RBAV Revista Brasileira de Aplicações de Vácuo https://doi.org/10.17563/rbav.v40.1214

Assembly of UV-ozone reactor to combat coronavirus and other pathogenic microorganisms

Montagem de reator de UV-ozônio para combater coronavírus e outros microrganismos patogênicos

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Section Editor: Maria Lúcia P Silva

Received: 18 Sep 21 **Approved:** 20 Oct 21

ABSTRACT

The contamination on the surface of objects caused by fungi, microbes, bacteria, and viruses (and also coronavirus) can be solved using ultraviolet (UV) rays and/or ozone gas. For this reason, a UV-ozone reactor apparatus with low cost was mounted to test two different types of high-intensity discharge lamps: high-pressure mercury vapor lamp (HPMVL), and metal halide lamp (MHL). Both had nominal power of 400 watts and E-40 (base, screw) and were studied as possible methods of disinfection. Each lamp used the respective electromagnetic ballasts, and both were manufactured by Osram company. These lamps have two bulb types: the outer bulb, which was removed, and it is responsible for filtering the UV wavelengths; and the internal bulb (in which there is mercury, argon or metal halide confined at high pressure), that is the main source of UV rays. The complete apparatus was assembled using aluminum reflector (as a chamber), two microcomputer fans, and a wooden base covered by an aluminum foil. A rubber strip was placed at the edge of the reflector for better adhesion on the aluminum foil (for better confinement ozone gas). The ozone concentration inside the reactor was measured with a monitor, the temperatures were measured near lamps with a thermocouple, and a spectroradiometer with optical fiber was used to obtain the wavelengths. The results revealed to the elapsed time of 2 min a maximum peak of ozone concentration of 23 ppm for HPMVL, while the MHL presented 4.5 ppm only. The temperature obtained by HPMVL was lower with 31.5ºC, while the MHL presented 48ºC. The HPMVL presented higher number of wavelengths at the ranges UV-A, UV-B and UV-C, while the MHL presented only UV-A. For these reasons, the use of HPMVL is suggested as the most promissory to combat the coronavirus and other pathogenic microorganisms.

KEYWORDS: Ultraviolet, Ozone, Temperature, Wavelength, Coronavirus, Pathogenic microorganisms.

RESUMO

A contaminação das superfícies de objetos causada por fungos, micróbios, bactérias e vírus (e também coronavírus) pode ser resolvida por meio de raios ultravioletas (UV) e/ou gás ozônio. Por essa razão, um aparato de reator de UV-ozônio de baixo custo foi montado para testar dois tipos diferentes de lâmpadas de alta descarga de intensidade: lâmpada de vapor de mercúrio em alta pressão (LVMAP) e lâmpada de multivapor metálico (LMM). Ambas tinham potência nominal de 400 watts e E-40 (base, rosca) e foram estudadas como possíveis métodos de desinfecção. Cada lâmpada usou o respectivo reator eletromagnético, e ambas foram fabricadas pela empresa Osram. Essas lâmpadas possuem dois tipos de bulbo: o bulbo externo, que foi removido, responsável pela filtragem dos comprimentos de onda UV; e o bulbo interno, no qual há mercúrio, argônio ou halogênios metálicos confinados em alta pressão e a principal fonte de raios UV. O aparato completo foi montado utilizando refletor de alumínio (como câmara), dois ventiladores de microcomputador e base de madeira coberta por uma folha de alumínio. Na borda do refletor foi colocada uma tira de borracha para melhor adesão na folha de alumínio (para melhor confinamento do gás ozônio). A concentração de ozônio no interior do reator foi medida com um monitor, as temperaturas foram medidas com um termopar próximo às lâmpadas, e um espectrorradiômetro com fibra óptica foi utilizado para obter os comprimentos de onda. Os resultados revelaram para o tempo decorrido de 2 minutos pico máximo da concentração de ozônio de 23 ppm para a LVMAP, enquanto a LMM apresentou apenas 4,5 ppm. A temperatura obtida pela LVMAP foi menor, com 31,5ºC, enquanto a LMM apresentou 48ºC. A LVMAP apresentou maior quantidade de comprimentos de onda nas faixas UV-A, UV-B e UV-C, enquanto a LMM a apresentou apenas na UV-A. Por essas razões, sugere-se que o uso da LVMAP seja mais promissor para combater o coronavírus e outros microrganismos patogênicos.

PALAVRAS-CHAVE: Ultravioleta, Ozônio, Temperatura, Comprimento de onda, Coronavírus, Microrganismos patogênicos.

INTRODUCTION

Ultraviolet radiation

The solar spectrum is divided in three different bands[1-3]:

- Infrared band: causes feeling of heat, mainly on summer days (generates wavelengths above 700 nm);
- Visible band: promotes the human vision related to the complete colors of rainbow (from 400 to 700 nm);
- Ultraviolet band: used for some applications, as examples the skin tanning and decontamination with germicidal effect (from 100 to 400 nm).

The ultraviolet range involves different wavelengths and intensities responsible to inactive pathogenic microorganisms on water and air. For this reason, this technology has been used to the water treatment (consumption and swimming pools, for example), decreasing the amount of chlorine or other chemicals as decontaminants[4,5].

Inside the ultraviolet band, there are three ranges with different emission of wavelengths, known as[6]:

- UV-A: from 315 to 400 nm;
- UV-B: from 280 to 315 nm;
- UV-C: from 100 to 280 nm.

Figure 1 shows the electromagnetic spectrum divided at different ranges: ultraviolet (UV), visible and infrared (IR)[7].

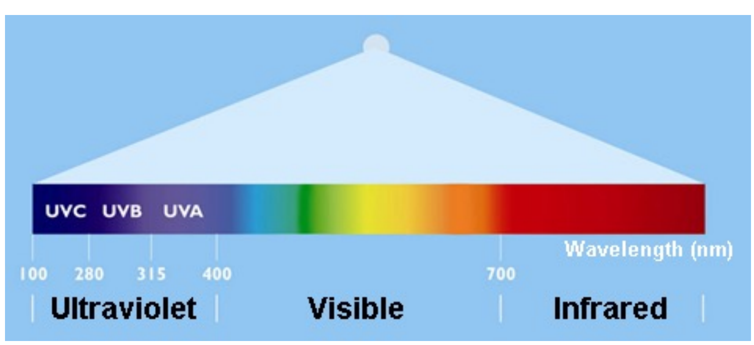

Figure 1: Electromagnetic spectrum showing the different ranges: ultraviolet, visible, and infrared radiation[7].

