such as SARS-CoV-2, the virus that causes COVID-19, can be rendered inactive by UV-C radiation. Additionally, UV-C radiation has a variety of uses, including sterilising surfaces, tools, food, water, air, and personal protection equipment. Additionally, UV-C radiation can be used in a variety of locations, including homes, offices, public transit, hospitals, and schools. However, because it can lead to skin burns, eye damage, and cancer, UV-C radiation can also be dangerous to people and other living things. As a result, UV-C radiation is a potent and promising phenomenon that poses both health dangers and opportunities for disinfection [29][30].

1.2.4. UV-C LED

A particular kind of LED called a UV-C LED emits ultraviolet radiation with a wavelength of 200–280 nm, which can damage bacteria and viruses by destroying their DNA. The way germicidal lights are used to clean and sterilize surfaces, water, and the air is changing thanks to UV-C LED. Since Niels Finsen originally found them in 1893, germicidal lights have been in use for more than a century. He developed a method to treat tuberculosis using UV light, which earned him the Nobel Prize in Medicine. In 1910, a prototype for the first UV water treatment facility was built in Marseilles, France. The disadvantages of conventional germicidal lights include their limited lifespan, mercury content, ozone production, warm-up duration, and warm-up requirement. By being ozone-free, instant-on, long-lasting, and mercury-free, UV-C LED eliminates these drawbacks. Compared to traditional germicidal lamps, they also offer better design flexibility and energy efficiency. Many applications that call for disinfection benefit from using UV-C LEDs, particularly in light of the COVID-19 epidemic. They can be used to disinfect personal items, clean air ducts, sterilize medical equipment, cleanse drinking water, and shield public areas from infections [31][32][33].

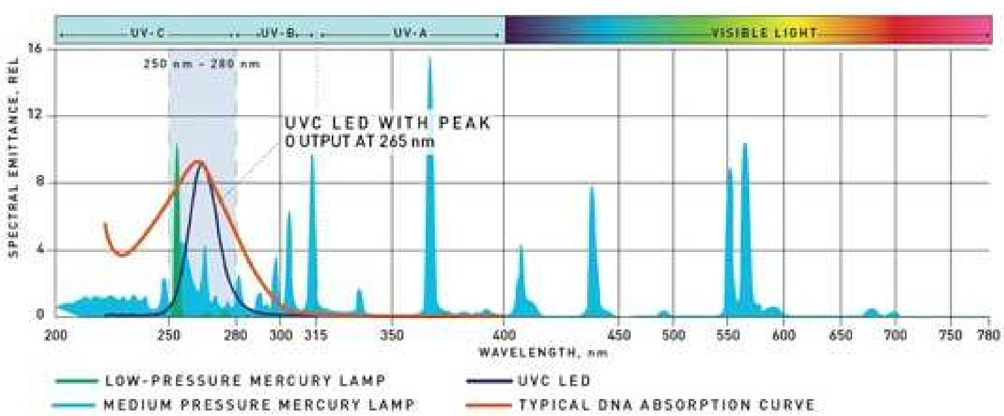

Fig. 8. Spectral comparison of germicidal lamps against UV-C LED on their effectiveness when sterilizing microorganisms [34].

Besides the huge number of advantages of UV-C LED when compared whit germicidal lamps, there is one more very important parameter. It is a UV-C LED wavelength. **Fig. 8.** displays the DNA absorption curve of microorganisms as well as the emission spectra of various UV light sources. The chart shows that UV-C LEDs emit more light in the 250–280 nm range, which is best for inactivating the DNA of bacteria than low-pressure and medium-pressure mercury lamps. This means that UV-C LEDs have a better emission spectrum for disinfection. The image also demonstrates that medium-pressure mercury lamps emit a wide range of wavelengths, including unwanted and potentially hazardous wavelengths for disinfection, while low-pressure mercury lamps produce a single wavelength at 253.7 nm, which is below the peak absorption of DNA. Figure 7 shows that UV-C LEDs are a more effective and focused source of germicidal light than conventional mercury lamps. It can be clearly seen by the area coverage of UV-C LED that it is superior technology compared to low and medium-pressure lamps. The graph illustrates the top peak of UV-C LED at 265 nm wavelength. Such wavelength it a recent invention by Japan scientists and is not so widely available [35]. However, there is another very popular type of UV-C LED with a wavelength of 275 nm which has similar abilities and it will be investigated in this work [34][36].

1.2.5. UV dose

Ultraviolet is a non-ionizing form of radiation, however, some types of it for example UV-C is very harmful to living organisms at certain doses. Human skin and eyes are especially sensitive to this radiation type. It may cause symptoms similar to the sand in the eye feeling or burning and later consequences may lead to skin cancer development. UV-C radiation on our planet earth in only produced by artificial sources, because the ozone layer is protecting the UV-C radiation that comes from the sun. Various standards and scientific researches define what doses are safe for people and harmful for the majority of microorganisms, due to the UV-C radiation purpose of disinfection. The fluence or more common term dose describe the total radiant energy incident on a certain area or surface. The main units of dose are $W \cdot s/m^2$ or J/m^2, but it may alter to other decimal units' variations for simplicity reasons. The dose can be calculated when the intensity of the radiation and time of irradiation is known and is defined by the formula:

$$D = I * t \tag{4}$$

In this equation D – dose, I – intensity of radiation, t – time. The dose is measured by J/m^2, intensity is measured by W (sometimes μW or mW), and time is measured in s.

The dose required to sterilize different bacteria or viruses does not only depend on the type and structure of the microorganism but also depends on the medium where the germ is located whether it may be surface, water or air. Surface-located microorganisms need the highest doses due to the attachment and surface material properties, while germs in the air are the easiest to sterilize [37].

Another important thing to mention is UVGI (Ultraviolet germs irradiation) effectiveness curve, which is a mathematically modelled curve that describes the UV-C radiation wavelength disinfection abilities. It is used as a response curve to determine how much area of the germicidal curve the used UV-C source is covering at a certain wavelength. **Fig. 9.** displays the example of a specifically designed 265 nm wavelength UV-C LED source in response to the UVGI curve. It can be seen that UV-C source intensity matches the germicidal curve peak at 265 nm and it shows that this wavelength is most effective during the disinfection process [38].

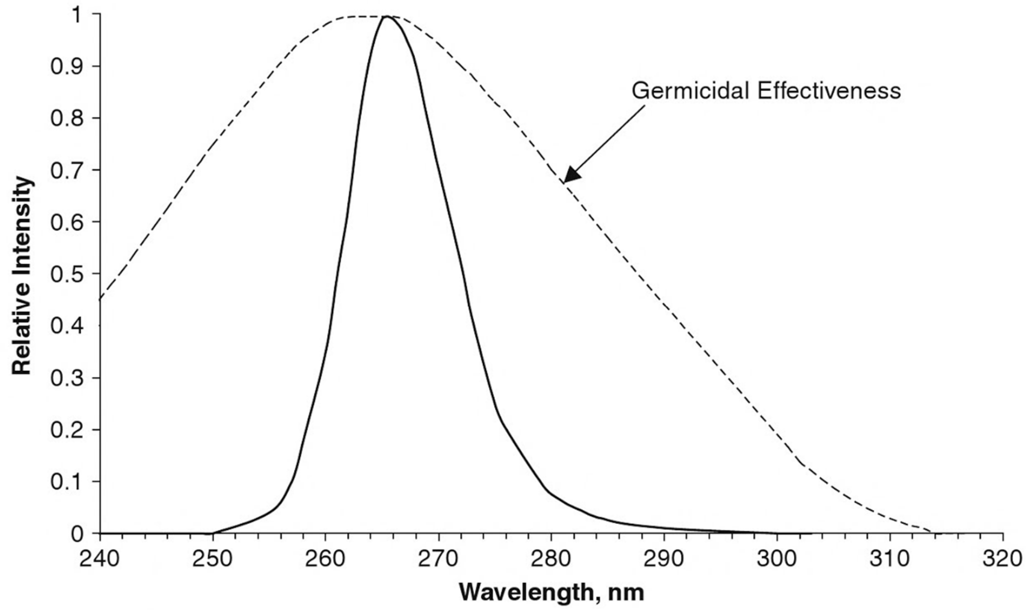

Fig. 9. UVGI effectiveness curve in comparison to the 265 nm UV-C LED [39].

However, the given UV-C LED curve is produced by relatively new and expensive LED technology and is not yet commercially beneficial to use compared to the currently used UV-C germicidal lamps [40].

1.2.6. UV interaction with human eyes and skin

In previous chapters, the interaction of UV-C and human eyes or skin was mentioned. UV-C radiation has a lethal impact on living organisms' DNA and RNA structures, which is dangerous and harmful thing, but if it is used correctly, it can even save lives by sterilizing hazardous microorganisms from the environment. However, UV-C radiation is capable to penetrate the outer layers of human skin or the eye and cause serious damage due to its highly energetic exposure (**Fig. 10.**).

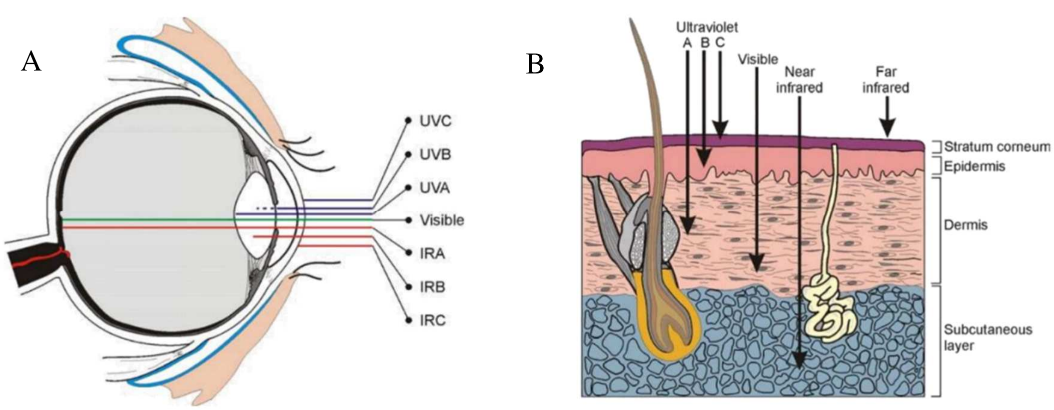

Fig. 10. A – Human eye and B – skin interaction with UV spectra example [38].

The basic principle is that UV-C energy, which is photons get absorbed by the human body molecules that include DNA, proteins and lipids found in most of the human cells. Then reactive oxygen species (ROS) are created and the outer layers of cells are ruptured due to the lack of oxygen which is partly responsible for nutrient transportation and finally the cell is dead without the possibility to replicate or regenerate [41][42][43].

1.2.7. Short term effects

Some of the UV-C source radiation effects can appear instantly or just in a short time. Of course, it depends on many variables that include the time under irradiation, the irradiation intensity, and personal human's ability to heal which also depends on age and many other variables. Short-term effects are the ones that appear after a few hours of exposure. The main short-term effects on human eyes are photokeratitis which is inflammation of the cornea and photo conjunctivitis which is inflammation of the conjunctiva. A few more short-term UV-C exposure consequences for the skin are simple redness and swelling of the skin, in other words, erythema and oedema [44].

1.2.8. Long term effects

As for the long-term effects, the dependence is the same as for the short-term, however, the consequence of this long-term radiation is way worse. Long-term effects appear after constant exposure every day that repeats for a few months or even years. First of all, UV-C radiation can weaken a person's immune system as well as weaken autoimmune to allergic illnesses. The skin may no longer produce a "protective layer" of antimicrobial cells which also leads to a weak immune system and increases the chance to get an infection. Unwanted wrinkles, sagging and dryness of the skin are one of the symptoms, but these are not that harmful compared that at least three different types of cancer may occur due to UV-C exposure to the skin. Those are basal cell carcinoma, squamous cell carcinoma and the most popular skin cancer species melanoma. Pterygium is one of the long-term UV-C exposure to the eyes consequence which does not affect vision but changes the eye appearance if not treated in time. However, UV-C exposure to the eyes can lead to cataracts which means the eye lens is clouded and blindness may occur [44].

1.3. Microorganisms

According to the scientists, there are at least a billion species of various microorganisms. Most of them are harmless and even provide good for humanity however, some of them are dangerous [45]. In general, all of these microorganisms are sorted into eight groups: fungi, protists, bacteria, archaea, viruses, viroid, satellites, and prions (**Fig. 11.**). Every one of those is different in its cellular composition, development rate, morphology or even replicating abilities. Nevertheless, the most popular that most of humanity is familiar with are bacteria and viruses, which have very similar cellular compositions and mainly consist of nucleic acids and proteins. However, many additional varieties of microbes are in charge of numerous global activities. While some are unhealthy and bring about illnesses in both people and plants, others produce oxygen, break down organic debris, provide plants nourishment, and protect people's health [46].

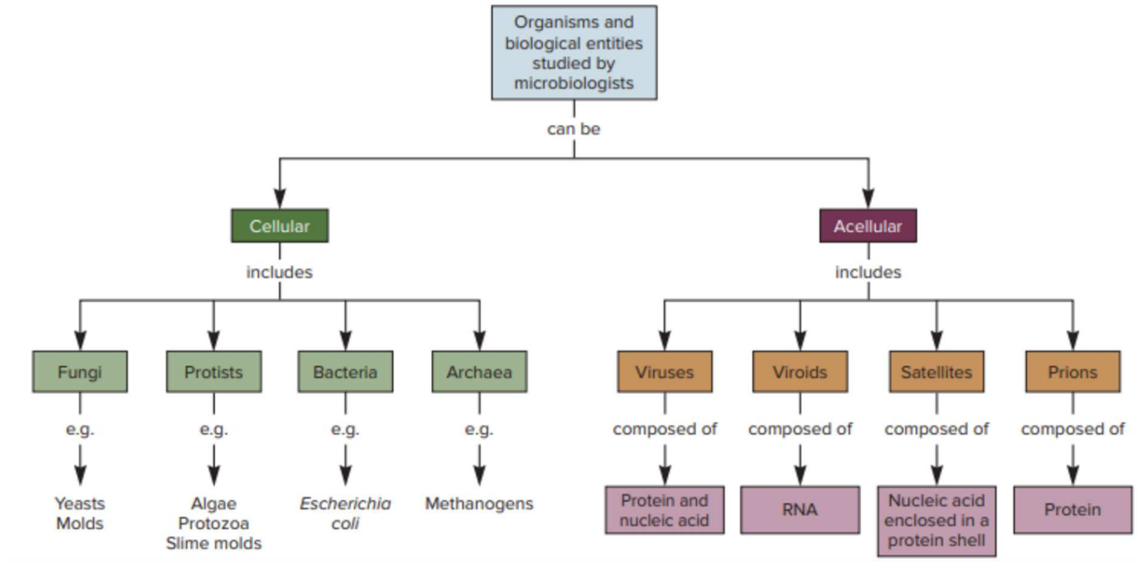

Fig. 11. Map of biological entities according to microbiologists [43].

1.3.1. Human interactions with microorganisms

Microorganisms are numerous, diverse forms of life that interact in a variety of ways with people. While some of these contacts are constructive, others can be detrimental. By carrying out vital bodily processes including food digestion, vitamin production, immune regulation, and thwarting disease colonization, microbes can benefit humans. By creating beneficial compounds like antibiotics, enzymes, hormones, and biofuels, microbes can also benefit people. Additionally, microbes can be utilized in biotechnology, bioremediation, and biosensing [47].

Microbes can cause infectious diseases that affect many body organs and systems, but they can also cause harm to people. Microbes can enter the human body through a variety of channels, including ingestion, skin contact, and inhalation, and they can grow quickly in the right circumstances. By generating poisons, enzymes, or antigens that set off inflammatory and immunological reactions, microbes can harm the host cells and tissues. By changing, cloaking themselves, or building biofilms, microbes can also get around or outwit the host's defences. The common illnesses brought on by bacteria are COVID-19, HIV/AIDS, malaria, influenza, and tuberculosis [48].

A hospital is one of the environments where microorganisms present a significant risk of infection. Such a facility sees a lot of patients every day, some of whom may be carrying different infections from different sources. Additionally, it is challenging to stop the transmission and spread of bacteria and viruses because of the continuous movement of patients, visitors, and personnel inside and outside the hospital. Because nosocomial infections can harm both patients and healthcare providers, hospitals must take stringent action to prevent and reduce them. These precautions include good hygiene, cleaning, sterilization, isolation, and monitoring techniques. Due to these causes many people can catch various infections in such facilities and talking about viruses the most popular are Staphylococcus aureus, Escherichia coli, Klebsiella pneumoniae, Pseudomonas aeruginosa, Clostridium difficile, Methicillin-resistant Staphylococcus aureus [49].