The UV radiation can be used by the three states of material: solids, liquids, and gases. Air disinfection was the first application of UV, followed by liquids and afterwards to prolong the organic food lifetime. Nowadays, this technology is also used as a photoactive process, like irradiation to the resin cure for teeth whitening8.

The application of UV rays used to the water treatment has been the most common, due to present many benefits, such as[9-11]:

- Very effective to combat most viruses, spores, and cysts;
- Does not influence the taste and smell of water;
- There is no by-product that can damage humans and aquatic life;
- UV is a physical process that does not generate chemical attack;
- Causes no skin irritation or red eyes;
- Presents no problems as allergies or asthma;
- It is independent of chlorine gas;
- Lower cost with maintenance or energy;
- It keeps the water clear;
- Better to the environment (compared with traditional methods);
- Acts instantly;
- Easy to operate;
- There is no overdose problem.

The use of the radiation with UV is not restricted only to air or water treatments. It can be also used to: surfaces on the hospital equipment; bacteriological researches; pharmaceutical institutions; natural and artificial food; cold storage rooms; industries such as dairies, breweries, and bakeries; drinking; air-conditioning systems; packing material; and other applications/areas[12].

In the case of pathogenic microorganisms, the radiation with UV rays inactivates the reproduction in a few minutes (or seconds).

Heraeus company of lamps reports that the UV radiation has better efficiency with wavelengths between 200 and 300 nm, and this UV range is absorbed by DNA, breaks up the structure and kills living cells of bacteria, fungi, viruses, and yeasts[13-15].

The Philips company reports that UV works using a photolytic effect to combat the pathogenic microorganisms, and this effect causes adjacent thymine bases to form a chemical bond, creating a dimmer. If the absorption of UV-A, UV-B and UV-C is sufficient, the deoxyribonucleic acid (DNA) cannot be replicated, causing bond splitting in a molecule and resulting in the creation of free radicals. Then, the pathogenic microorganism can be disfigured or destroyed living in solids or liquids states[16].

The Sylvania company reports that the UV radiation does not necessary kill or destroy the pathogenic microorganisms, but it causes damage to their reproductive capabilities[17]. The exposition of UV causes absorption by DNA and ribonucleic acid (RNA) within a cell nucleus, and this process interferes with the DNA template for cell division and replication[17]. The dose is the amount of energy applied to eliminate a pathogenic microorganism action, and it is dependent on three different parameters[18]:

a. UV flux (or UV power), measured in watt of UV radiation (W);

b. Irradiated area, generally measured in square meter or centimeter (m^2 or cm^2);

c. Exposure time, generally measured in second (s).

The (a) and (b) parameters can be combined to form UV irradiance (W/m^2), resting the exposure time (c), and the unit measure of UV dose is described by Watt-second per square meter (Ws/m^2)[18].

Joule is equal 1 watt per second. Then, it is very used in Joule per square meter (J/m^2) or then millijoule per square centimeter (mJ/cm^2)[18]. To combat different pathogenic microorganisms, it makes little difference if the UV dose has a powerful irradiance to low time, or a weaker irradiance for a higher duration time. For example, if a dose of 100 J/m^2 is applied, it can be represented by multiple forms, such as[18]:

- $100\ W/m^2 \times 1\ s = 100\ J/m^2$;
- $10\ W/m^2 \times 10\ s = 100\ J/m^2$;
- $2\ W/m^2 \times 50\ s = 100\ J/m^2$.

Ultraviolet and ozone

Commercial equipment that uses UV rays has one or more germicidal lamps with internal mercury gas under low pressure confined into the quartz envelope, known as cold cathode lamp[19-22].

The literature indicates that it is necessary radiation below than 243 nm (≈ 185 nm) to create dissociation of chemical bonds between oxygen molecules (from atmospheric air, for example), while the radiation below than 320 nm (≈ 254 nm) is necessary to dissociate the ozone gas molecule (O_3) releasing in the atmosphere free radicals of oxygen (O·) that participate of the chemical attack on surfaces[23-25].

Due to these lamps produce UV rays, they are very prejudicial to health. For this reason, it is necessary the confinement inside the appropriate environment and isolated from direct contact with humans (eyes and skin, especially)[26-28].

The chemical equations 1 to 4 are used to explain the formation and dissociation of ozone gas, based on the model denominated as Chapman's cycle (proposed by Sydney Chapman in 1930)[29-31]:

$$O_2 \text{ (atmospheric air)} + (\lambda < 243 \text{ nm}) \rightarrow 2\, O\cdot \text{ free radicals} \qquad \text{(1) ozone formation}$$

$$O\cdot + O_2 \rightarrow O_3 \text{ (ozone)} \qquad \text{(2) ozone formation}$$

$$O_3 + (240 < \lambda < 320 \text{ nm}) \rightarrow O_2 + O\cdot \text{ free radicals} \qquad \text{(3) ozone dissociation}$$

$$O\cdot + O3 \rightarrow 2\, O_2 \qquad \text{(4) ozone dissociation}$$

Free radicals of oxygen (O·) act as strong oxidant and they can be used together with UV rays producing significant results to combat pathogenic microorganisms[32-35], but this technique is not still very well clarified by literature. Then, it is necessary more knowledge to humans.

The ozone (O_3) dissociation promotes the oxygen molecules that make chemical bonds with nitrogen (N) from atmospheric air to form nitrogen oxide compounds (NO_x)[36]. Some researchers believe that this nitrogen oxide formed is the responsible to cause the typical smell attributed to the ozone produced[25,36]. The ozone produced in gas form is toxic, colorless, odorless, and its concentration can be measured by commercial equipment with acceptable levels to humans, identified as threshold limit value (TLV), measured in ppm unit[25].