1.3.2. Bacteria and viruses' interaction with the surface

There are many places, rooms and facilities that have an enormous number of bacteria and viruses, and one of such places are hospitals or clinics. The ill patients can spread these harmful microorganisms very fast by coughing, sneezing or even talking and touching things around the area. The germs are so small that they can land on any surface or even stay floating in the air depending on their weight and density. Talking about airborne germs, it is not difficult to clear them from the environment. It can be done by simply opening windows periodically or by installing good ventilation systems in the buildings so that the air would be fresh and germ-free. However, surfaces require much more attention, because of course depending on the surface material, most of it provides perfect conditions for bacteria and viruses multiplication and spreading. These surfaces need to be cleaned and sterilized by a variety of specific chemicals and human labour as well, which can be expensive, time-consuming, and possibly dangerous. Therefore, minimizing the amount of bacterial and viral contamination of surfaces is crucial for infection control and prevention in health care facilities.

Therefore, the interaction of these microorganisms with the surface must be discussed. There are various surfaces and there are a lot of materials that surfaces can be made of as well as their roughness, geometry and interaction angle. Some of those can be hydrophilic or hydrophobic, they can be just standard surface or antimicrobial types and have various effects on most bacteria or viruses. However, the most popular mechanisms of surface interactions for both bacteria and viruses are attachment, adhesion, activation, inactivation and coating.

Attachment is the mechanism mostly applied for bacteria where the cells are capable to attach to the surface by using their flagella. Flagella are the tiny "tails" of the bacteria cell which are responsible for movement, sensation, and attachment. Due to the size of the flagella connection between cell and surface can happen by simple electrostatic forces depending on the charge of the cell and surface, however, this connection is temporal and easily disrupted [50].

Adhesion is already a steadier connection type which includes van der Waals forces and it overcomes the repulsion that microorganisms meet during a simple attachment process. Besides van der Waals forces there are additional hydrophobic interactions, hydrogen bonds and ligand-receptor interactions. The dipole-dipole interactions between molecules give rise to the van der Waals force, a weakly attractive force. The Hamaker theory, which considers the accumulation of all pairwise interactions between molecules, can be used to determine the van der Waals force. The van der Waals force is influenced by the molecules' proximity, orientation, and polarizability. The van der Waals force can be weakened by extending the distance or adding a material with a lower dielectric constant because it is typically dominant at close distances of up to ten nanometres [51]. The exclusion of water molecules from nonpolar regions due to entropy produces the hydrophobic interaction, an attractive force. The degree of hydrophobicity of the entities and the contact surface area determines the hydrophobic interaction. The hydrophobic interaction can be altered by lowering the humidity or raising the hydrophobicity because it often dominates at intermediate distances of 10 to 100 nanometres [52][53].

Inactivation and activation are two processes based on reactive oxygen species' (ROS) properties. Inactivation is the process when the attached microorganisms' connections are disrupted by metals, coating or polymers when the ions are released which disrupt membranes. Numerous physical processes, including photocatalysis, electron transfer reactions, Fenton reactions, oxidation-reduction events, and plasma production are used in the inactivation techniques. The surface's composition, shape, and charge as well as environmental factors like temperature, humidity, and light have an impact on the inactivation efficiency [54]. As the inactivation was the mechanism of microorganisms' destruction, the activation is the opposite. The materials on the surface such as titanium dioxide, zinc oxide or porphyrins help bacteria and viruses to replicate. Different physical processes, like photoexcitation, interfacial charge transfer, or photothermal effects, are involved in the activation mechanisms. The surface material, shape, and charge as well as external elements like light wavelength, intensity, and duration all affect how effectively a surface is activated [55][56].

By creating biofilms or aggregates, bacteria and viruses cover surfaces, it is called coating. Complex bacterial populations known as biofilms are encased in an extracellular polymeric substance (EPS) matrix. Clusters of bacteria or viruses known as aggregates are bound together by viral proteins or EPS. Different physical processes, such as self-assembly, phase separation, or gelation, are involved in the coating. The surface material, roughness, and chemistry, as well as the bacterial or viral strain, concentration, and phenotype, all affect the coating qualities [57][58].

1.3.3. UV interaction with microorganisms

The mechanism of UV radiation interaction with various microorganisms is based on the UV ability to damage the nucleus which contains all DNA and RNA of the germ. Comparing chemicals that are used for disinfection and UV-C radiation, the radiation has the upper hand due to its ability to penetrate through the entire cell directly to the nucleus instantly. For instance, talking about bacteria, just after the UV-C radiation reaches the nucleus the pyrimidine dimers are formed in RNA and DNA structures (**Fig. 12.**). Such damages interfere with the cell's ability to reproduce and replicate. Latter formed reactive oxygen species (ROS) damage the cell structure form the inside and cause a lot of stress by disrupting all the mechanisms of a living bacteria cell leading it to death [59].

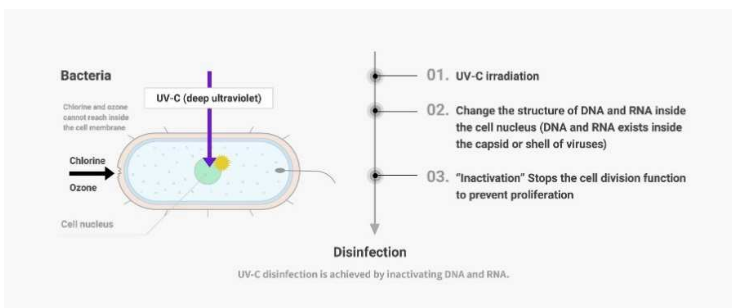

Fig. 12. Example of bacteria interaction with UV-C radiation [60].

The interaction between various microorganisms and UV radiation is already widely investigated with UV-C germicidal lamps that usually provide 254 nm wavelength. In recent years developed UV-C LED source which is specialized in 265-275 nm wavelength is not explored so much. It is proven that specific UV-C LED wavelength is way more effective compared to low or medium-pressure sodium lamps (check section 1.2.4 **Fig. 8.**). Despite effectiveness differences, both wavelength radiation types are used for microorganisms' sterilization. This process of disinfection depends on various factors, whilst the most important is the medium. Different UV-C radiation doses are required when the microorganisms are irradiated on surface, air and water. Surface disinfection needs the highest doses and air request the lowest. Sometimes surface may need ten or more times higher doses due to the distance, surface interactions, surface structure, geometry, and roughness. If disinfection is applied in various premises, the objects may stand in the way of radiation as well, because UV-C radiation cannot go through most of the materials [61].

The official doses required to kill 90% or D^{90} (dose 90%) of bacteria or viruses are given in various UV-C sources suppliers and the formula to determine higher percentages is given as well. However, this information is only suitable for 254 nm wavelength UV-C sources. The majority of the research is done using D^{90} doses and the median dose value when the main microbes are tested is 37 J/m^2. Even if the investigations are made using low-pressure sodium lamps at 254 nm it is assumed that 275 nm UV-C LED would provide similar results. In the previous section provided graph would suggest otherwise but as many researchers there were obtained similar results compared with 254 nm UV-C sources it may be a close call [61].

The most popular bacteria were mentioned in section 1.3.1 and here in **Table 1** there are some of these bacteria D^{90} requirements for 254 nm wavelength provided by one of the biggest United Kingdom UV-related companies "UV Light Technology Limited". These numbers can be valued as the 275 nm wavelength due to the small difference in nanometres and some other factors that include UV source stability and effectiveness. Of course, results would not be identical but because these new UV-C LED sources of wavelength 265-275 nm are not so widely investigated, the given doses in the table below can be used as a reference in this work [62].

Table 1. Various microbes and required D^{90} doses.

Microbe	**Species**	**D^{90}**	**Media**	**Source**
Escherichia coli	Bacteria	55 J/m^2	Surface	Hollaender 1955 [63]
Escherichia coli	Bacteria	11 J/m^2	Air	Koller 1939 [64]
Pseudomonas aeruginosa	Bacteria	55 J/m^2	Surface	Hollaender 1955 [63]
Pseudomonas aeruginosa	Bacteria	4 J/m^2	Air	Sharp 1940 [65]
Staphylococcus aureus	Bacteria	66 J/m^2	Surface	Gates 1934 [66]
Staphylococcus aureus	Bacteria	20 J/m^2	Air	Nakamura 1987 [67]
Coronavirus (ssRNA)	Virus	4 J/m^2	Air	Walker 2007 [68]
SARS-CoV-2	Virus	50 J/m^2 (2 log)	Surface	Dr Anthony Griffiths [69]

As a guideline, there is simple formula needed for higher log doses which goes by multiplying the D^{90} value as follows:

- D^{90} * 2 gives a 99% (2 log) reduction;
- D^{90} * 3 gives a 99.9% (3 log) reduction;
- D^{90} * 4 gives a 99.99% (4 log) reduction;
- D^{90} * 5 gives a 99.999% (5 log) reduction;
- D^{90} * 6 gives a 99.9999% (6 log) reduction.

After comparing similar research it is clearly seen that UV-C LED always require less dose due to the 265-275 nm wavelength influence. However, differences are not that huge so results obtained by using UV-C dose at 254 nm references are acceptable [70].

1.4. Safety and standards

The previous chapters described how artificial UV-C sources are capable to kill various microorganisms and how hazardous it is to humans, especially to their skin and eyes. As mentioned, direct contact with UV-C light can cause skin burns and eye damage (photokeratitis). Therefore, many safety precautions should be taken to avoid the harmful effects of UV radiation. Of course, if the UV-C source is used in some kind of premises like storages, shops, hospitals and similar these UV light sources must comply with specific standards which include not only UV radiation safety instructions but many others as well.

1.4.1. Safety precautions

There are a few most important safety precautions when using UV-C radiation sources whether it would be used for daily disinfection or testing in laboratories. Some of those may be obvious but still necessary to mention. The list of precautions includes:

1. Avoid direct contact with UV-C light sources, especially with the skin and eyes.
2. Wear protective gear, eyes must be protected with specific glasses and skin should be covered by using cloves and clothing that radiation cannot penetrate.
3. UV-C sources must be in well-ventilated premises and rooms due to the produced ozone (UV-C LED do not produce ozone, only lamps), which is dangerous for the human respiratory system.
4. Limiting the use time of UV-C light sources is very important to prevent accidental radiation exposure on humans.
5. Determine the distance of the UV-C radiation to cover only necessary areas.
6. Do not use the UV-C luminaires when the premises are occupied.

Taking everything into account, UV-C light sources like low-pressure lamps, medium-pressure lamps or UV-C LED are very harmful to human health and need to be limited in time, distance and strength to avoid all possible accidents of radiation exposure [61].

1.4.2. Standards

In the majority of cases, UV-C light sources are used as disinfection devices for air, water and various surfaces. These devices are called luminaires that emit UV-C radiation. In order to use these luminaires, there are various standards that must be adhered to. It is necessary for the main reason of safety, however, when it is the UV-C LED type luminaire there are not many strict standards, because this technology is quite new to the market. There are still some very important standards that must be mentioned, and it includes:

1. Directive 2014/30/EU EMC. Standard states that all luminaire all electronic components must be coordinated, work smoothly and do not overload the network [72].

2. Directive 2014/35/EU. Standard states that the device must comply with low voltage margins, which are up to 1000 V [73].

3. Directive 2011/65/EU or ROHS Directive. Standard states that all materials used in the device must be non-toxic and should not produce any chemical reactions that are harmful to humans [64].

4. UNE 0068:2020. Standard describes the basic safety requirements (most of them are listed in precious section 4.1) about the wavelengths, spectra specifications, dangerous limits, compatibility of materials and components with UV radiation and the basic consequences of UV radiation exposure [65].

5. Directive 2012/19/EU. Indicates protective measures for the environment and human health related to waste electronic equipment. Requires the manufacturer or supplier to register with the RII-AEE (Integrated Industry Register), where they confirm that they are ready to take action and punish the polluter [76].

6. Directive 2006/25/EC *ANNEX I Table 1.1.* Basic health and safety rules related to the risks posed to workers by physical agents (artificial optical radiation) are presented. Ensures that the use of the product will not harm workers or those who may be exposed to artificial optical radiation during work. UV-C radiation must not exceed 30 J/m^2 in 8 hours for the following body parts: eyes and skin [77].

According to described standards, all the devices including UV-C luminaires, must be safe and doses must be either not used on people or should be low enough to cause no harm. It is important to mention that all of these standards are only applied in Europe, but not all of them are mandatory, it is unfortunate but some of these are just recommendations.

Moreover, this work specializes in the UV-C LED luminaires applications to healthcare premises and luminaires have not necessarily only providing UV radiation. Simple illumination is very important as well and requires some additional standards and recommendations describing the most important parameters that are important in such facilities. Three main standards are:

1. EN 60598-2-25/ LST EN 60598-2-25:1999/A1:2005. Standard provides information about luminaires’ electrical components compatibility, low voltage limits (up to 1000 V) and other important parameters. All the given information is applied for use in clinical areas of hospitals and healthcare buildings [78].

2. EN ISO 9680:2022. Standard explains all the needs and hazardous limits that must be taken into account at dentistry premises [79].

3. AS/NZS 1680.2.5 (Australia). The standard requires specific wavelengths, CCT and CRI parameters in order to calculate the cyanosis observation index (COI). Certain COI lets to diagnose some skin diseases and blood discrepancies [71].

To conclude the chapter about standards, it can be seen that all the requirements are based on human safety and well-being by ensuring the high quality of used devices and offered products or services.

1.5. Literature summary

Taking everything into account, the necessary information about hybrid UV-C LED luminaire must be separated into three groups, that would be photometric, photobiological properties, and standard requirements. Photometric properties cover important LED luminaire characteristics including luminous flux measured in lumens, correlated colour temperature (CCT) in Kelvins, colour rendering index (CRI) and cyanosis observation index (COI). Each of the mentioned features describes the quality of LED luminaire. According to the standards here are some of the values that define the LED light source as a high-quality device:

- CCT must be between 3000 K and 5500 K, which changes the colour warmth from a yellow-white to a bright blue-white colour.
- CRI defines a light source's ability to accurately reproduce the colours of objects compared to a reference light. All values above 90 are considered excellent results of the light source.
- COI defines the severity of cyanosis by scoring the degree of bluish discolouration of the skin and mucous membranes. According to the standard, its value must not exceed 3.3.

Photobiological characteristics describe the properties of UV radiation and its disinfection effectiveness. There are three types of UV radiation which differ in wavelength: UV-A (320 – 400 nm), UV-B (280 – 320 nm), and UV-C (200 – 280 nm). The only type that has effective sterilization properties is UV-C radiation and dose is the characteristic defining its efficiency. The most common dose unit is J/m^2 and it is obtained by multiplying the intensity of the UV-C source (W/m^2) and the exposure time (s). In order to sterilize the various microorganisms like fungi, protists, bacteria, archaea, viruses, viroid, satellites, and prions different doses are needed and a few very important variables play a role. Despite the resistance ability of each individual microorganism, the crucial variables are the media (air, water, surface), distance, irradiance power and time of irradiation.

UV-C radiation is dangerous for all living organisms including humans. Irradiation effects usually appear on human skin and eyes and are divided into short-term and long-term effects. Short-term effects can be seen after a few hours of exposure and can include symptoms such as redness, swelling, and itching of the skin or redness, tearing, and pain in the eyes. Long-term effects may occur after continuous or repeated exposure over a period of weeks, months, or years and can result in more serious health effects such as skin cancer and damage to the eyes, immune system, and DNA.

Such devices, as UV-C LED luminaires, can be effectively applied in healthcare institutions where the contamination of dangerous viruses and bacteria is always at a high level. To achieve successful disinfection of healthcare premises and to avoid radiation damage to the people there are some important standards and recommendations that must be followed when UV-C LED luminaire is used. Firstly, the limit for UV-C radiation exposure of 30 J/m^2 per 8-hour workday should not be exceeded and should be designed to emit radiation in a safe and controlled manner. Secondly, the luminaire should meet the basic requirements for general lighting, including luminous flux, colour rendering index, electric parameters margins and correlated colour temperature. Finally, it is important to note that the use of UV-C LED luminaires is not a replacement for standard cleaning and disinfection procedures, but rather a supplementary measure to improve overall hygiene and infection control.

2. Methodology and equipment

UV-C LEDs are a relatively recent and innovative invention in the field of sterilization and disinfection. As a result of the ongoing global pandemic, the need for effective and efficient UV-C LED-based disinfection systems has increased considerably. Of course, there is an enormous variety of UV-C germicidal lamps like T5 or T8 type low/medium pressure mercury lamps, excimer lamps or far-UV lamps. However, UV-C LEDs are way superior technology according to the electrical efficiency, lifetime longevity, size, application possibilities and wavelength options varying from 265 nm to 280 nm [81].

Given the market's abundance of options, finding the right components for such systems might be difficult. To ensure the best performance, a comprehensive market analysis was conducted before selecting the best UV-C LED chips. More than five huge lighting solution companies were investigated, and their offered products were analysed. Most of the researched companies did not even have anything related to UV-C sources or could only provide old-school germicidal lamps containing dangerous mercury gas. There are a few reasons why UV-C LEDs are not popular yet. One would be that it is not entirely developed technology and it is quite difficult to manufacture high-quality UV-C LED chips of accurate wavelength. The second reason is obvious, this new technology is yet very expensive, as an example one UV-C LED chip of size 5x5 mm costs around 20 € on average.

However, with the help of “Northcliffe Lighting” logistics department some alternative version of UV-C LED was found in one South Korean company called “Seoul Viosys Co”. This company kindly agreed to provide 24 UV-C LED chips that were suitable for easy soldering on PCB plate.

2.1. Equipment

2.1.1. UV-C LED modules

The first and most important part of this master's work is the artificial UV-C light source, which will primarily comprise a recently developed UV-C LED module. This certain module includes two main components: UV-C LED chips and a PCB plate. The used UV-C LED chips (model CUD7GF1B) are capable to irradiate deep UV radiation with peak emission at 275 nm and are illustrated in **Fig. 13**.

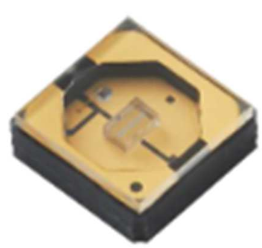

Fig. 13. Used UV-C LED chip model CUD7GF1B [72].

The final UV-C LED module was created by using the reflow soldering technique which will be explained in the next chapter 2.2 Workflow. Chips could not be attached to the PCB plate manually, so the Lithuanian company “AKTO” was hired for this soldering process. There were three UV-C LED modules created in total.

The size of these UV-C LED chips was 3.5x3.5 mm and the size of the PCB plate was 117x50.8 mm with only one possible connection type when eight chips connected in series (8S). There are various parameters that are important when it comes to LED modules, but the most critical part is electrical parameters including current and voltage limits which must not be overloaded for high-quality operations. These parameters are given in **Table 2**.

Table 2. Single UV-C LED chip characteristics [72].

Parameter	Symbol	Value	Unit
Peak wavelength	λ_p	275	nm
Radiant Flux	Φ	16	mW
Forward Voltage	V	6.1	V
Forward Current	I	20-250	mA
Operating temperature	T_{op}	-40…+90	°C
Radiation angle	Θ	125	deg.

All these values provided by the manufacturer were tested and confirmed in the "Northcliffe lighting" laboratory by the author of this work. Each given parameter has a tolerance to differ by up to 10 %. According to the LED module connection type 8S, the electrical parameters of voltage are described in the following **Table 3**.

Table 3. Electrical voltage parameters of UV-C LED modules.

Parameter	Symbol	Quantity of LED modules	Value	Unit
Forward Voltage	V	1	48.8	V
		2	97.6	
		3	146.4	

The given parameters are measured in the ideal environment and may differ depending on current overload or ambient temperature. The final view of created UV-C LED modules is illustrated in **Fig. 14**. An image consists of two parts where in the picture above a few samples of plain UV-C LED chips are presented and in the bottom part of the image, eight UV-C LED chips are already soldered on the PCB plate. Naturally, the shape and dimensions of the PCB plate can vary, but this option was the most suitable for this project.

Fig. 14 Separate UV-C LED chips above and created LED module below.

During this research, the constructed UV-C LED modules were adapted to the already existing LED luminaire that was provided by the Lithuanian company “Northcliffe Lighting”. First, the model of the new hybrid luminaire was created using the software “SolidWorks” and it is presented in **Fig. 15**.

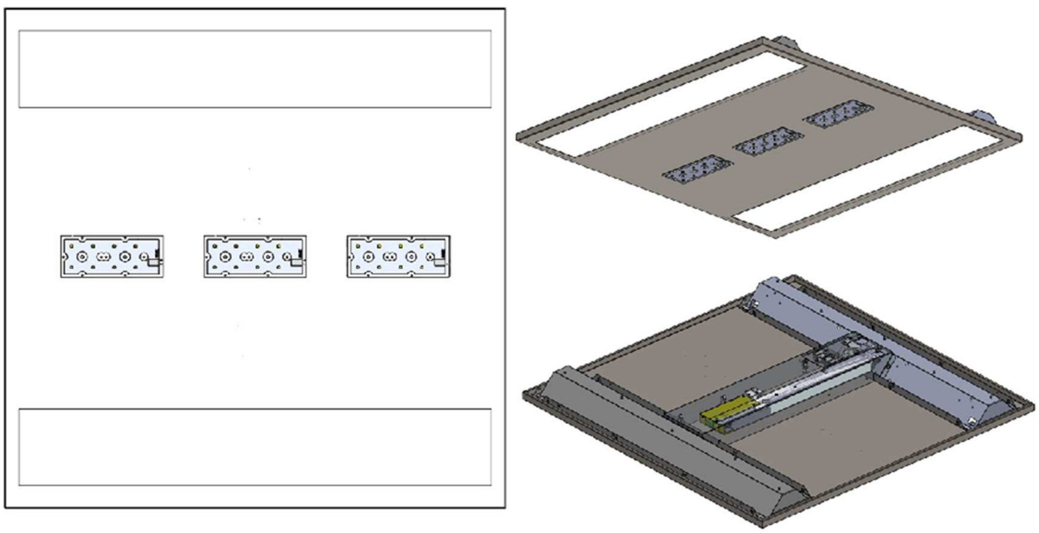

Fig. 15. Sketch of the UV-C LED hybrid luminaire. On the left, the luminaire and the UV-C LED modules are presented with a front view. The right side of the image shows a profile view of the luminaire’s both sides together with the electrical components' position.

Second, the hybrid UV-C LED luminaire was constructed according to the prepared sketches and the prototype version is presented in **Fig. 16**.

Fig. 16. Prototype of hybrid UV-C LED luminaire.

2.1.2. LED drivers

LED drivers are electronic devices used to control the electric output given to LED modules. Previously mentioned electrical limits of LED modules require specific voltages and currents. Specifically for this reason LED drivers are used to convert alternating current (AC) from the net to direct current (DC) that would be stable and suitable for chosen modules. In this work, three different combinations of LED modules were tested using three different currents and so there were chosen LED drivers for each combination sorted by operating voltage window (presented in the following **Table 4**) [83].

Table 4. LED Drivers' electrical characteristics and using preferences.

LED driver	**Operating voltage window, V**	**LED modules combination**
Tridonic - LC 25W 75–350mA flexC NF h16 EXC4 (Current set using Near Field Communication (NFC) programming function)	40-166.7 [84]	1 LED module at 150 mA
		2 LED modules at 150 mA, connection in series
		3 LED modules at 150 mA, connection in series
Helvar - LL18SEC-CC-200-350 (Current set using dip switches)	30-52 [85]	1 LED module at 200 mA
Helvar - LL1x10-42-E-CC (Current set with the current setting resistor of 2.74 kΩ connected to the R_{set} terminal)	~50-210 [86]	2 LED modules at 200 mA, connection in series
		3 LED modules at 200 mA, connection in series
Helvar - LL18SEC-CC-200-350 (Current set using dip switches)	30-52 [86]	1 LED module at 250 mA
Helvar - LL1x10-42-E-CC (Current set with the current setting resistor of 1 kΩ connected to the R_{set} terminal)	~40-170 [85]	2 LED modules at 250 mA, connection in series
		3 LED modules at 250 mA, connection in series

According to **Table 4**, all the operating voltage windows are chosen correctly, not one combination of LED modules was overloaded, and testing results were obtained without any interference.

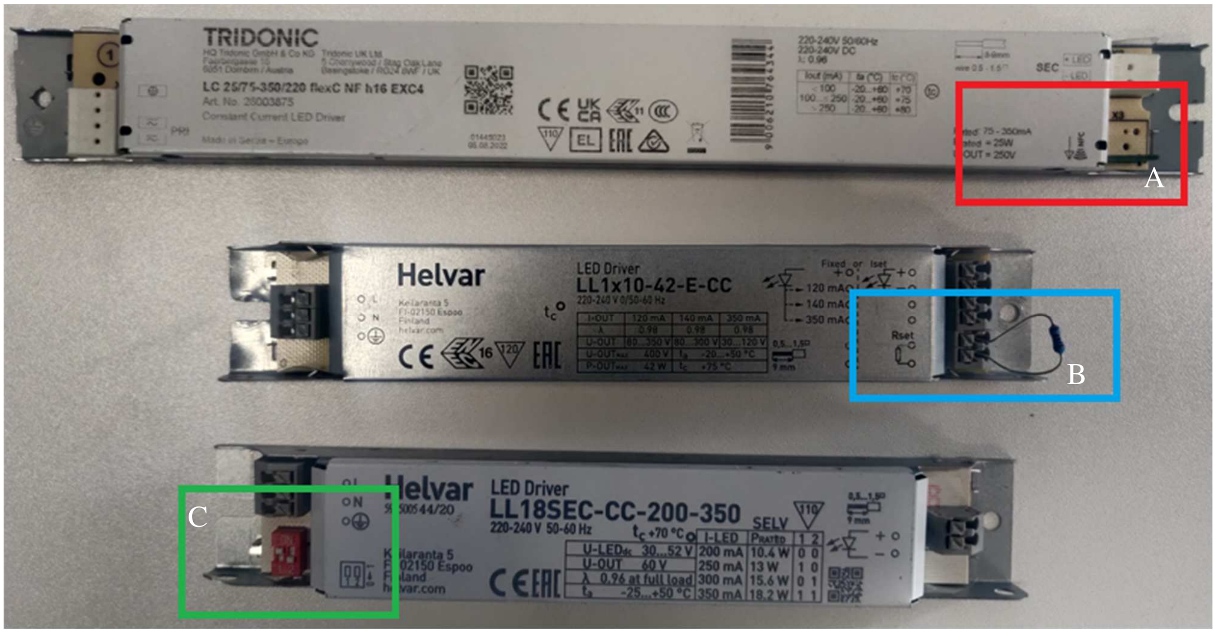

Fig. 17. LED drivers used in the research. A – NFC current set option, B – resistor current set option, C- DIP current set option.

All LED drivers were provided by "Northcliffe Lighting" company and are depicted in **Fig. 17.** Coloured squares notify different current setting options for each LED driver that were discussed in the table above. The red colour shows the NFC setting option which requires either specific software and programming pad or a smartphone app called "4service NFC" provided by "Tridonic" company. The blue square shows the current setting option by connecting the resistor of chosen resistance value to the given push-in terminals. The last green square current setting option is the simplest one and requires switching given dips to recommended positions.

2.1.3. LabSpion Goniometer and spectrometer

A precise light measurement equipment created by Viso Systems is the LabSpion goniometer and the UV-VIS model 2 spectrometer is used in this research work. The connection scheme of the setup is presented in **Fig. 18**. It is capable of measuring a variety of light sources, starting with small and unique lamps or LED chips, to complicated shapes and sizes of LED panels or streetlights. The LabSpion goniometer provides the whole 3D distribution measured with an astonishing precision of 0.1 degrees resolution. For quick and precise measurements, the system makes use of a 2-axis goniometer, a spectrometer sensor, and an integrated power analyzer. The investigation of photometric parameters and evaluation of illumination devices in space requires a coordination system to determine the angle and direction in which measurements are made [87].

Fig. 18. Light measurement system connection scheme [88].

2.1.4. Goniometer

This specific goniometer system can also be called by another name, the "far-field rotating source goniophotometer" because it is specifically designed for various illumination device measurements (**Fig. 19**). The working principle of the device is based on the mounted light source moving around its axes in a pre-set precision to cover and collect all possible illumination data of each angle by the spectrometer. Technically, the luminaire itself is not moving; the light source is mounted directly in the centre of the goniometer coordinate system, and the device rotates in pre-set directions. The system must be placed in a dark room where no additional light is present so that only the tested source data will be present.

Fig. 19. LabSpion goniometer [89].

The goniometer itself moves around its axis in both directions, covering the horizontal plane. It is capable of moving around 360 degrees, depending on the needs of the measurement. The vertical plane also rotates around its axis, with the defined resolution ranging from 0.1 to 5 degrees accuracy, and the number of planes chosen from 2 to 36 planes, depending on the measurement needs. Overall, the mentioned coordinate system and its rotating principle are based on two angles. One is the angle between the half-plane which is the "zero" point and the half-plane at which the direction is considered. The second angle is between the intersection axis and the considered direction. All the orientations and directions are chosen individually based on the measured light source type to obtain the most accurate results. Examples of the European-type planes and measurement directions are illustrated in **Fig. 20** [88].

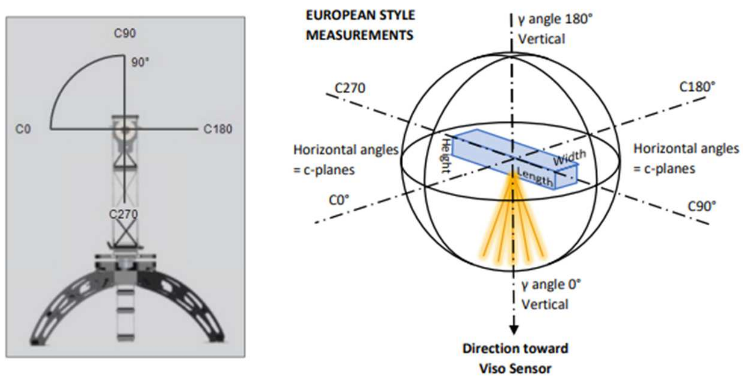

Fig. 20. Goniometer planes and angles [88].

2.1.5. UV-VIS spectrometer

The device used in this research work is a UV–VIS (Ultraviolet–Visible) light source spectrometer LabSensor model 2 (**Fig. 21.**). This scientific device is a specific laboratory sensor that is used to measure the chosen light source wavelength and relative intensities to create a spectrum. The spectrometer consists of several main components that describe the whole working principle of the spectrometer and those are an entrance slit, a diffraction grating or prism, a detector/sensor, mirrors, routing optics and higher-order filters. Usually, the sample is included in the system and its optical characteristics like transmittance, reflectance and absorbance are measured. However, in this case, there is no sample or it is calibrated specifically for light parameters like lumens (lm), wavelength (nm) etc. measurements.

Fig. 21. LabSpion UV-VIS spectrometer model 2 [90].

The working principle starts with the light entering the device through the entrance slit which narrows the beam of light. Right after that, the light beam is reoriented by the collimated concave mirror to the direction of a diffraction grating or the prism where light is separated by the relative intensity wavelengths. The separated light once more changes its direction by interacting with routing optics. This time light is reoriented towards the detector which measures the intensity of each separated wavelength and converts it to the electrical signal that is analyzed by a computer program. The light of course has to pass through the high-order filter to remove all the higher-order diffractions that can possibly appear in separated light. The schematic visualization is presented in **Fig. 22** [91][92].

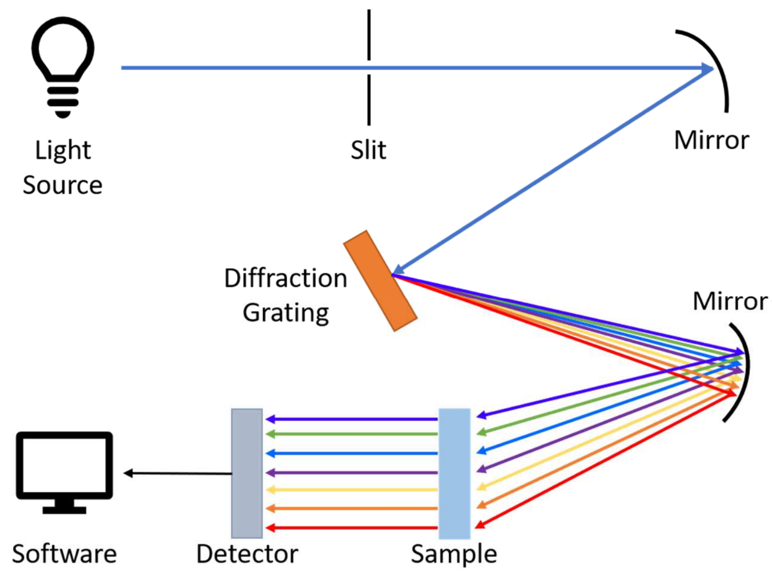

Fig. 22. Spectrometer working principle scheme [93].