For example, to produce UV rays (UV-C), the Atlantic Ultraviolet company reports that 254 nm is the maximum effective wavelength to germicidal effect and highly lethal to combat pathogenic microorganisms, such as: mold, viruses, bacteria, and protozoa[37]. It also reports that the humans should not be exposed to ozone concentration above 0.05 ppm[37]. In Fig. 2, this company shows the relative spectral distribution of germicidal lamp that produces UV-C with main peaks of 185 nm and 254 nm, most pronounced in comparison with all obtained inside the UV range[37].

The Atlantic Ultraviolet corporation also relates that the middle lifetime of UV-C lamp from 10,000 to 20,000 hours depends on the type and nominal power varying from 10 to 240 watts[37]. In its website, there are tables for different pathogenic microorganisms (bacteria, mold, protozoa, virus, and yeast) with the respective UV dose with wavelength of 254 nm, that is necessary to inhibit the colony formation more than 99%[38].

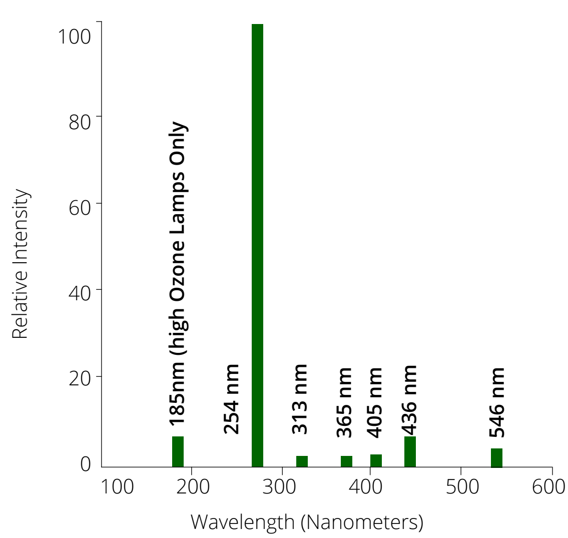

Figure 2: Relative spectral distribution of germicidal lamp produced by Atlantic Ultraviolet company[38].

The Philips company reports that the temperature reached on the bulb wall of germicidal lamps with low pressure of mercury has direct influence on the intensity peak of 254 nm, and, in this case, the better temperature found is approximately 40°C (Fig. 3), similar value as pointed out by Atlantic Ultraviolet Company with 42.2°C[38,39].

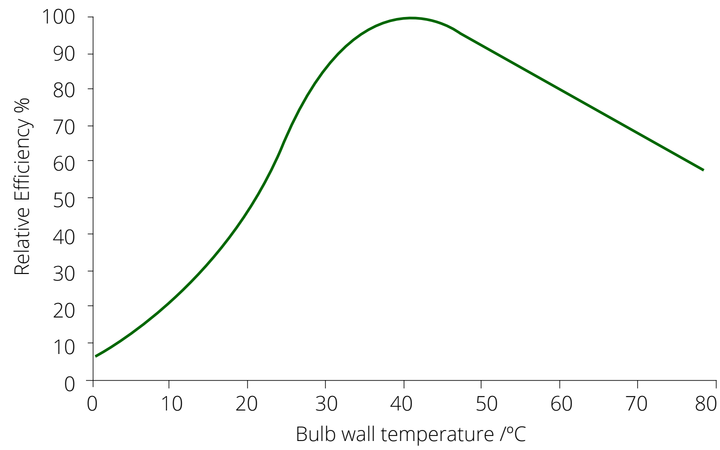

Figure 3: Relative efficiency vs. bulb wall temperature for low pressure mercury lamp reported by Philips Company[39].

Some wavelengths inside the UV range are responsible for different effects, for example[40]:

- Ozone production: from 180 to 220 nm;
- Bactericidal (germicidal action): from 220 to 300 nm;
- Erythema (skin reddening): from 280 to 320 nm;
- Black light: from 320 to 400 nm.

Madhavi et al. reports that the ozone destroys microorganisms by strong oxidation power of vital cellular and residual components. The ozone decomposes to nontoxic product. For this motive, it is an eco-friendly antimicrobial method for use in the jaggery production, for example[41].

A straight floor squeegee with UV radiation technology (Fig. 4) was developed to the disinfection of floors avoiding preventing the spread of the pathogenic microorganisms through shoes[42]. This equipment was developed by Physics Institute of Universidade de São Paulo (IFUSP), located in São Carlos, SP, Brazil, and it was donated for Hospital Santa Casa de Misericórdia of São Carlos[42].

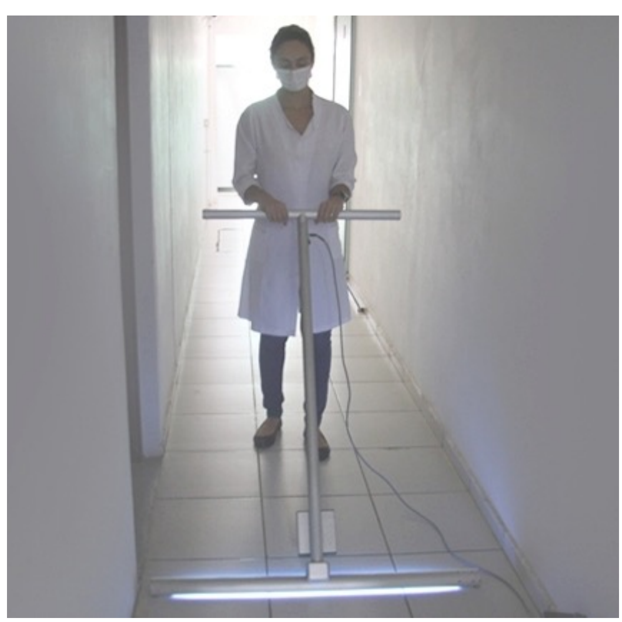

Figure 4: Straight floor squeegee with ultraviolet radiation technology developed by Physics Institute of Universidade de São Paulo (IFUSP)[42].

In 2019, a work published by Oliveira et al. (also of IFUSP) developed a reactor that uses UV radiation (UV-C) to decontamination of fresh broccolis[43]. This equipment uses six tubular mercury lamps with total power of 10 W for UV produced consuming about 40 W of electrical energy, and it presented microbial inactivation during tests carried out performed intervals of 25 minutes with *Escherichia coli* ATCC 25922, eliminating 99.99% on this of the nature food[42].