2.1.6. Light inspector software

The software "Light Inspector" is a tool for light measurements that allows one to quickly measure, evaluate, and analyse data from a broad wavelength spectrum that includes UV and NIR (near infrared) regions. The software is simple to use and gives an overview of various lighting characteristics-related measurements in real-time and is perfectly adapted for the lighting industry (**Fig. 23.**). Despite all the visible light analysis features it can measure and provide a variety of results related to the UV field. The software is capable of producing a wide range of results, but among them, the most important are undoubtedly light efficiency, light quality, and light distribution. These results are particularly valuable as they provide critical insights into the underlying data, enabling users to make informed decisions and take appropriate actions based on the findings. When measuring UV spectra, the software gives results of spectra intensity, dose effectiveness and evaluation of time needed to sterilize chosen microorganisms, it measures different intensities at various distances as well [94].

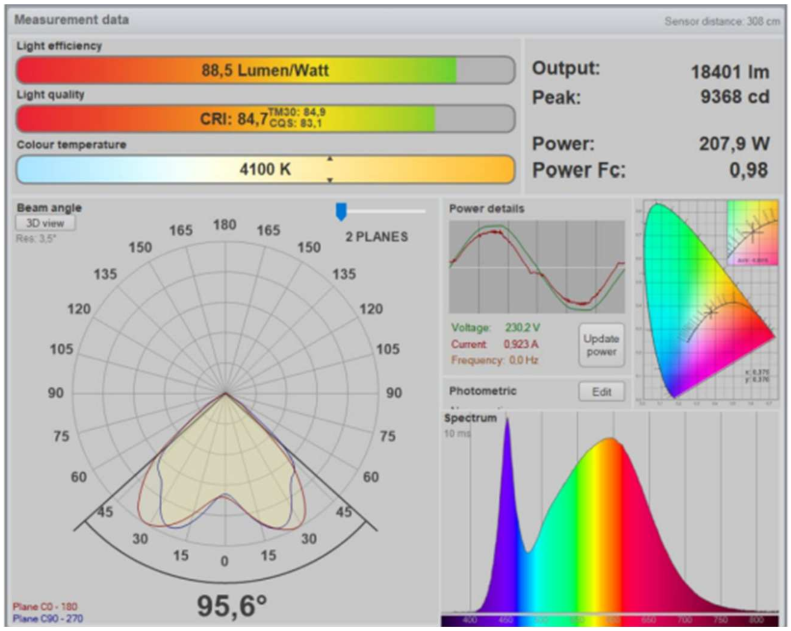

Fig. 23. Dashboard with a variety of VIS light source characteristics provided by the “Light inspector” software [94]

2.2. Workflow

There are various essential steps that must be followed in order to properly accomplish this study's aim and complete all required tasks. However, it was essential to conduct a thorough theoretical investigation into the characteristics and features of UV sources before beginning the experimental phase. The difference between the currently most popular UV-C disinfection lamps and the innovative UV-C LED modules was investigated. After the comparison, it was clear that UV-C LEDs are exponentially developing technology which is way more advanced than germicidal lamps. Despite the price difference, UV-C LEDs are way more compact, consumes less energy, have a longer lifetime, do not contain mercury gas and are ozone-free UV-C solution. Concluding, all the workflow was covered in these steps:

- Creating a UV-C LED light source.
- Preparing the UV-C LED modules for measurements by mounting them on an aluminium plate and ensuring their thermal conductivity to avoid overheating.
- The aluminium plate was mounted on the centre of the goniometer and the distance was set for the measurement.
- Measurements were performed in compliance with all safety requirements.
- The settings of “Light Inspector” software were adjusted to obtain accurate results.
- Obtained results were analysed and processed for further use.

As mentioned at the beginning of chapter 2.1.1, certain UV-C LED chips were acquired with the help of the Lithuanian company “Northcliffe Lighting”. LED chips were soldered onto PCB plates using the reflow soldering method (**Fig. 24.**) with the help of another Lithuanian company “AKTO”.

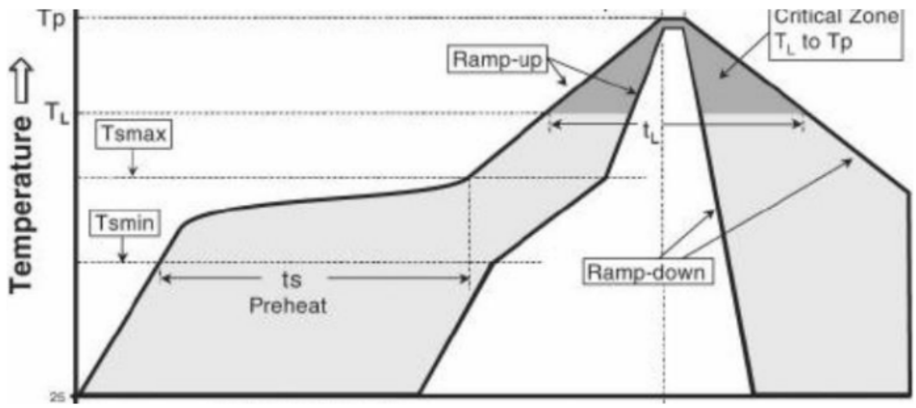

Fig. 24. Reflow soldering temperatures graph [82].

The second step was carefully mounting the UV-C LED modules onto the aluminium plate to prepare for testing. The aluminium plate was cleaned with isopropanol and covered with thermal paste to prevent overheating of UV-C LEDs (**Fig. 25**).

Fig. 25 LED modules mounted on the aluminium plate.

Later the whole plate was mounted on the goniometer vertical axis and centred for accurate measurement. Distance from the spectrometer and the centre of the UV-C source was measured at 2 meters in order to meet the testing standard requirements (**Fig. 26.**).

Fig. 26. UV-C source mounted on the goniometer and the set distance in the testing facility.

There were nine combinations chosen to find the most optimal and effective source variation. LED modules were applied with three different currents: 150 mA, 200 mA, and 250 mA. All connections between LED modules were in series, and three combinations were prepared: 1 LED module, 2 LED modules, and 3 LED modules for each of the mentioned currents.

When using a spectrometer for measurements, it is important to consider potential errors in the readings. In this case, the value of the error was determined to be 3.3%, which means that the measured values could deviate from the true values by up to 3.3%. However, it should be noted that the spectrometer used in this study was new and had been calibrated by the manufacturer, which ensured that the errors were precise and within an acceptable range.

To reflect the potential range of error, error bars were included in some of the graphs that can be found in the results section. These bars provided a visual representation of the potential deviation from the measured values and allowed for a better understanding of the data.

Additionally, the electrical parameters of the LED drivers were subject to an error of 5%. This means that the output values for these drivers could differ from the expected values by up to 5%. It is important to take these sources of error into account when conducting measurements and analysing data to ensure accurate and reliable results.

Before each test the source was left turned on for 15-30 minutes to reach its working temperature, the chosen resolution was 5 degrees, and the test was done with 4 planes measurement for each of the combinations. After the testing software was prepared to analyse results but some additional values had to be filled and the following steps were made:

- The photometric measurement setup was set to calculate the radiation dose (**Fig. 27.**).

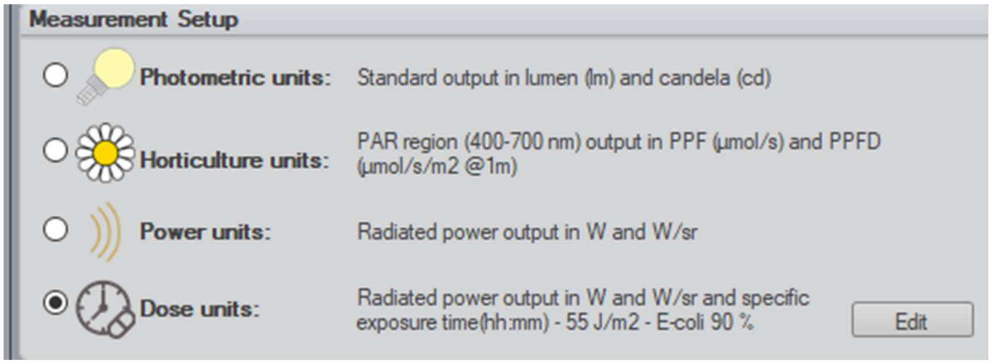

Fig. 27. Dose measurement selection.

- The testing wavelength region was customised (**Fig. 28.**).

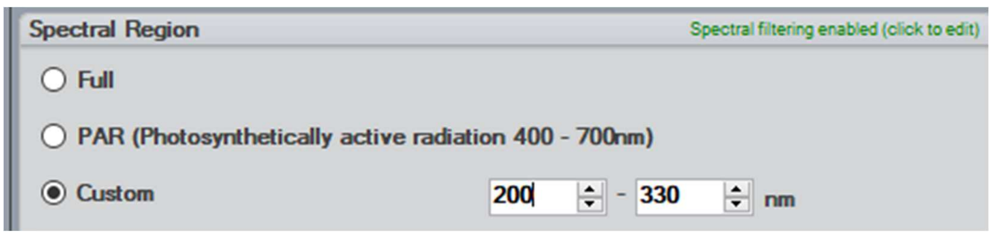

Fig. 28. Spectral region customisation.

- Dose values for different microorganisms' sterilization calculations were found in scientific articles and filled in (**Fig. 29.**).

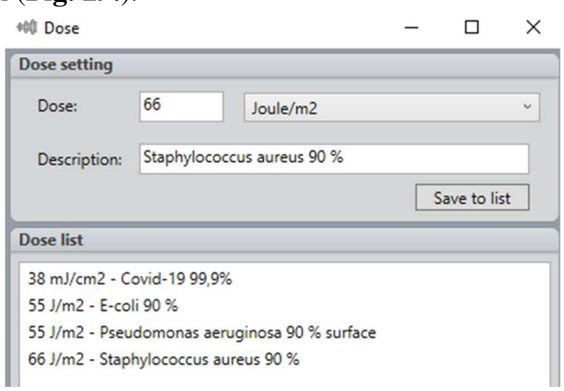

Fig. 29. Dose values.

- A response curve was added to the obtained spectra to evaluate the effectiveness of the measured source in relation to the germicidal sterilization effectiveness curve (**Fig. 30.**).

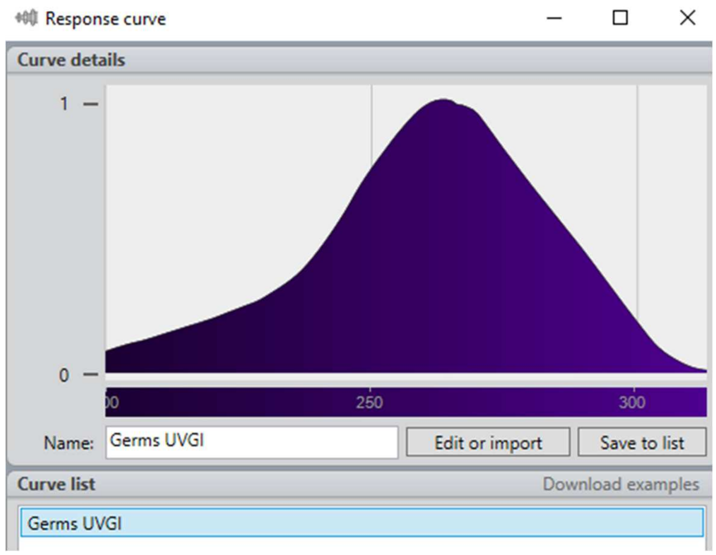

Fig. 30. Response curve.

Some additional measurements of simple LED luminaire were made to prove the newly created UV-C LED hybrid luminaire suitability for healthcare facilities. When all the required reference values were added and applied the data was exported, normalized, and can be found in Chapter 3 Results.

3. Results

3.1. Photometric measurements

Photometric data is very important for standard LED luminaires and especially when the lighting solution is applied to specific areas which require high-quality illumination. The luminaire “X” was mounted directly in the middle of the goniometer and it’s the distance between the spectrometer sensor and the luminaire central coordinate was exactly 6 meters (10 x the length of the luminaire required by a testing standard). Measurement was made using 8 planes with 1-degree resolution.

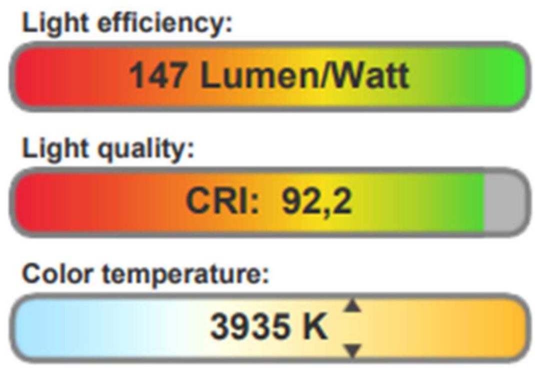

Fig. 31. Photometric properties of the luminaire "X".

The information obtained from the measurement is presented in **Fig. 31.** Light of the luminaire provides high efficiency in the relation between lumens (lm) and consumed system power (W). The colour rendering index (CRI) 92.2 of the luminaire “X” is considered excellent and allows to see things just as they are. The colour temperature (CCT) is nearly at 4000 K, which is close to the white light intended for work requiring concentration. Moreover, the Cyanosis observation index (COI) has a value of 3.3, which does not exceed any regulation limits and is perfectly suitable for healthcare facilities' services. The wavelength spectra is given in **Fig. 32.**, the highest intensities are reached in blue colour spectra at around 450 nm and the red colour at 652 nm wavelength.

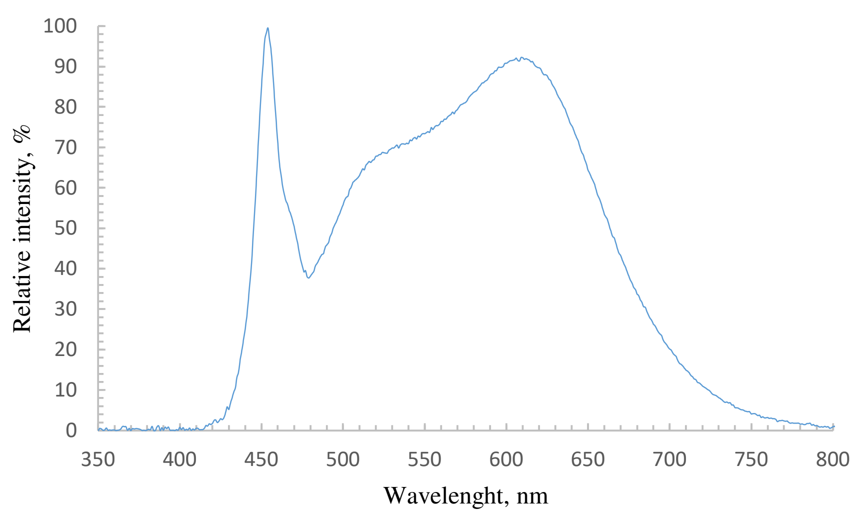

Fig. 32. Wavelength spectra in relevance to normalised power (W) per nm.

Polymethyl methacrylate (PMMA) de-glaring micro-prismatic diffuser (DPRZ) with a matt light scattering layer was used for specific healthcare premises applications to keep workers focused and not distracted by the bright light. Even if it narrows the angle of the light (**Fig. 33.**) it is more important that the luminaire “X” can provide professional and non-disturbing area illumination.

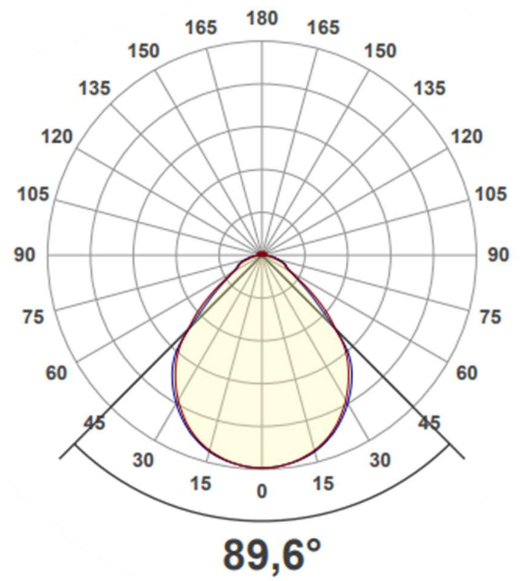

Fig. 33. Beam angle of the luminaire "X".

Finally, the most important parameter is the lumen output, which is exactly 5000 lm. Such light output is perfect for the standard healthcare premises ceiling height (2.4 meters) and compared with currently used light sources the LED luminaire would save up to 50 % energy consumption per year.

3.2. Photobiological measurements

Photobiological parameters of UV-C radiation sources are depending on many variables and are very important when the purpose of the use is microorganisms like bacteria and viruses’ disinfection. Using such radiation devices may be dangerous not only for most microorganisms but for people as well. The radiation effect on the microorganisms mentioned in section 1.3.3 will be discussed in this result chapter and the most suitable UV-C light option will be chosen considering such variables as electrical parameters, distance, time, media and the number of LEDs.