Ozone and coronavirus

The International Ozone Association (IOA) published at the website on March 17, 2020 the follow information[44]:

> The International Ozone Association (IOA) has received several inquiries regarding the effectiveness of ozone to disinfect water and surfaces for the coronavirus SARS-CoV-2 that causes the illness coronavirus Disease 2019 (COVID-19). While ozone is highly effective for the inactivation of many viruses, the IOA is not aware of any research and testing that has been conducted specifically on the SARS-CoV-2 coronavirus. To the best of our knowledge, Peer Reviewed Research has not yet been completed and therefore definitive conclusions cannot be made regarding ozone inactivation of SARS-CoV-2.

This published information is very important, because it is related to the fact that more researches and studies on this theme (ozone and coronavirus) are necessary and they can be very useful to humanity. "The IOA has also compiled the available research on ozone inactivation of various pathogens and viruses (not SARS-CoV-2) contained in the journal Ozone Science and Engineering (OS&E)"[44,45].

The Geosyntec Consultants company reports that ozone (O3) is very used as the most effective disinfectant and efficient method to destroy bacteria and viruses, including the virus that causes COVID-19[46]. The exposure with low dose of ozone concentration from 0.5 to 2.5 ppm used by over a few hours (or within seconds at higher concentrations in enclosures) is effective to inactivation of COVID-19.

Hernández et al. reports that the ozone gas has some properties in the biological field, and for this reason, it is suggested the use as possible role in SARS-CoV-2 therapy[47]. The cysteine (that is a natural amino acid) lots present on the viral surface of coronavirus can be easily damaged by ozone effect[47]. The cysteine has an important role for the maintenance and production of virus[47].

Martínez et al. cites that ozone therapy has a potential useful in combat SARS-CoV-2, revealing that the action of ozone has already been proven with infections caused by other virus types, leading to blockage of viral reproduction[48].

Since ozone is a gas, it can be used as a disinfection method of viral contaminated environments spreading easily for all common areas, where people walk, acting on the surfaces of equipment and other objects with much more efficiency than liquid sprays and aerosols, but the physical space to be treated must be free of people and animals, due to the relative toxicity of the gas[49].

But the efficiency of ozone gas is very dependent on time exposure and ozone concentration. For example, Berrington and Pedler tested the exposure time of ozone concentration from 4 to 7 hours with bacterial called as *Staphylococcus aureus* disposed as culture inside the petri dishes in hospital rooms at different distances between the ozone equipment and the samples, and the study revealed that the ozone concentration effect between 0.1 and 0.15 ppm is dependent on distance for both[50]. In close cultures (with distance of 15 centimeters), they verified a decrease of bacterial growth, while the more distant cultures (with distance of 3 meters) presented no significant differences in comparison with non-exposed by ozone[51,52].

Ultraviolet and coronavirus

In the literature, there is much information about coronavirus (SARS-CoV-2), including the Science Direct, that is offering open access to emerging research related to the viruses[53].

The UV has been used to inactivate the coronavirus with special attention of UV-C and UV-B. In this case, Singh and Dua reported that the UV-A rays promote low absorption by DNA and RNA of SARS-CoV, then it is much less effective than UV-C and UV-B rays[54].

As contradictory results, Leite et al. showed efficient results for coronavirus irradiated with UV-A produced by light-emitting diodes (LEDs) with 343 nm, target distance of 4 cm and dose of 2 mW/cm^2, but the irradiation was carried out with long time of exposition from 96 to 120 h[55].

In the official website of United States government, U.S. Food & Drug Administration (FDA) describes[56]:

> The effectiveness of UV-C lamps in inactivating the SARS-CoV-2 virus is unknown because there is limited published data about the wavelength, dose, and duration of UV-C radiation required to inactivate the SARS-CoV-2 virus. It is important to recognize that, generally, UV-C cannot inactivate a virus or bacterium if it is not directly exposed to UV-C. In other words, the virus or bacterium will not be inactivated if it is covered by dust or soil, embedded in porous surface or on the underside of a surface.

In another work conducted by also Dua et al., a colony of SARS-CoV was irradiated with the conditions: UV irradiation of 254 nm, heat treatment of 65°C or higher, and alkaline (pH > 12) or acidic (pH < 3). The results showed an efficient method produced by irradiation of UV[57]. But, in the literature, it is still very discussed if the irradiation of 254 nm is the most efficient wavelength to combat the coronavirus and other pathogenic microorganisms (such as: fungi, microbes, bacteria, and other viruses). For this reason, other wavelengths have been studied to the exposure of pathogenic microorganisms with specific wavelengths promoted by LEDs[58-60].

A document published by Office for Product Safety and Standards (OPSS) of England reports that the wavelength of 254 nm has been used for many decades, but in theory the peak effectiveness is related at 260–270 nm. This wavelength range is the most absorbed by RNA/DNA. Longer wavelengths have a reduced capability to inactivate viruses and kill bacteria, and this document also reveals that wavelengths above 320 nm is not effective for inactivation of SARS-CoV-2[61].

In general terms, Mackenzie relates that the International Ultraviolet Association (IUA) declares that it is generally accepted that a dose of 40 mJ/cm^2 of 254 nm irradiation kills at least 99.99% of "any pathogenic microorganism"[62].

A study carried out by Kitagawa et al. revealed that the UV-C with radiation of 222 nm is viable to combat SARS-CoV-2, suggesting that this wavelength could be used for infection prevention and control against the COVID-19[63].

Gerchman et al. related sensitivity of coronavirus for UV irradiated by LEDs instead UV lamps with different wavelengths, and the sensitivity is dependent on the increase of the wavelength irradiated: 267 nm ~ 279 nm > 286 nm > 297 nm[64].

MATERIALS AND METHODS

As a possible method of disinfection using radiation, in this work the use of two source lights that were modified to generate UV and ozone gas (or UV-ozone) was proposed to combat pathogenic microorganisms. Then, two different high-intensity discharge (HID) lamps were compared, both with 400 watts, base (screw) model E40 and manufactured by Osram company: high-pressure mercury vapor lamp (HPMVL), model HQL; and metal-halide lamp (MHL), model Powerstar HQI-T Daylight. These light sources are used as illumination of public streets, are available in Brazilian lighting market and present high lifetime of 24,000 for HPMVL and 12,000 hours for MHL[65,66]. They have two bulb types: the outer bulb, responsible to filter the UV rays (as barrier to humans); and the internal bulb (in which there are confined mercury and argon gas or metal halides, all in high pressure), that is the main source of UV rays[67]. Figure 5A shows the original HID lamp and Fig. 5B the ignition tube extracted and used as UV source during the experiment[67].