The most important measurement of the research is also the one which proves that exactly the UV-C light source was investigated and **Fig. 34.** represents the obtained wavelength at a peak of 277 nm. The rest of the spectrum did not show any unexpected deviations, no significant noise peaks were detected during the measurement and obtained results are accurate. The uploaded UVGI curve increased the measurement accuracy because without it the software uses the full spectra of 200-850 nm as the flat response and gives false results when the effect on microorganisms is investigated.

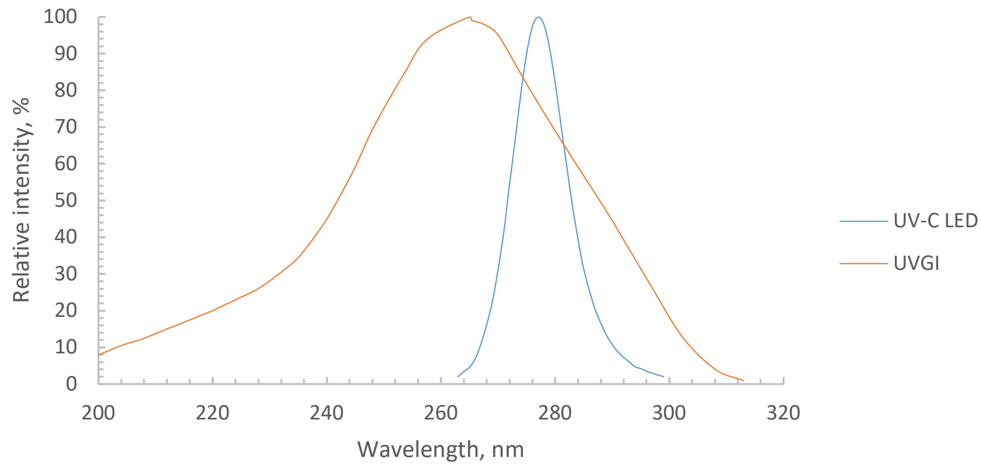

Fig. 34. Wavelength of investigated UV-C light source in blue and UVGI response in orange curves comparison.

3.2.1. Irradiating power

The total average irradiation power was determined for each UV-C LED combination by gradually increasing the applied current by 50 mA from 150 mA to 250 mA (**Fig. 35.**). The significance of chosen current values was based on the UV-C LED module limits and relevance to sterilization ability. The obtained result was as expected, the lowest total average irradiance of 70.4 mW was achieved when 150 mA current was applied to a single UV-C LED module and the highest of 257.3 mW when 250 mA current was applied to 3 UV-C LED LEDs connected in series. The error bars given in the chart represent a 3.3 % possible deviation in total radiation output and a 5 % deviation in current measurements. However, the current settings were measured with a multimeter and such high deviation was not detected.

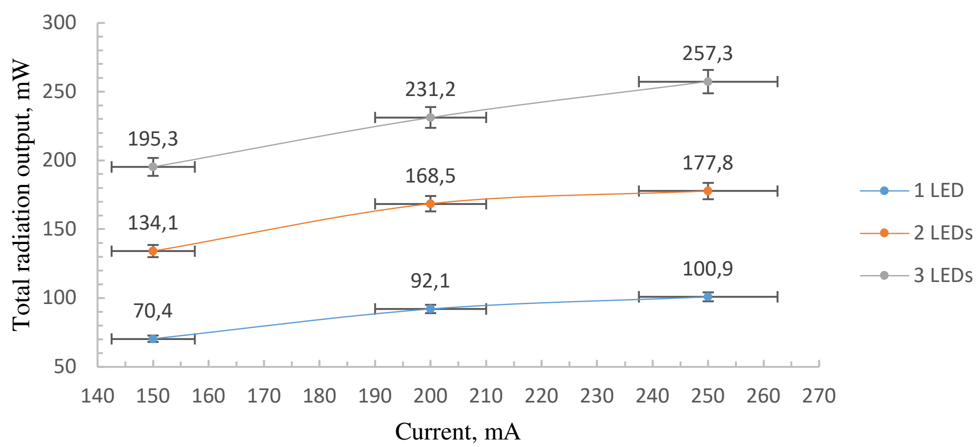

Fig. 35. Total average irradiation power dependence on the applied current.

The total average irradiance power is a combination of all measured UV spectra, that includes UV-A, UV-B, and UV-C radiation. However, the only radiation that can effectively disinfect microorganisms is UV-C and its irradiation power at the peak for each combination is presented in **Table 5**.

Table 5. Peak irradiance at all possible variations and power consumption.

Current, mA	Quantity of LED modules	UV-C Irradiance at the peak, mW	Consumed power, W
150	1	89.9	9.1
	2	172.3	15.6
	3	251.8	22.2
200	1	117.8	11.0
	2	216.9	20.2
	3	299.5	28.9
250	1	129.6	13.8
	2	230.8	25.6
	3	335.5	37.4

According to the table, the highest UV-C irradiance at the peak was achieved by 3 UV-C LEDs at the 250 mA current, while obviously consuming the most energy. The single UV-C LED module consumed the least energy and achieved the lowest irradiance, with only 89.9 mW. As the highest applied current of 250 mA is the maximum allowed limit for these certain UV-C LEDs, it may be close to overload and damage the efficiency of the device.

3.2.2. Distance dependence

The standard height of the ceiling in healthcare facilities is 2.4 meters, however, due to the various architectural designs it may differ and the dependence on the distance has to be measured, evaluated and taken into account. The irradiance efficiency was measured and presented in the following graphs.

The irradiance per m^2 for each measured variation was evaluated at distances varying from 1 meter to 5 meters. The first distance evaluation started with all variations at 150 mA current see **Fig. 36**. 3 UV-C LEDs obviously have the highest irradiance of 57.4 mW/m^2 at the shortest measured distance of 1 m and a single UV-C LED has the lowest of 20.8 mW/m^2. The irradiance values are drastically dropping down from 3 m distance and further.

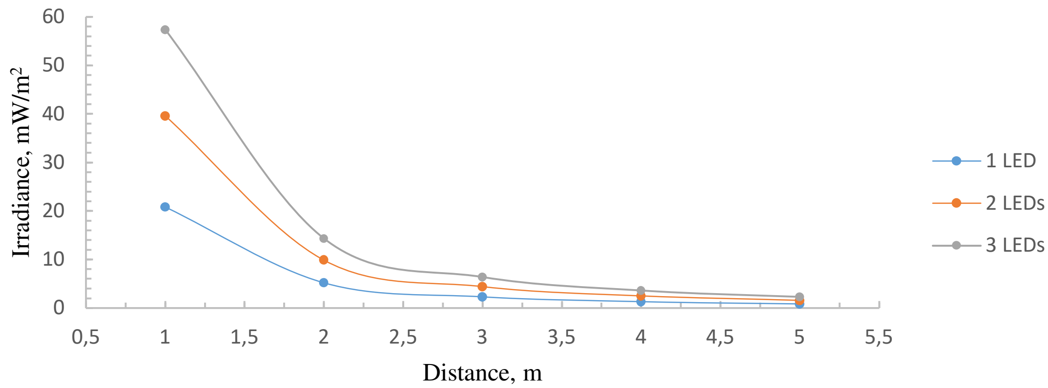

Fig. 36. Irradiance per m^2 dependence on the distance and number of UV-C LED modules at 150 mA.

With the current raised up to 200 mA, the gap between 1-LED and 3-LEDs irradiance increased at the shortest distance of 1 m (**Fig. 37.**). Measurement at 1 m resulted in 67.8 mW/m^2 with 3 UV-C LEDs, 49,5 mW/m^2 for 2 UV-C LEDs and 27.5 mW/m^2 for single UV-C LED. Again, at roughly 3 meters distance, the clear difference between all three options faded to almost non-existent.

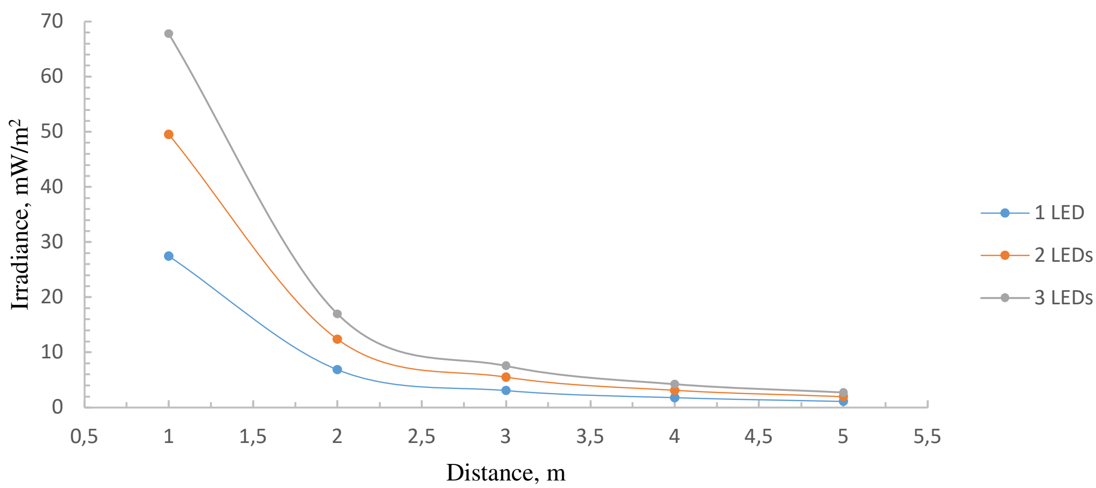

Fig. 37. Irradiance per m^2 dependence on the distance and number of UV-C LED modules at 200 mA.

As expected, with the highest applied current, the system power was the biggest as well for each group, resulting in the largest irradiation outputs of all the investigated samples. Graph **Fig. 38.** represents almost identical linear dependence as the previous charts represent distance influence on the irradiance per area. The largest values of irradiation at 1 meter were 75.1 mW/m^2, 52.1 mW/m^2, and 29.9 mW/m^2 for 3 LEDs, 2 LEDs, and 1 LED respectively.

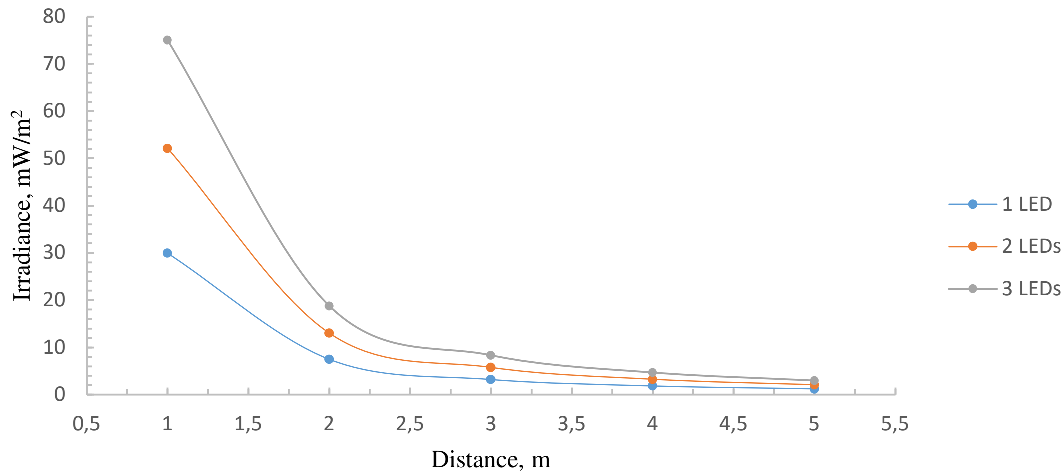

Fig. 38. Irradiance per m^2 dependence on the distance and number of UV-C LED modules at 250 mA.

Despite the applied current, all of the measured variations, have quite similar results in each group whether it would be a single, two or three UV-C LED module group. The 3-LED variation always shows the highest irradiance values and single LED always the lowest. However, all the graphs show that differences are starting to fade when the distance exceeds the standard room height of 2.4 m. All the values are coming close and do not make a significant difference to the sterilization process, because such irradiance is simply not enough for proper surface disinfection. Results show that with the distance increase the irradiation per area suddenly gets lower and lower meaning that at certain distances it requires more time to achieve the needed dose for microorganisms' disinfection.

By evaluating a considerable number of various microorganisms, the average dose required to achieve 90% of sterilization on the surface is roughly 75 J/m^2. The proper amount of time for disinfection is around 15-60 minutes when a high-intensity UV-C radiation source is used [62]. Taking this information into account, the combinations of single UV-C LED and 2 UV-C LEDs are not suitable for surface disinfection, because the time needed for sterilization would not be convenient for healthcare institution employees. Considering that these combinations of UV-C LED modules should not be mounted into hybrid LED luminaire for such application.

3.2.3. Time dependence

The SARS-CoV-2 virus has garnered widespread attention due to its significant impact on humanity. However, other dangerous microorganisms, such as Escherichia coli, Pseudomonas aeruginosa, and Staphylococcus aureus, are also commonly found in healthcare institutions. Although hospitals and clinics have measures in place to control the spread of bacteria and viruses, it is crucial to prevent future pandemics like the one that occurred in the year 2020.

For this reason, various UV-C LED combinations were investigated to determine the optimal duration of premises disinfection needed to avoid the potential transmission of diseases outside of healthcare institutions. The angle of radiation is presented in **Fig. 39**.

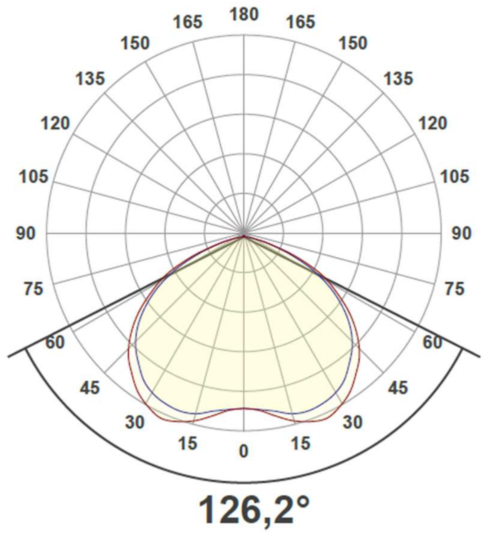

Fig. 39. Beam angle of UV-C LED.

The total UV-C illuminated radius at the distance of standard ceiling height of 2.4 m was calculated by rounding the beam angle to 120 degrees and applying simple 30 degrees angle rule to obtain the hypotenuse marked as "X" in **Fig. 40.** and then the radius marked as "Y" by applying Pythagorean theorem. Given the calculations radius of the investigated UV-C light source, light is roughly 4 meters at the standard ceiling height.

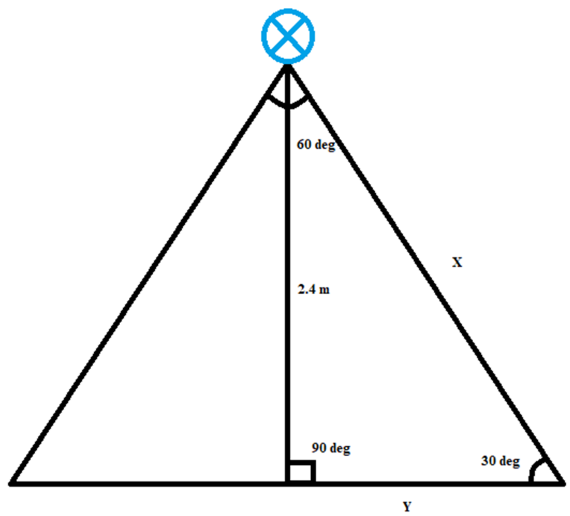

Fig. 40. Visualisation of how the beam radius was determined.

Escherichia coli and Pseudomonas aeruginosa bacteria require the same dose of 55 J/m^2 to achieve sterilization of 90 %, so the results for these two bacteria are identical assuming the surface is the same. Single UV-C LED module irradiation power is too weak to properly sterilize these bacteria. The time map of 1 UV-C LED with 250 mA current applied presented in **Fig. 41.** shows that even at the centre of radiation it would take over 3 hours for disinfection of 90 %. Moreover, radiation loses its significance at a radius of 3.5 meters.