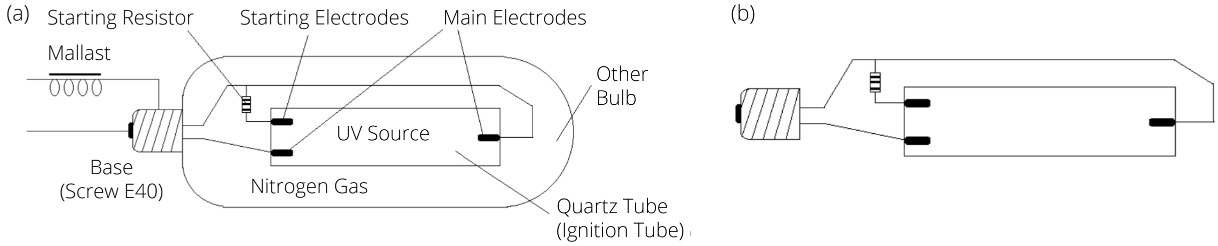

Figure 5: (a) Original high-intensity discharge lamp (HID), as manufactured by Osram Company, and (b) only the ignition tube used as ultraviolet (UV) source during the experiments.

The UV-ozone reactor with low cost was mounted using aluminum reflector (or reflector)–with diameter of ≈ 36 cm and height of ≈ 16 cm (with total volume of ≈ 8.6 liters)–, two fans used in microcomputers with geometry of 12 × 12 cm and straight base with wooden base covered by aluminum foil[68]. Figure 6 shows the complete arrangement.

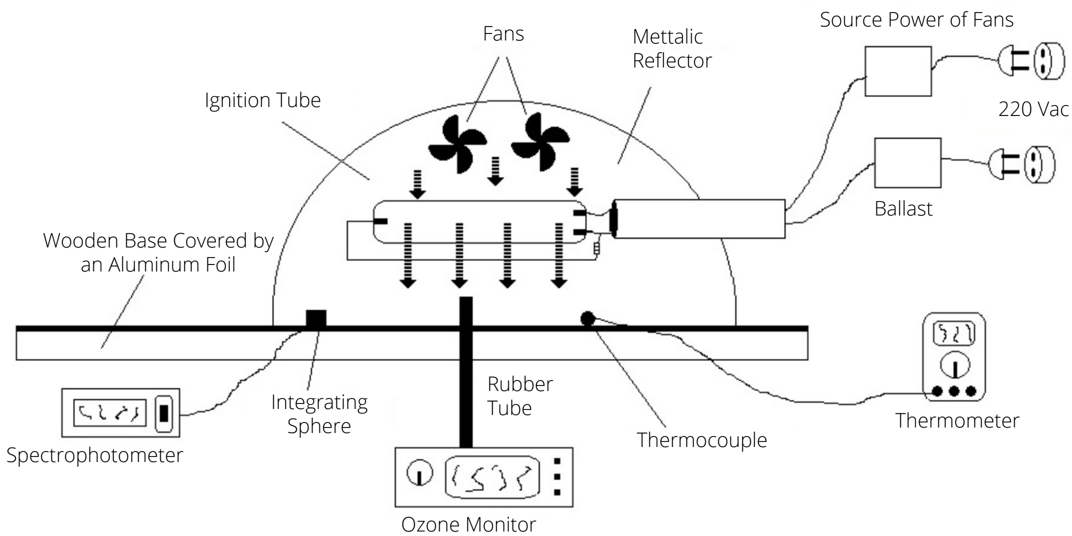

Figure 6: Complete arrangement of ultraviolet (UV)-ozone reactor apparatus tested during the experiments.

At the edge of round reflector, a rubber stripe was adapted, to better adhesion on the aluminium foil (providing the confinement of ozone gas) and on the wooden base. A hole was carried out to cross the rubber tube with length of ≈ 1 meter and diameter of ≈ 7 millimeter connected to the ozone monitor. Each modified lamp used the respective ballast and connected to the reflector. The function of ballast is to limit the electrical current from energy line and send it to electrodes located inside the ignition tube. When the electrodes are heated, they contribute to the evaporation of gas confined producing the UV rays[69].

An ozone monitor manufactured by 2B Technologies company, model IndevR, was used to obtain the ozone concentration by elapsed time[70,71]. The tube tip was positioned near the ignition tube (≈ 2 centimeters). The spectral energy distributions of the ignition tubes were obtained using a spectroradiometer manufactured by Luzchem company, model SPR-03 (measured from 235 to 700 nm), connected with integrating sphere[72,73]. The temperatures near the ignition tubes (≈ 2 centimeters) were measured using a multimeter manufactured by Minipa, model ET-2882, set as thermometer and connected with a thermocouple model K type (Cromel/Alumel at temperature range from -200 to 1,300ºC)[74].

RESULTS

Ozone concentration inside the reactor and temperature results were obtained at the same time from 0 (initial) to 5 minutes (final), with intervals of 20 seconds. It was verified that each ignition tube presented different behavior by elapsed time. In this case, the ozone production was more pronounced by HPMVL than by MHL. Figure 7 shows the ozone concentration vs. time for both modified HID lamps: HPMVL and MHL tested.

This experiment (Fig. 7) revealed a maximum peak of ≈ 23 ppm for HPMVL, while the MHL presented only ≈ 4.5 ppm, at the same time of 2 minutes analyzed. After 2 minutes, the HPMVL presented a decrease of the ozone concentration. The hypothesis for this behavior can be attributed by the oxygen amount from the atmospheric air available inside the UV-ozone reactor to be transformed in ozone gas. In this case, the rubber strip promoted to the UV-ozone reactor good results related by ozone gas confined inside the reflector.

An important characteristic and observed during the measurements of ozone concentration can be related to the rubber tube used to collect the ozone produced and sent to the ozone monitor. For example, in other experiment using the same arrangement, equipment and HPMVL, it was used a polytetrafluorethylene (PTFE) tube instead of the rubber tube, and this change increased the ozone concentration collected reaching to ≈ 65 ppm.