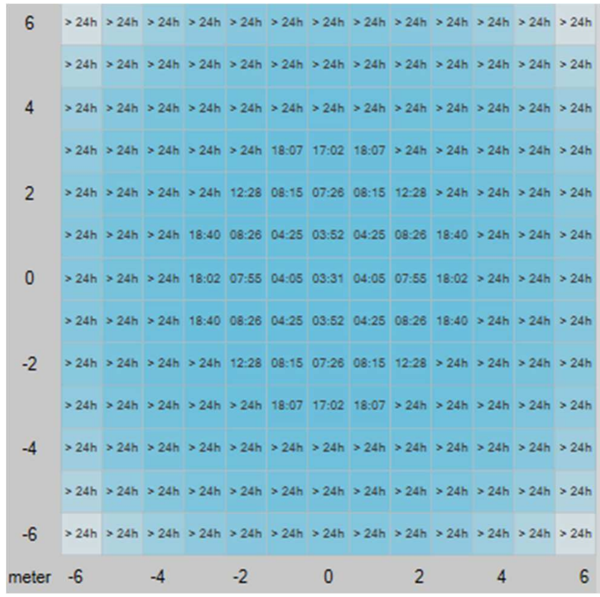

Fig. 41. Disinfection time map of single UV-C LED for E. Coli and P. aeruginosa (250 mA).

Staphylococcus aureus bacteria requires an even higher dose of 66 J/m^2 and a single UV-C LED would need more than 4 hours to achieve 90 % sterilization.

According to the disinfection time map of 2 UV-C LEDs with 250 mA current (**Fig. 42.**), results are better and time at the centre is reduced to 2 hours for 90 % sterilization. However, even if a large time reduction is achieved, it is still not an acceptable result. Moreover, doubling the number of LEDs helped to achieve slightly more significant results at a 4 m radius.

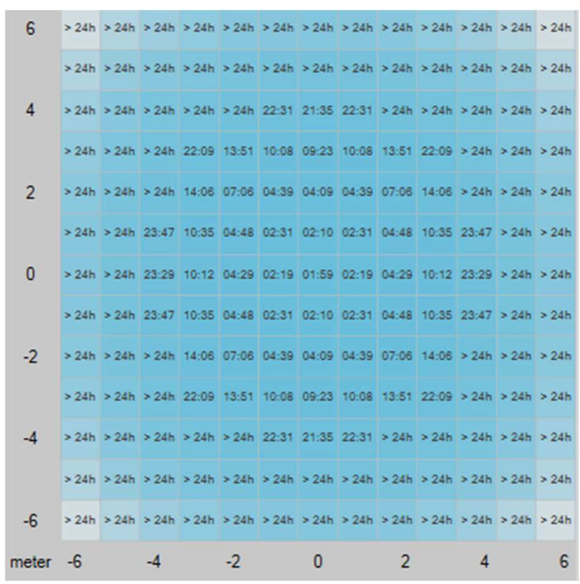

Fig. 42. Disinfection time map of 2 UV-C LEDs for E. Coli and P. aeruginosa (250 mA).

The disinfection time map for Staphylococcus aureus with 2 UV-C LEDs at the highest allowed 250 mA current does not provide satisfying results as well (**Fig. 43.**). The time at the centre of the beam for sterilization of 90 % is almost 2 hours and 30 minutes, while at wider radius it increases up to almost 17 hours. Unfortunately, there is no healthcare institution that would be totally absent for such a long period of time.

6	> 24h	> 24h	> 24h	> 24h	> 24h	> 24h	> 24h	> 24h	> 24h	> 24h	> 24h	> 24h	> 24h
	> 24h	> 24h	> 24h	> 24h	> 24h	> 24h	> 24h	> 24h	> 24h	> 24h	> 24h	> 24h	> 24h
4	> 24h	> 24h	> 24h	> 24h	> 24h	> 24h	> 24h	> 24h	> 24h	> 24h	> 24h	> 24h	> 24h
	> 24h	> 24h	> 24h	> 24h	16:37	12:10	11:15	12:10	16:37	> 24h	> 24h	> 24h	> 24h
2	> 24h	> 24h	> 24h	16:55	08:31	05:35	04:58	05:35	08:31	16:55	> 24h	> 24h	> 24h
	> 24h	> 24h	> 24h	12:42	05:46	03:02	02:36	03:02	05:46	12:42	> 24h	> 24h	> 24h
0	> 24h	> 24h	> 24h	12:14	05:23	02:47	02:23	02:47	05:23	12:14	> 24h	> 24h	> 24h
	> 24h	> 24h	> 24h	12:42	05:46	03:02	02:36	03:02	05:46	12:42	> 24h	> 24h	> 24h
-2	> 24h	> 24h	> 24h	16:55	08:31	05:35	04:58	05:35	08:31	16:55	> 24h	> 24h	> 24h
	> 24h	> 24h	> 24h	> 24h	16:37	12:10	11:15	12:10	16:37	> 24h	> 24h	> 24h	> 24h
-4	> 24h	> 24h	> 24h	> 24h	> 24h	> 24h	> 24h	> 24h	> 24h	> 24h	> 24h	> 24h	> 24h
	> 24h	> 24h	> 24h	> 24h	> 24h	> 24h	> 24h	> 24h	> 24h	> 24h	> 24h	> 24h	> 24h
-6	> 24h	> 24h	> 24h	> 24h	> 24h	> 24h	> 24h	> 24h	> 24h	> 24h	> 24h	> 24h	> 24h
meter	-6		-4		-2		0		2		4		6

Fig. 43. Disinfection time map of 2 UV-C LEDs for Staphylococcus aureus (250 mA).

After evaluating the results of the first two options, it can be seen that currents lower than 250 mA are not suitable for proper disinfection when single or two UV-C LED modules are used. Considering the electricity consumption when 3 UV-C LED modules are used, the 200 mA current is a more economical option, but for the best possible disinfection results, the 250 mA current is the more optimal option. This consideration is mentioned because the irradiance difference between these two measurements is relatively small.

According to the disinfection time map of 3 UV-C LEDs at 250 mA current, the lowest amount of time for 90 % sterilization of E. coli and P. aeruginosa is achieved (**Fig. 44.**). However, time at the centre is roughly 1 hour and 20 minutes which is much better compared to previous results but still not acceptable for surface disinfection considering that irradiation at radius at 2 meters reaches over 2 hours and over 19 hours at the furthest point.

6	> 24h	> 24h	> 24h	> 24h	> 24h	> 24h	> 24h	> 24h	> 24h	> 24h	> 24h	> 24h	> 24h
	> 24h	> 24h	> 24h	> 24h	> 24h	> 24h	> 24h	> 24h	> 24h	> 24h	> 24h	> 24h	> 24h
4	> 24h	> 24h	> 24h	> 24h	19:26	15:33	15:01	15:33	19:26	> 24h	> 24h	> 24h	> 24h
	> 24h	> 24h	> 24h	15:07	09:31	07:00	06:32	07:00	09:31	15:07	> 24h	> 24h	> 24h
2	> 24h	> 24h	20:04	09:41	04:52	03:13	02:53	03:13	04:52	09:41	20:04	> 24h	> 24h
	> 24h	> 24h	16:21	07:18	03:18	01:44	01:31	01:44	03:18	07:18	16:21	> 24h	> 24h
0	> 24h	> 24h	16:13	07:03	03:06	01:37	01:23	01:37	03:06	07:03	16:13	> 24h	> 24h
	> 24h	> 24h	16:21	07:18	03:18	01:44	01:31	01:44	03:18	07:18	16:21	> 24h	> 24h
-2	> 24h	> 24h	20:04	09:41	04:52	03:13	02:53	03:13	04:52	09:41	20:04	> 24h	> 24h
	> 24h	> 24h	> 24h	15:07	09:31	07:00	06:32	07:00	09:31	15:07	> 24h	> 24h	> 24h
-4	> 24h	> 24h	> 24h	> 24h	19:26	15:33	15:01	15:33	19:26	> 24h	> 24h	> 24h	> 24h
	> 24h	> 24h	> 24h	> 24h	> 24h	> 24h	> 24h	> 24h	> 24h	> 24h	> 24h	> 24h	> 24h
-6	> 24h	> 24h	> 24h	> 24h	> 24h	> 24h	> 24h	> 24h	> 24h	> 24h	> 24h	> 24h	> 24h
meter	-6		-4		-2		0		2		4		6

Fig. 44. Disinfection time map of 3 UV-C LEDs for E. Coli and P. aeruginosa (250 mA).

Regarding the results of the other UV-C LEDs combinations, there is no need to mention that 3 UV-C LEDs are not suitable for Staphylococcus aureus disinfection as well. At the center it needs 1 hour 40 minutes and at the furthest point 23 hours and 20 minutes for 90 % surface sterilization.

Out of all the investigated bacteria, E. coli is the most common microorganism in healthcare facilities and in recent years it has had a relatively huge spread growth. Although the majority of E. coli strains are not harmful, certain strains can result in diarrhoea upon exposure to contaminated food or water. Furthermore, some strains can lead to respiratory illnesses, pneumonia, and urinary tract infections [95]. **Fig. 45.** represents the summary of how much dose time at the peak is needed to sterilize 90 % of E. coli on the surface. Obtained results, once more proves that 3 UV-C LEDs are the most efficient option for disinfection resulting in the best performance of 62 min dose time at the very peak of irradiation.

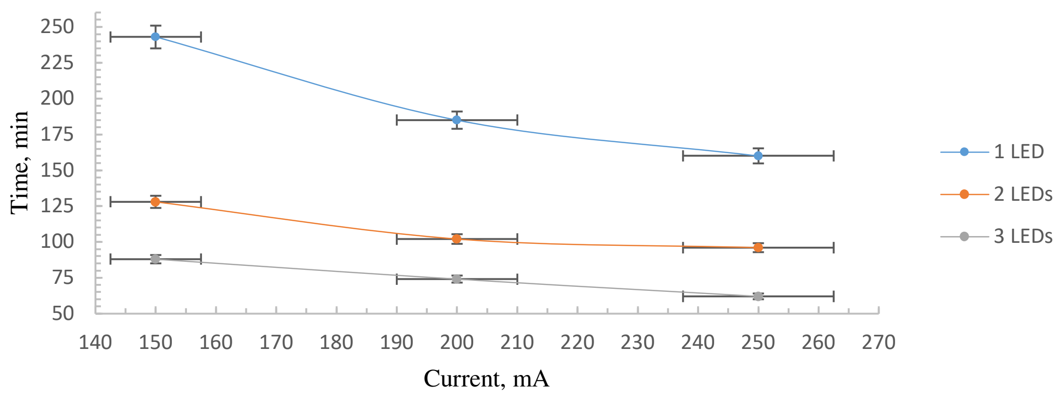

Fig. 45. Dose time at peak irradiance required to sterilize 90 % of E. coli.

After evaluating each UV-C LED combination, it can be seen that 3 UV-C LEDs have the best sterilization abilities of all measured variations. The only left microorganism to evaluate is the SARS-Cov-2 virus or coronavirus, which requires a 50 J/m^2 dose for even 99 % sterilization. According to the given dose, the visualization of needed time dependence on distance is presented in **Fig. 46**. Regarding various variables viruses should need higher doses of UV-C irradiation, however in this case the found information in the article about SARS-CoV-2 sterilization claims that this specific virus needs less dose compared to bacteria. Given time values are measured at the centre, but it already needs way less time compared to bacteria disinfection examples of similar height. Assuming that distance from the UV-C light source and the objects in healthcare premises (tables, shelves etc.) is 2 m, then the required time would only be 42 minutes. If the effectiveness of sterilization would be 90 % instead of 99 %, the time would be reduced by double.

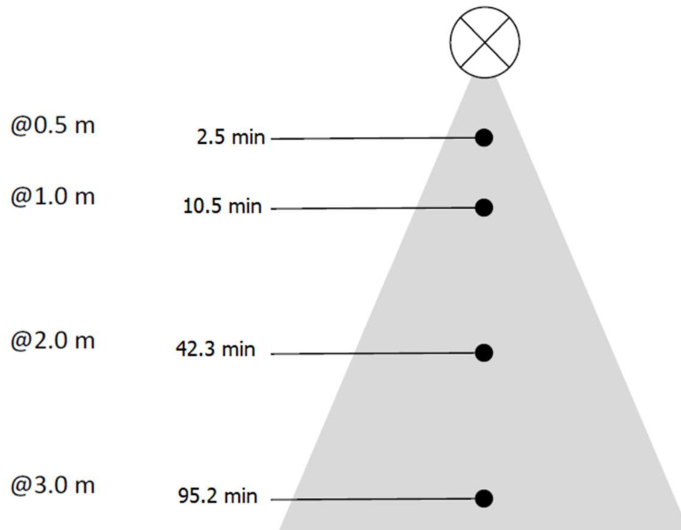

Fig. 46. Exposure time dependence on distance for COVID-19. 3 UV-C LEDs (250 mA)

3.3. Summary of results

The standard LED luminaire provides an excellent amount of illumination reaching 5000 lumens with a 92.2 colour rendering index, almost 4000 K correlated colour temperature, and a cyanosis observation index of 3.3. All mentioned photometric details are summarized in **Table 6**. Despite high-quality lighting, the de-glaring micro prismatic PMMA diffuser is used to avoid glare. Moreover, out of all the most commonly used plastic materials PMMA is the most resistant to UV radiation compared to polycarbonate (PC), acrylonitrile butadiene styrene (ABS), or polyvinyl chloride (PVC).

Table 6. Most important measured photometric parameters

Photometric characteristic	Value	Unit
Luminous flux	5000	Lumens
Light efficiency	147	Lumens/Watts
Colour rendering index	92.2	-
Correlated colour temperature	3935	Kelvins
Cyanosis observation index	3.3	-

UV-C light source was measured, and the resulting wavelength was 277 nm. The irradiance power of UV-C LEDs increased with the growth of LED number and the increase of current. Therefore, 1 UV-C LED module with 150 mA current had the lowest irradiance power at the peak of 89.94 mW and 3 UV-C LEDs with 250 mA current had 335.54 mW.

According to distance dependence results, the variation of 3 UV-C LEDs with 250 mA has once again offered the highest values of irradiance efficiency regardless of the distance. However, all the measured options from 150 mA to 250 mA have shown a rapid decrease of irradiance per area when the distance reached 2.5-3 meters. At the distance of 5 meters, the difference between all measured combinations of irradiance was insignificant and values were extremely low.

Responding to time dependence results, none of the measured variations was suitable for standard premises disinfection due to the low irradiance power at wider angles. The measured exposure time at the peak of irradiance for 3 UV-C LEDs combination with 250 mA current can be considered as good results for E. coli, P. aeruginosa, and SARS-Cov-2, however, at wider angles, the exposure time grows up to ~19.5 hours which is a too long period of time for disinfection.

Summarizing, the best results were measured with 3 UV-C LEDs option at a maximum allowed 250 mA current. It provided the highest irradiation power at a peak of 335.5 mW and the fastest disinfection time for all investigated microorganisms which are given in **Table 7**.

Table 7. Time required for sterilization with 3 UV-C LEDs at 250 mA.

Microorganism	Time required for 90 % sterilization at a standard 2.4 m distance directly under the source
Escherichia coli	1 h 23 min
Pseudomonas aeruginosa	1 h 23 min
Staphylococcus aureus	2 h 23 min
Covid-19 (99 % sterilization) *	1 h 3 min

Surface disinfection requires 3-5 times higher doses compared to air disinfection. The measured and investigated UV-C LED modules are not suitable for efficient application at healthcare premises as surface disinfection devices. There is a need for either stronger UV-C LED options or a greater number of UV-C LEDs. It may be applicable for lower height, but not for standard height rooms. However, with suitable current settings, it may be applied in air ventilation systems to produce fresh and germ-free air for the employees and patients of healthcare institutions.

Conclusions

1. With the assistance of the company "Northcliffe Lighting" and after conducting market analysis, the specific 275 nm wavelength UV-C LED chips " CUD7GF1B " were obtained. Following this, in collaboration with company "AKTO", chips were soldered onto a PCB plate, effectively creating UV-C LED modules.
2. The created UV-C LED modules were applied to the LED luminaire in three possible variations: with 1, 2, and 3 UV-C LEDs in the middle of the luminaire housing to avoid UV radiation incompatibility with other components and materials. Applications for surface sterilization are limited, but it's suitable for air disinfection.
3. In the photometric measurements, the luminaire "X" was tested using 8 planes with the 1-degree resolution, and it was found to provide high efficiency of 147 lm/W in terms of lumens (lm) per consumed system power (W). The colour rendering index (CRI) of the luminaire was 92.2, which is excellent, and the colour temperature (CCT) was close to 4000 K, making it suitable for work requiring concentration. The cyanosis observation index (COI) was 3.3, which is within regulation limits and is suitable for healthcare facilities.
4. The lumen output of the luminaire was 5000 lm, which is perfect for standard healthcare premises ceiling height and could save up to 50% of energy consumption per year compared to currently used light sources.
5. In photobiological measurements, the lowest irradiance at the peak was determined with a single UV-C LED regardless of the applied current. Irradiance values were 89.9 mW, 117.8 mW, and 129.6 mW with 150 mA, 200 mA and 250 mA applied currents respectively. On the other hand, a combination of 3 UV-C LEDs provided the best results of all investigated variations. Irradiance values were 251.8 mW, 299.5 mW, and 335.5 mW with 150 mA, 200 mA and 250 mA applied currents respectively.
6. Distance influence to flux decrease confirmed inverse square law. The strongest option of 3 UV-C LEDs at the highest allowed current of 250 mA had a 75.1 mW/m^2 irradiation power at 1 meter, however, it decreased to 8.3 mW/m^2 at 3 meters and to 3.0 mW/m^2 at 5 meters. Other UV-C source options provided similar results with lower irradiation power values.
7. Out of the three investigated bacteria E. coli and P. aeruginosa required the shortest time periods for 90 % sterilization. The strongest 3 UV-C LED option requires slightly more than 1 hour to sterilize the surface directly under the source. However, at further radius, sterilization time grows up to more than 19 hours, which is not an appropriate result and would require stacking more UV-C LED luminaires up close in order to shorten the disinfection period.

Recommendation

The constructed UV-C LED radiation source has some limitations to its use. It is suitable for surface disinfection purposes in premises with a ceiling height of up to 2 meters. However, even when the lowest possible current is applied, the UV-C source still emits radiation that exceeds the 30 J/m2 per 8 work hours dose specified in the Directive 2006/25/EC ANNEX I Table 1.1. standard. This means that it is not suitable for constant daily use, and caution should be taken to limit exposure.

The best possible applications for these investigated UV-C LED sources are for air and water disinfection, and any direct contact with humans should be avoided. It is important to keep these limitations in mind when considering the use of this UV-C LED radiation source to ensure safe and effective use.

List of references

1. GIDARI, Anna, SABBATINI, Samuele, BASTIANELLI, Sabrina, PIERUCCI, Sara, BUSTI, Chiara, BARTOLINI, Desirée, STABILE, Anna Maria, MONARI, Claudia, GALLI, Francesco, RENDE, Mario, CRUCIANI, Gabriele and FRANCISCI, Daniela. SARS-CoV-2 Survival on Surfaces and the Effect of UV-C Light. *Viruses 2021, Vol. 13, Page 408* [online]. 5 March 2021. Vol. 13, no. 3, p. 408. [Accessed 5 May 2023]. DOI 10.3390/V13030408. Available from: https://www.mdpi.com/1999-4915/13/3/408/htm
2. AHMAD, Shamim I., CHRISTENSEN, Luisa and BARON, Elma. History of UV lamps, types, and their applications. *Advances in Experimental Medicine and Biology* [online]. 2017. Vol. 996, p. 3–11. [Accessed 5 May 2023]. DOI 10.1007/978-3-319-56017-5_1/COVER. Available from: https://link.springer.com/chapter/10.1007/978-3-319-56017-5_1
3. WANG, Chien Ping, CHANG, Chin Sheng and LIN, Wei Chen. Efficiency improvement of a flow-through water disinfection reactor using UV-C light emitting diodes. *Journal of Water Process Engineering*. 1 April 2021. Vol. 40, p. 101819. DOI 10.1016/J.JWPE.2020.101819.
4. LED luminaire - Illuminating Engineering Society. [online]. [Accessed 9 April 2023]. Available from: https://www.ies.org/definitions/led-luminaire/
5. BRÜTTING, Wolfgang, FRISCHEISEN, Jörg, SCHMIDT, Tobias D., SCHOLZ, Bert J. and MAYR, Christian. Device efficiency of organic light-emitting diodes: Progress by improved light outcoupling. *physica status solidi (a)* [online]. 1 January 2013. Vol. 210, no. 1, p. 44–65. [Accessed 9 April 2023]. DOI 10.1002/PSSA.201228320. Available from: https://onlinelibrary.wiley.com/doi/full/10.1002/pssa.201228320
6. MATIOLI, Elison, BRINKLEY, Stuart, KELCHNER, Kathryn M., HU, Yan Ling, NAKAMURA, Shuji, DENBAARS, Steven, SPECK, James and WEISBUCH, Claude. High-brightness polarized light-emitting diodes. *Light: Science & Applications 2012 1:8* [online]. 3 August 2012. Vol. 1, no. 8, p. e22–e22. [Accessed 9 April 2023]. DOI 10.1038/lsa.2012.22. Available from: https://www.nature.com/articles/lsa201222
7. The Physics of Light and Color - Color Temperature | Olympus LS. [online]. [Accessed 9 April 2023]. Available from: https://www.olympus-lifescience.com/en/microscope-resource/primer/lightandcolor/colortemp/
8. JUDD, Deane B. Sensibility to Color-Temperature Change as a Function of Temperature*. *JOSA, Vol. 23, Issue 1, pp. 7-14* [online]. 1 January 1933. Vol. 23, no. 1, p. 7–14. [Accessed 9 April 2023]. DOI 10.1364/JOSA.23.000007. Available from: https://opg.optica.org/viewmedia.cfm?uri=josa-23-1-7&seq=0&html=true
9. CIE chromaticity diagram with CCT chart. | Download Scientific Diagram. [online]. [Accessed 10 May 2023]. Available from: https://www.researchgate.net/figure/CIE-chromaticity-diagram-with-CCT-chart_fig9_320671416
10. Calculate color temperature (CCT) from CIE 1931 xy coordinates | Waveform Lighting. [online]. [Accessed 10 May 2023]. Available from: https://www.waveformlighting.com/tech/calculate-color-temperature-cct-from-cie-1931-xy-coordinates
11. Color Rendering Index (CRI) - Everything You Need To Know. [online]. [Accessed 9 April 2023]. Available from: https://straitslighting.com/blog/news-item/color-rendering-index-cri/
12. The principle and basic calculation of CRI - LISUN. [online]. [Accessed 10 May 2023]. Available from: https://www.lisungroup.com/news/technology-news/the-principle-and-basic-

calculation-of-cri.html
13. Method for determination of Cyanosis Observation Index of a Light Source - Bentham. [online]. [Accessed 9 April 2023]. Available from: https://www.bentham.co.uk/knowledge/tools-resources/application-guides/method-for-determination-of-cyanosis-observation-index-of-a-light-source-156/
14. Assessing the suitability of a light source in healthcare environments using the Cyanosis Observation Index (COI) | Focal Point Lights. [online]. [Accessed 10 May 2023]. Available from: https://www.focalpointlights.com/blog/assessing-suitability-light-source-healthcare-environments-using-cyanosis-observation-index
15. LED - Working Principle, advantages & still much more! [online]. [Accessed 30 April 2023]. Available from: https://www.toppr.com/bytes/principles-of-led/
16. DEEGAN, Corrine, SERADJEH, Babak, MALTESE, Adam, PARKER, Kara, SANTONACITA, Joseph and SCHWAB, Daniel. Light-Emitting Diode (LED) Module Forefronts of Research Educational Modules (FOREM). .
17. 1W LED Chip White 6500K, 6V at Rs 0.59/piece in Indore | ID: 21027083348. [online]. [Accessed 30 April 2023]. Available from: https://www.indiamart.com/proddetail/1w-led-chip-white-6500k-21027083348.html
18. VAKRILOV, N and ANDONOVA, A. Innovative heat transfer analysis of LED modules by thermal simulations. *Bulgarian Chemical Communications*. 2015. Vol. 47, p. 519–527.
19. NICOLAU, Talita, FILHO, Núbio Gomes, PADRÃO, Jorge and ZILLE, Andrea. A Comprehensive Analysis of the UVC LEDs’ Applications and Decontamination Capability. *Materials 2022, Vol. 15, Page 2854* [online]. 13 April 2022. Vol. 15, no. 8, p. 2854. [Accessed 12 April 2023]. DOI 10.3390/MA15082854. Available from: https://www.mdpi.com/1996-1944/15/8/2854/htm
20. QIAN, C., FAN, J. J., HUANG, J. L., FAN, X. J. and ZHANG, G. Q. An introduction of the phosphor-converted white LED packaging and its reliability. *Nano-Bio- Electronic, Photonic and MEMS Packaging* [online]. 17 October 2020. P. 419–434. [Accessed 12 April 2023]. DOI 10.1007/978-3-030-49991-4_18/FIGURES/14. Available from: https://link.springer.com/chapter/10.1007/978-3-030-49991-4_18
21. QIAN, C., FAN, J. J., HUANG, J. L., FAN, X. J. and ZHANG, G. Q. An introduction of the phosphor-converted white LED packaging and its reliability. *Nano-Bio- Electronic, Photonic and MEMS Packaging* [online]. 17 October 2020. P. 419–434. [Accessed 9 May 2023]. DOI 10.1007/978-3-030-49991-4_18/FIGURES/14. Available from: https://link.springer.com/chapter/10.1007/978-3-030-49991-4_18
22. SCHWALM, Reinhold. Introduction to Coatings Technology. *UV Coatings*. 1 January 2007. P. 1–18. DOI 10.1016/B978-044452979-4/50001-9.
23. Ultraviolet | COSMOS. [online]. [Accessed 30 April 2023]. Available from: https://astronomy.swin.edu.au/cosmos/u/ultraviolet
24. SHAMA, G. Ultraviolet Light. *Encyclopedia of Food Microbiology: Second Edition*. 1 January 2014. P. 665–671. DOI 10.1016/B978-0-12-384730-0.00341-4.
25. SCARLETT, WL. Ultraviolet radiation: sun exposure, tanning beds, and vitamin D levels. What you need to know and how to decrease the risk of skin cancer. *Journal of Osteopathic Medicine* [online]. 1 August 2003. Vol. 103, no. 8, p. 371–375. [Accessed 15 April 2023]. DOI 10.7556/JAOA.2003.103.8.371. Available from: https://www.degruyter.com/document/doi/10.7556/jaoa.2003.103.8.371/html
26. Types of UV light and their characteristics - Infralia. [online]. [Accessed 15 April 2023].

Available from: https://www.infralia.com/en/uv-light-characteristics/
27. MOOZHIPURATH, Rahul Kalippurayil, KRAFT, Lennart and SKIERA, Bernd. Evidence of protective role of Ultraviolet-B (UVB) radiation in reducing COVID-19 deaths. *Scientific Reports 2020 10:1* [online]. 19 October 2020. Vol. 10, no. 1, p. 1–10. [Accessed 15 April 2023]. DOI 10.1038/s41598-020-74825-z. Available from: https://www.nature.com/articles/s41598-020-74825-z
28. BROSCHÉ, Mikael and STRID, Åke. Molecular events following perception of ultraviolet-B radiation by plants. *Physiologia Plantarum* [online]. 1 January 2003. Vol. 117, no. 1, p. 1–10. [Accessed 15 April 2023]. DOI 10.1034/J.1399-3054.2003.1170101.X. Available from: https://onlinelibrary.wiley.com/doi/full/10.1034/j.1399-3054.2003.1170101.x
29. SELLERA, Fábio P., SABINO, Caetano P., CABRAL, Fernanda V. and RIBEIRO, Martha S. A systematic scoping review of ultraviolet C (UVC) light systems for SARS-CoV-2 inactivation. *Journal of Photochemistry and Photobiology*. 1 December 2021. Vol. 8, p. 100068. DOI 10.1016/J.JPAP.2021.100068.
30. SINGH, Harpreet, BHARDWAJ, Sanjeev K., KHATRI, Madhu, KIM, Ki Hyun and BHARDWAJ, Neha. UVC radiation for food safety: An emerging technology for the microbial disinfection of food products. *Chemical Engineering Journal*. 1 August 2021. Vol. 417, p. 128084. DOI 10.1016/J.CEJ.2020.128084.
31. MILLER, Shelly L., LINNES, Jacqueline and LUONGO, Julia. Ultraviolet germicidal irradiation: future directions for air disinfection and building applications. *Photochemistry and photobiology* [online]. July 2013. Vol. 89, no. 4, p. 777–781. [Accessed 22 April 2023]. DOI 10.1111/PHP.12080. Available from: https://pubmed.ncbi.nlm.nih.gov/23581680/
32. BUONANNO, Manuela, WELCH, David, SHURYAK, Igor and BRENNER, David J. Far-UVC light (222 nm) efficiently and safely inactivates airborne human coronaviruses. *Scientific reports* [online]. 1 December 2020. Vol. 10, no. 1. [Accessed 22 April 2023]. DOI 10.1038/S41598-020-67211-2. Available from: https://pubmed.ncbi.nlm.nih.gov/32581288/
33. SONG, Kai, MOHSENI, Madjid and TAGHIPOUR, Fariborz. Application of ultraviolet light-emitting diodes (UV-LEDs) for water disinfection: A review. *Water research* [online]. 1 May 2016. Vol. 94, p. 341–349. [Accessed 22 April 2023]. DOI 10.1016/J.WATRES.2016.03.003. Available from: https://pubmed.ncbi.nlm.nih.gov/26971809/
34. Germicidal Effectiveness of UVC LEDs – WCP Online. [online]. [Accessed 22 April 2023]. Available from: https://wcponline.com/2016/12/15/germicidal-effectiveness-uvc-leds/
35. SHIMODA, Hiroshi, MATSUDA, Junji, IWASAKI, Tatsuyuki and HAYASAKA, Daisuke. Efficacy of 265-nm ultraviolet light in inactivating infectious SARS-CoV-2. *Journal of Photochemistry and Photobiology*. 1 September 2021. Vol. 7, p. 100050. DOI 10.1016/J.JPAP.2021.100050.
36. HSU, Tsung Chi, TENG, Yu Tsai, YEH, Yen Wei, FAN, Xiaotong, CHU, Kuo Hsiung, LIN, Su Hui, YEH, Kuo Kuang, LEE, Po Tsung, LIN, Yue, CHEN, Zhong, WU, Tingzhu and KUO, Hao Chung. Perspectives on UVC LED: Its Progress and Application. *Photonics 2021, Vol. 8, Page 196* [online]. 31 May 2021. Vol. 8, no. 6, p. 196. [Accessed 22 April 2023]. DOI 10.3390/PHOTONICS8060196. Available from: https://www.mdpi.com/2304-6732/8/6/196/htm
37. BOLTON, James R. and LINDEN, Karl G. Standardization of Methods for Fluence (UV Dose) Determination in Bench-Scale UV Experiments. *Journal of Environmental Engineering* [online]. 1 March 2003. Vol. 129, no. 3, p. 209–215. [Accessed 1 May 2023].

DOI 10.1061/(ASCE)0733-9372(2003)129:3(209). Available from: https://ascelibrary.org/doi/abs/10.1061/%28ASCE%290733-9372%282003%29129%3A3%28209%29

38. LUNGU, Cătălin I and NĂSTASE, Ilinca. Brief overview on the UVGI disinfection technology. *Romanian Journal of Civil Engineering*. 2021. Vol. 12, no. 2. DOI 10.37789/rjce.2021.12.2.1.

39. Ultraviolet germicidal irradiation - Wikiwand. [online]. [Accessed 1 May 2023]. Available from: https://www.wikiwand.com/en/Ultraviolet_germicidal_irradiation

40. LEE, Yong Wook, YOON, Hyung Do, PARK, Jae Hyoun and RYU, Uh Chan. Application of 265-nm UVC LED Lighting to Sterilization of Typical Gram Negative and Positive Bacteria. *Journal of the Korean Physical Society* [online]. 1 May 2018. Vol. 72, no. 10, p. 1174–1178. [Accessed 1 May 2023]. DOI 10.3938/JKPS.72.1174/METRICS. Available from: https://link.springer.com/article/10.3938/jkps.72.1174

41. BHARDWAJ, Sanjeev K., SINGH, Harpreet, DEEP, Akash, KHATRI, Madhu, BHAUMIK, Jayeeta, KIM, Ki Hyun and BHARDWAJ, Neha. UVC-based photoinactivation as an efficient tool to control the transmission of coronaviruses. *Science of The Total Environment*. 20 October 2021. Vol. 792, p. 148548. DOI 10.1016/J.SCITOTENV.2021.148548.

42. BUONANNO, Manuela, WELCH, David, SHURYAK, Igor and BRENNER, David J. Far-UVC light (222 nm) efficiently and safely inactivates airborne human coronaviruses. *Scientific Reports 2020 10:1* [online]. 24 June 2020. Vol. 10, no. 1, p. 1–8. [Accessed 22 April 2023]. DOI 10.1038/s41598-020-67211-2. Available from: https://www.nature.com/articles/s41598-020-67211-2

43. WILLEY, Joanne, SANDMAN, Kathleen and WOOD, Dorothy. *Prescott ' s Microbiology*. 2020. ISBN 9780077350130.

44. YOUNG, Antony R. Acute effects of UVR on human eyes and skin. *Progress in Biophysics and Molecular Biology*. 1 September 2006. Vol. 92, no. 1, p. 80–85. DOI 10.1016/J.PBIOMOLBIO.2006.02.005.