The hypothesis for this behavior can be explained by chemical interaction between the internal wall of rubber tube and the ozone collected decreasing the considerable concentration analyzed by monitor or then differences on the lengths of sizes for both tubes used.

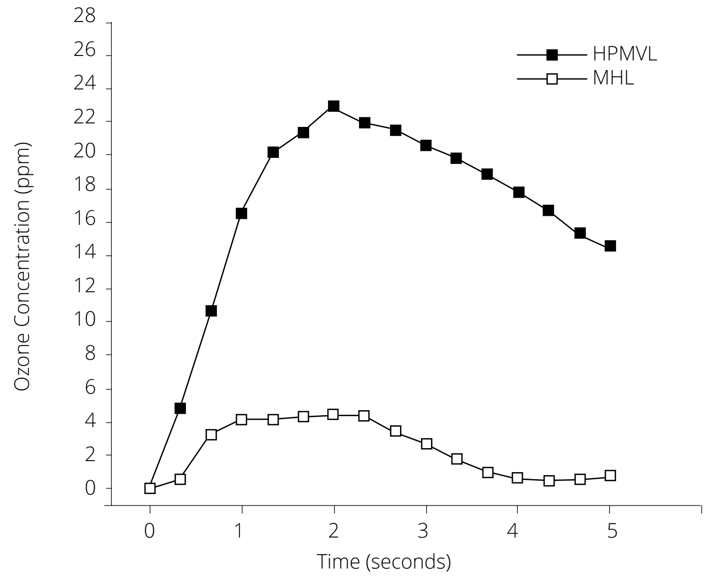

Figure 7: Ozone concentration vs. elapsed time for high-pressure mercury vapor lamp (HPMVL) and metal-halide lamp (MHL).

Another hypothesis for both values of ozone concentration found can be related to the usage time of little vacuum pump (located inside the ozone monitor), decreasing, consequently, the suction power of ozone gas collected.

Some process parameters can have direct influences on the ozone produced, such as:

• Geometry of the UV-ozone reactor: different formats (or geometries) of the UV-ozone reactor can produce different values of the ozone concentration collected[71];

• Materials used in the internal of UV-ozone reactor: to better performance of the ozone concentration collected, the internal walls of chamber can be used with different materials to avoid absorption or desorption of ozone gas, such as: chlorinated polyvinyl chloride (CPVC), ethylene propylene rubber (EPR), glass, Kel-F® (polychlorotrifluoroethylene–PCTFE), poly(ether-ether-ketone) (PEEK), polycarbonate, polyurethane (Millable), PTFE (Teflon), PVDF (Kynar), santoprene, silicone, titanium, vamac, and viton[75,76];

• Ventilation flux: different air flux promoted by fans to obtain homogeneous ozone gas produced also causes different ozone concentration values. For this reason, good sealing of the atmospheric air confined inside the reactor is necessary, avoiding the leakage of the ozone gas produced;

• Power lamp: it has direct influence on the ozone concentration produced for the HPMVLs[30].

• Hudson et al. developed an ozone generator apparatus to decontaminate rooms in health care facilities, hotels, and other buildings. They used eight corona (corona effect, another method for ozone production) as main UV source and obtained ozone concentration with peaks of 20–25 ppm by 15 minutes with high relative humidity to > 90% inactivation of viruses[77].

Triardianto and Bintoro produced ozone gas from oxygen of atmospheric air with commercial equipment to treat bananas (fruit) with the objective of reducing ethylene, and they obtained ozone concentration at room temperature of 0.3 (with 10 minutes), 0.4 (with 15 minutes) and 0.5 ppm (with 20 minutes)[78].

Robert et al. reported that the ozone can be also created by natural method (by lightning on rainy days) by interaction of oxygen and UV and that the most practical ozone concentration used by artificial method is related from 10 to 20 ppm, and, in the case, this range produced by corona effect is necessary high voltage (KV), but with low electrical current required[79].

The elevation of temperature was more pronounced by MHL than that HPMVL (Fig. 8). In this case, the temperature measured for both HID modified lamps increased by elapsed time reaching ≈ 48°C for HPMVL and ≈ 105.5°C for MHL, both measured by 7 minutes. These temperature values found were very different from the ones reported by Philips and Atlantic Ultraviolet companies for germicidal lamps with low pressure of mercury (as mentioned previously)[38,39]. In this case, these results of temperatures (Fig. 8) revealed that HID lamps heat much more than that low-pressure mercury vapor lamps with germicidal effect.

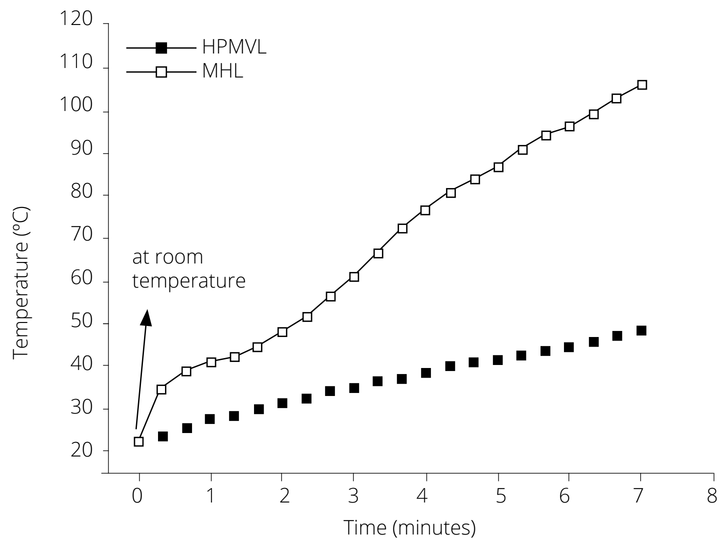

Figure 8: Temperature vs. elapsed time for high-pressure mercury vapor lamp (HPMVL) and metal-halide lamp (MHL).

The increase of temperature presents a limit to obtain better ozone production for both HID modified lamps, but the continued increase of temperature also decrease the ozone concentration production. For this reason, the HPMVL presented a temperature value of 31.5°C, while the MHL presented value of 48°C at the same elapsed time for 2 minutes.