45. MAY, Robert M. How Many Species Are There on Earth? *Science* [online]. 16 September 1988. Vol. 241, no. 4872, p. 1441–1449. [Accessed 1 May 2023]. DOI 10.1126/SCIENCE.241.4872.1441. Available from: https://www.science.org/doi/10.1126/science.241.4872.1441

46. 1.2A Types of Microorganisms - Biology LibreTexts. [online]. [Accessed 27 May 2022]. Available from: https://bio.libretexts.org/Bookshelves/Microbiology/Book%3A_Microbiology_(Boundless)/1%3A_Introduction_to_Microbiology/1.2%3A_Microbes_and_the_World/1.2A_Types_of_Microorganisms

47. Microbiomes of the Built Environment. *Microbiomes of the Built Environment*. 2017. DOI 10.17226/23647.

48. ADAMS, Rachel I., BATEMAN, Ashley C., BIK, Holly M. and MEADOW, James F. Microbiota of the indoor environment: a meta-analysis. *Microbiome*. 13 October 2015. Vol. 3, p. 49. DOI 10.1186/S40168-015-0108-3.

49. MONEGRO, Alberto F., MUPPIDI, Vijayadershan and REGUNATH, Hariharan. Hospital Acquired Infections. *Cambridge Handbook of Psychology, Health and Medicine, Second Edition* [online]. 12 February 2023. P. 736–738. [Accessed 22 April 2023]. DOI 10.1017/CBO9780511543579.182. Available from: https://www.ncbi.nlm.nih.gov/books/NBK441857/

50. EBOIGBODIN, K. E., NEWTON, J. R.A., ROUTH, A. F. and BIGGS, C. A. Bacterial quorum sensing and cell surface electrokinetic properties. *Applied Microbiology and Biotechnology* [online]. 20 December 2006. Vol. 73, no. 3, p. 669–675. [Accessed 17 December 2022]. DOI 10.1007/S00253-006-0505-4/FIGURES/5. Available from: https://link.springer.com/article/10.1007/s00253-006-0505-4
51. KOLEL-VEETIL, Manoj, SEN, Ayusman and BUEHLER, Markus J. Surface adhesion of viruses and bacteria: Defend only and/or vibrationally extinguish also?! A perspective. *MRS advances* [online]. 1 June 2021. Vol. 6, no. 13, p. 355–361. [Accessed 22 April 2023]. DOI 10.1557/S43580-021-00079-0. Available from: https://pubmed.ncbi.nlm.nih.gov/34150335/
52. ISRAELACHVILI, Jacob N. Intermolecular and Surface Forces, Third Edition. *Intermolecular and Surface Forces, Third Edition* [online]. 1 January 2010. P. 1–674. [Accessed 22 April 2023]. DOI 10.1016/C2009-0-21560-1. Available from: http://www.sciencedirect.com:5070/book/9780123751829/intermolecular-and-surface-forces
53. YANG, Kun, SHI, Jirong, WANG, Lei, CHEN, Yingzhi, LIANG, Chunyong, YANG, Lei and WANG, Lu Ning. Bacterial anti-adhesion surface design: Surface patterning, roughness and wettability: A review. *Journal of Materials Science & Technology*. 10 February 2022. Vol. 99, p. 82–100. DOI 10.1016/J.JMST.2021.05.028.
54. RAKOWSKA, Paulina D., TIDDIA, Mariavitalia, FARUQUI, Nilofar, BANKIER, Claire, PEI, Yiwen, POLLARD, Andrew J., ZHANG, Junting, GILMORE, Ian S., RAKOWSKA, Paulina D., TIDDIA, Mariavitalia, FARUQUI, Nilofar, BANKIER, Claire, PEI, Yiwen, POLLARD, Andrew J., ZHANG, Junting and GILMORE, Ian S. Antiviral surfaces and coatings and their mechanisms of action. *CoMat* [online]. 1 December 2021. Vol. 2, no. 1, p. 53. [Accessed 22 April 2023]. DOI 10.1038/S43246-021-00153-Y. Available from: https://ui.adsabs.harvard.edu/abs/2021CoMat...2...53R/abstract
55. GERRITY, Daniel, RYU, Hodon, CRITTENDEN, John and ABBASZADEGAN, Morteza. Photocatalytic inactivation of viruses using titanium dioxide nanoparticles and low-pressure UV light. *Journal of environmental science and health. Part A, Toxic/hazardous substances & environmental engineering* [online]. September 2008. Vol. 43, no. 11, p. 1261–1270. [Accessed 22 April 2023]. DOI 10.1080/10934520802177813. Available from: https://pubmed.ncbi.nlm.nih.gov/18642149/
56. FURER, Lea A., CLEMENT, Pietro, HERWIG, Gordon, ROSSI, René M., BHOELAN, Farien, AMACKER, Mario, STEGMANN, Toon, BUERKI-THURNHERR, Tina and WICK, Peter. A novel inactivated virus system (InViS) for a fast and inexpensive assessment of viral disintegration. *Scientific reports* [online]. 1 December 2022. Vol. 12, no. 1. [Accessed 22 April 2023]. DOI 10.1038/S41598-022-15471-5. Available from: https://pubmed.ncbi.nlm.nih.gov/35803968/
57. HALL-STOODLEY, Luanne, COSTERTON, J. William and STOODLEY, Paul. Bacterial biofilms: from the natural environment to infectious diseases. *Nature reviews. Microbiology* [online]. February 2004. Vol. 2, no. 2, p. 95–108. [Accessed 22 April 2023]. DOI 10.1038/NRMICRO821. Available from: https://pubmed.ncbi.nlm.nih.gov/15040259/
58. NEU, Ursula and MAINOU, Bernardo A. Virus interactions with bacteria: Partners in the infectious dance. *PLoS pathogens* [online]. 1 February 2020. Vol. 16, no. 2, p. e1008234. [Accessed 22 April 2023]. DOI 10.1371/JOURNAL.PPAT.1008234. Available from: https://pubmed.ncbi.nlm.nih.gov/32045465/
59. PEREIRA, R. V., BICALHO, M. L., MACHADO, V. S., LIMA, S., TEIXEIRA, A. G.,

WARNICK, L. D. and BICALHO, R. C. Evaluation of the effects of ultraviolet light on bacterial contaminants inoculated into whole milk and colostrum, and on colostrum immunoglobulin G. *Journal of dairy science* [online]. 2014. Vol. 97, no. 5, p. 2866. [Accessed 4 May 2023]. DOI 10.3168/JDS.2013-7601. Available from: /pmc/articles/PMC4351796/

60. How UV-C effect for disinfection | STANLEY ELECTRIC CO., LTD. [online]. [Accessed 4 May 2023]. Available from: https://www.stanley.co.jp/e/product/uvc_product/effect/
61. Disinfection with UV-C LEDs Application Note. [online]. [Accessed 1 May 2023]. Available from: www.we-online.comANO008a//
62. UV-C Dose Required to Kill Microorganisms. [online]. [Accessed 1 May 2023]. Available from: https://uv-light.co.uk/uv-dosage-required-to-kill-microorganisms/
63. HOLLAENDER, A. Effects of ultraviolet radiation. *Annual review of physiology* [online]. 1946. Vol. 8, p. 1–16. [Accessed 1 May 2023]. DOI 10.1146/ANNUREV.PH.08.030146.000245. Available from: https://pubmed.ncbi.nlm.nih.gov/20986686/
64. EAHL, Paul A., KOLLER, L. R. and HASKINS, C. P. THE EFFECTS OF ULTRAVIOLET RADIATION ON SPORES OF THE FUNGUS ASPERGILLUS NIGER. *The Journal of general physiology* [online]. 20 July 1939. Vol. 22, no. 6, p. 689–698. [Accessed 1 May 2023]. DOI 10.1085/JGP.22.6.689. Available from: https://pubmed.ncbi.nlm.nih.gov/19873127/
65. SHARP, D. Gordon. The Effects of Ultraviolet Light on Bacteria Suspended in Air. *Journal of bacteriology* [online]. May 1940. Vol. 39, no. 5, p. 535–547. [Accessed 1 May 2023]. DOI 10.1128/JB.39.5.535-547.1940. Available from: https://pubmed.ncbi.nlm.nih.gov/16560312/
66. GATES, Frederick L. A STUDY OF THE BACTERICIDAL ACTION OF ULTRA VIOLET LIGHT : III. THE ABSORPTION OF ULTRA VIOLET LIGHT BY BACTERIA. *The Journal of general physiology* [online]. 20 September 1930. Vol. 14, no. 1, p. 31–42. [Accessed 1 May 2023]. DOI 10.1085/JGP.14.1.31. Available from: https://pubmed.ncbi.nlm.nih.gov/19872573/
67. Sterilization efficacy of ultraviolet irradiation on microbial aerosols under dynamic airflow by experimental air conditioning systems - PubMed. [online]. [Accessed 1 May 2023]. Available from: https://pubmed.ncbi.nlm.nih.gov/3127068/
68. WALKER, Christopher M. and KO, Gwangpyo. Effect of ultraviolet germicidal irradiation on viral aerosols. *Environmental Science and Technology* [online]. 1 August 2007. Vol. 41, no. 15, p. 5460–5465. [Accessed 1 May 2023]. DOI 10.1021/ES070056U/SUPPL_FILE/ES070056USI20070422_114454.PDF. Available from: https://pubs.acs.org/doi/abs/10.1021/es070056u
69. STORM, Nadia, MCKAY, Lindsay, DOWNS, Sierra, JOHNSON, Rebecca, BIRRU, Dagnachew, CENNINI, Giovanni and GRITHS, Anthony. Rapid and complete inactivation of SARS-CoV-2 by ultraviolet-C irradiation. [online]. 3 September 2020. [Accessed 1 May 2023]. DOI 10.21203/RS.3.RS-65742/V1. Available from: https://www.researchsquare.com
70. BAK, Jimmy, LADEFOGED, Søren D., TVEDE, Michael, BEGOVIC, Tanja and GREGERSEN, Annette. Disinfection of Pseudomonas aeruginosa biofilm contaminated tube lumens with ultraviolet C light emitting diodes. *Biofouling* [online]. January 2010. Vol. 26, no. 1, p. 31–38. [Accessed 1 May 2023]. DOI 10.1080/08927010903191353. Available from:

https://pubmed.ncbi.nlm.nih.gov/20390554/
71. RAEISZADEH, Milad and ADELI, Babak. A Critical Review on Ultraviolet Disinfection Systems against COVID-19 Outbreak: Applicability, Validation, and Safety Considerations. *ACS Photonics* [online]. 18 November 2020. Vol. 7, no. 11, p. 2941–2951. [Accessed 1 May 2023]. DOI 10.1021/ACSPHOTONICS.0C01245/ASSET/IMAGES/LARGE/PH0C01245_0004.JPEG. Available from: https://pubs.acs.org/doi/full/10.1021/acsphotonics.0c01245
72. DIRECTIVE 2014/30/EU OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 26 February 2014 on the harmonisation of the laws of the Member States relating to electromagnetic compatibility (recast) (Text with EEA relevance). .
73. market of electrical equipment designed for use within certain voltage limits (recast) (Text with EEA relevance). .
74. DIRECTIVE 2011/65/EU OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 8 June 2011 on the restriction of the use of certain hazardous substances in electrical and electronic equipment (recast) (Text with EEA relevance). .
75. ESPAÑOLA, Asociación. UNE Specification Safety requirements for UV-C equipment used for room air and surface disinfection This specification was sponsored by ANFALUM. [online]. 2020. [Accessed 1 May 2023]. Available from: www.une.org
76. DIRECTIVE 2012/19/EU OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 4 July 2012 on waste electrical and electronic equipment (WEEE) (recast) (Text with EEA relevance). .
77. B DIRECTIVE 2006/25/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 5 April 2006 on the minimum health and safety requirements regarding the exposure of workers to risks arising from physical agents (artificial optical radiation) (19th individual Directive within the meaning of Article 16(1) of Directive 89/391/EEC). . 2007.
78. EN 60598-2-25:1994 - Luminaires - Part 2-25: Particular requirements - Luminaires for use in. [online]. [Accessed 1 May 2023]. Available from: https://standards.iteh.ai/catalog/standards/clc/5c80c845-00c8-460f-9e2e-9e9df6ffb010/en-60598-2-25-1994
79. ISO 9680:2021 - Dentistry — Operating lights. [online]. [Accessed 1 May 2023]. Available from: https://www.iso.org/standard/74496.html
80. Interior lighting Part 2.5: Hospital and medical tasks. .
81. KEBBI, Yasmine, MUHAMMAD, Aliyu Idris, SANT'ANA, Anderson S., DO PRADO-SILVA, Leonardo, LIU, Donghong and DING, Tian. Recent advances on the application of UV-LED technology for microbial inactivation: Progress and mechanism. *Comprehensive Reviews in Food Science and Food Safety* [online]. 1 November 2020. Vol. 19, no. 6, p. 3501–3527. [Accessed 29 April 2023]. DOI 10.1111/1541-4337.12645. Available from: https://onlinelibrary.wiley.com/doi/full/10.1111/1541-4337.12645
82. ELEKTRONIK GMBH, Neumüller. Datasheet CUD7GF1B. [online]. [Accessed 29 April 2023]. Available from: www.neumueller.com
83. WANG, Yijie, ALONSO, J. Marcos and RUAN, Xinbo. A Review of LED Drivers and Related Technologies. *IEEE Transactions on Industrial Electronics*. 1 July 2017. Vol. 64, no. 7, p. 5754–5765. DOI 10.1109/TIE.2017.2677335.
84. Driver LC 25W 75–350mA flexC NF h16 EXC4. [online]. [Accessed 29 April 2023]. Available from: https://www.tridonic.com/en/int/product/30935?tab=0
85. LL18SEC-CC-200-350 • Helvar. [online]. [Accessed 29 April 2023]. Available from:

https://helvar.com/product/ll18sec-cc-200-350/
86. LL1x10-42-E-CC • Helvar. [online]. [Accessed 29 April 2023]. Available from: https://helvar.com/product/ll1x10-42-e-cc/
87. LabSpion Light Measurement System - Viso Systems - Easy-to-use photometric lab equipment. [online]. [Accessed 29 April 2023]. Available from: https://www.visosystems.com/products/labspion/
88. for internal use of CIE supportive member: Lisun Group. .
89. LabSpion | Acal BFi. [online]. [Accessed 29 April 2023]. Available from: https://www.acalbfi.com/uk/technologies/photonics/photonics-test-and-measurement/labspion
90. LabSpion UV/Light Measurement System - Viso Systems - Easy-to-use photometric lab equipment. [online]. [Accessed 29 April 2023]. Available from: https://www.visosystems.com/products/labspion-uv/
91. LI, Ang, YAO, Chunhui, XIA, Junfei, WANG, Huijie, CHENG, Qixiang, PENTY, Richard, FAINMAN, Yeshaiahu and PAN, Shilong. Advances in cost-effective integrated spectrometers. *Light: Science & Applications 2022 11:1* [online]. 7 June 2022. Vol. 11, no. 1, p. 1–18. [Accessed 29 April 2023]. DOI 10.1038/s41377-022-00853-1. Available from: https://www.nature.com/articles/s41377-022-00853-1
92. SAVAGE, Neil. Spectrometers. *Nat. Photonics* [online]. October 2009. Vol. 3, no. 10, p. 601–602. [Accessed 29 April 2023]. DOI 10.1038/nphoton.2009.185. Available from: http://www.nature.com/articles/nphoton.2009.185
93. What is a Spectrometer? UV, VIS and IR Spectrometer Explained. [online]. [Accessed 29 April 2023]. Available from: https://wavelength-oe.com/blog/what-is-a-spectrometer/
94. VISO SYSTEMS LIGHTSPION LIGSP001 USER MANUAL Pdf Download | ManualsLib. [online]. [Accessed 29 April 2023]. Available from: https://www.manualslib.com/manual/2048130/Viso-Systems-Lightspion-Ligsp001.html
95. FRICKMANN, Hagen, HAHN, Andreas, BERLEC, Stefan, ULRICH, Johannes, JANSSON, Moritz, SCHWARZ, Norbert Georg, WARNKE, Philipp and PODBIELSKI, Andreas. On the Etiological Relevance of Escherichia coli and Staphylococcus aureus in Superficial and Deep Infections – A Hypothesis-Forming, Retrospective Assessment. *European Journal of Microbiology & Immunology* [online]. 12 December 2019. Vol. 9, no. 4, p. 124. [Accessed 5 May 2023]. DOI 10.1556/1886.2019.00021. Available from: /pmc/articles/PMC6945993/