A possible problem with the high temperature of the HID lamp modified by elapsed time is that high temperature values can interfere directly in the combat of pathogenic microorganisms sensitive to sudden heat changes irradiated by lamp. Thus, it is not possible to perceive the real action of effectiveness caused by UV rays emitted on pathogenic microorganisms. For this reason, the HPMVL lamp showed better result, presenting less interference caused by the increase of the temperature.

The ignition tube of HPMVL presented most varied wavelengths than the one of MHL, both analyzed by spectroradiometer using integrating sphere near lamps.

In the HPMVL, the complete UV radiation range with UV-A, UV-B and UV-C bands and a visible region with some wavelengths were noticed. In the case of UV-C, the wavelength peak of 254 nm was pronounced, and during the experiment the typical ozone smell was much more evident. Table 1 shows the different wavelengths obtained for the HPMVL[80].

In the MHL analyzed by the spectrophotometer, only the UV-A presenting a peak of 365 nm (it was verified that it was the most intense for HPMVL) and some wavelengths at the visible range were observed. Table 2 shows the different wavelengths obtained for the MHL.

Due to the HPMVL to present large number of different wavelengths (UV-A, UV-B and UV-C) inside the UV region, this lamp can present varied applications not only to the field of the irradiation for pathogenic microorganisms.

For a better understand of some results found in the literature, Table 3 summarized was mounted with results based on the references describing authors, UV source light (wavelength irradiated), dose used, time exposure, distance (between the UV source and colony) and pathogenic microorganisms irradiated.

In comparison of performance presented by HPMVL with the germicidal lamp showed by Fig. 2 and Table 3, the HPMVL presented a larger number of wavelengths inside the UV region. This fact shows that it can be promissory to inactivate pathogenic microorganisms and, for this reason, this modified lamp needs to be better investigated.

An important point of view related to the HPMVL modified is that it presented broad UV range, that is a characteristic found in only this source light type, and this characteristic is very different, when it is compared with other source lights, as cited by references of this work (Table 3). Another observation is related to the ozone produced by this source light modified, that can be very considerable to the combat of pathogenic microorganisms. Then, the interaction using both techniques UV and ozone can bring many benefits to humans.

Table 1: Ultraviolet (UV) and visible regions with respective wavelength peaks obtained by high-pressure mercury vapor lamp (HPMVL).

Lamp type	UV and visible region	Wavelengths peaks (nm)
HPMVL	UV-C	254
		265
		268
		274
		278
	UV-B	288
		295
		300
		312
	UV-A	365
		389
		400
	Visible	436
		490
		550
		577
		689

Table 2: Ultraviolet (UV) and visible regions with respective wavelength peaks obtained by metal-halide lamp (MHL).

Lamp type	UV and visible region	Wavelengths peaks (nm)
MHL	UV-A	365
	Visible	407
		436
		494
		536
		546
		579

In the study carried out by Hayashi et al., it was revealed that the 265 nm has high potential as new wavelength used to disinfection method. They irradiated *E. coli*, *S. aureus*, and *Bacillus cereus* during 10 minutes with dose of 9.2 mJ/cm^2, revealing the inactivation[93].

The work reported by Ortiz-Mateos showed that the 365 nm wavelength contributes to the destabilization of enzymes like RNase A (very contaminant in laboratories) with irreversible inactivation. She used it in combination with 278 nm, showing effective radiation for fungal inactivation[94].

The FDA informs that the UV-C is effective, if the virus is directly exposed to radiation and the inactivation on surface is not efficient when the virus is blocked by dust or other contaminants and some UV-C lamps available in the marketing of lighting have low dose. Then, it is necessary longer exposure of time providing effective inactivation of a bacteria or virus[95]. The FDA also says that the radiation UV-B is more dangerous than that UV-C to humans, because it can penetrate deeper into the skin and eye with risk factor in developing skin cancer and cataracts, and the UV-A is less dangerous, but it can promote these same diseases[91].

Table 3: Summarized results found in the literature for different authors: UV source light used, wavelength irradiated, dose, time exposure, distance (between UV and colony) and pathogenic microorganisms irradiated (with % inactivation).

Authors	UV source light	Wavelength (nm)	Dose (mJ/cm^2)	Time exposure (s)	Distance (cm)	Pathogenic microorganism (Inactivation) (%)
Shimoda et al.[81]	Deep UV LED	265	5.1	24	*	SARS-CoV-2 (- %)
	Cold cathode lamp	254	5.0	14		
	Deep UV LED	280	10.0	60		
Minamikawa et al.[82]	Deep UV LED	265	1.8	5, 15 and 30	*	SARS-CoV-2 (99.9%)
		280	3.0			
		300	23			
Ma et al.[83]	Low-pressure mercury vapor lamp	254	6	*	*	SARS-CoV-2 (- %)
	LEDs	270				
		282				
Nichia Corporation (in colaboration with Masako Nomaguchi and Takaaki Koma)[84]	LED	280	51	30	*	SARS-CoV-2 (99.99%)
				10	*	SARS-CoV-2 (98.42%)
				5	*	SARS-CoV-2 (93.28%)
Nichia Corporation[85,86]	LED (model NCSU334B)	280	8.5	5	5	SARS-CoV-2 (93.28%)
			17	10		SARS-CoV-2 (98.42%)
			51	30		SARS-CoV-2 (99.99%)
Asahi Kasei Corporation[87]	100 LEDs (in array of 10 × 10 with total 440 μW/cm²)	226	*	6	*	SARS-CoV-2 (99.9%)
Signify Company (in collaboration with Dr. Anthony Griffiths)[88]	Lamp	UV-C (wavelength range not revealed)	5	6	*	SARS-CoV-2 (99%)
			22	25	*	SARS-CoV-2 (99.9999%)
Hadas Mamae et al.[89]	LED	285	*	>30	*	OC43 (HCoV-OC43) (- %)
Heilingloh et al.[91]	Lamps[92]	254	1,048	540	3	SARS-CoV-2 (- %)
		365	292	900		

UV: ultraviolet; LED: light-emitting diode; *not revealed.

The FDA cites some different lamps that produce UV-C rays, such as:

- Low-pressure mercury lamp: the most common type of UV-C source with emission at 254 nm;
- Excimer lamp or Far-UV-C lamp: presents a peak of 222 nm;
- Pulsed xenon lamp: emits a short pulse of broad spectrum (UV, visible and infrared) and uses a filter to UV-C radiation. It has been very used to disinfection of the surfaces in hospitals as operating rooms or other spaces;
- LED: produces very narrow UV with wavelengths at 265, 273 and 280 nm, among others. However, the use of LEDs is carried out in small surface areas and is less effective for germicidal applications.

The UV-B range with specific wavelength of 312 nm and UV-A, both produced by fluorescent lamps or UV LEDs, have been used as treatment method for skin diseases as: atopic eczema, pruritus, lichen planus, polymorphous light eruption, early cutaneous T-cell lymphoma dermographism, psoriasis, parapsoriasis, eczemas, and vitiligo[96-99].

The phototherapy is a common process to the vitiligo treatment. In this case, the UV-B has been used from 304 to 312 nm, because this range can induce the repigmentation in a short time. The results showed that the radiation is dependent on lesions location presenting better results obtained on the face and trunk, and the extremities generally showed low influences, as observed in the experiments carried by Dong et al.[100].

The website of Ledrise informs that the UV has been used during some years to decontamination of hospitals rooms or on furniture, objects, clothing, or instruments killing pathogenic microorganisms[101]. To better efficiency of decontamination in hospitals, the UVD company developed large autonomous robot (Fig. 9) that irradiate UV-C, eliminating 99.99% of pathogenic microorganisms with exposure time of 10 minutes[102].

Figure 9: Autonomous robots contribute to kill pathogenic microorganisms in hospitals rooms using UV-C radiation[99].

The Ledrise reports that the UV-C produced by this robot can be substituted by UV-A produced by LEDs, but it is necessary the radiation functioning by 8 hours, daily to kill up to 99% of viruses and bacteria (with irradiance limited to 10 W/m^2 at 2 meters from the floor)[101].

The Philips company developed a trolley that has similar function as developed by UVD company to disinfection of rooms, classrooms, reception areas, guest rooms, chairs, tables, surfaces of equipment, laboratories, interior surfaces such as seats and handhelds for buses and trains[103]. This equipment uses UV-C (ozone less) with 254 nm produced by four tubular lamps each with 30 watts and coverage area of up to 36 m^2 of circular area or 20 m^2 of square area to combat of SARS-CoV-2.

The Biolambda company developed a luminary that uses UV-C lamps with peak of 254 nm to be used in ambient. For this equipment, it is necessary the operation time/area of disinfection[104]: 30 minutes/12,5 m^2, 60 minutes/30 m^2, 90 minutes/40 m^2 and 120 minutes/45 m^2.

To confirm if the disinfection system is achieving the UV-C exposure (254 nm), the Atlantic Ultraviolet corporation developed a dosimeter card that has colorimetric indicator that changes color to measure three energy levels: 25, 50, and 100 mJ/cm^2, when it is irradiated[105]. This card can be used in universities, hospitals, hotels, restaurants, gyms, homes, stores, airports, trains, buses, and other areas.

CONCLUSION

The contamination on the surface of objects caused by fungi, microbes, bacteria, and viruses (and also coronavirus) can be solved using UV rays and/or ozone gas, as showed by references. For this reason, a UV-ozone reactor apparatus was mounted testing two different types of HID lamps modified: HPMVL and MHL, both with nominal power of 400 watts and E-40 (base, screw), that were studied as possible methods of disinfection. The outer bulb was removed of each lamp, resting only the internal bulbs, that were used as UV sources. The assembly of UV-ozone reactor used aluminum reflector (as chamber and isolation), two microcomputer fans and a wooden base covered by an aluminum foil. A rubber strip was placed at the edge of the reflector for better adhesion on the aluminum foil (to confinement of ozone gas). Ozone gas, temperature, and spectral distribution of lamps were measured.

The results revealed to the elapsed time of 2 minutes a maximum peak of ozone concentration for both lamps. The ozone concentration of HPMVL reached 23 ppm, while the MHL reached lower efficiency, only 4.5 ppm. The temperature obtained by HPMVL was lower with 31.5ºC, while the MHL presented 48ºC, showing that the HPMVL can be used to irradiation of the pathogenic microorganisms less sensible to temperature effect with low exposition time and high ozone concentration. The HPMVL presented high peaks of wavelengths at the bands UV-A (365, 389 and 400 nm), UV-B (288, 295, 300 and 312 nm) and UV-C (254, 264, 268, 274 and 278 nm), while the MHL presented only UV-A (peak of 365 nm).

In the literature, several benefits to human have been found promoted by UV wavelengths range for diversified applications. Then, for these reasons, it is suggested the use of HPMVL is the most promissory, showing great potential to be applied not only to combat the coronavirus and other pathogenic microorganisms, but also other applications not reported in this work, using UV and ozone gas together to increase and improve the quality of human life.

The World Health Organization (WHO) alerts that the SARS-CoV-2 can also spread in poorly ventilated and/or crowded indoor settings, where people tend to spend longer periods of time. The virus remains suspended in the air or travel farther than 1 meter. People may also become infected by touching surfaces that have been contaminated by the virus and auto-infect when touching their eyes, nose, or mouth without cleaning the hands.

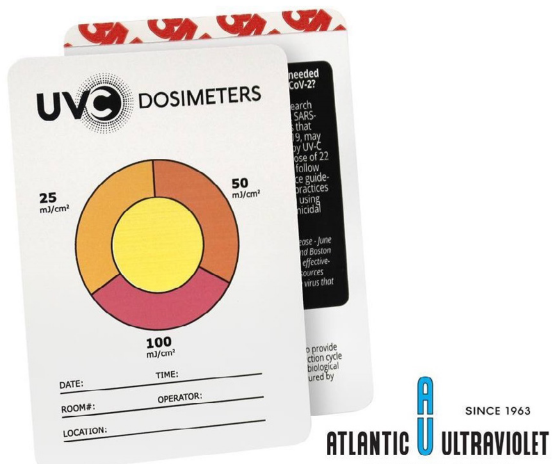

Figure 10: Ultraviolet (UV)-C dosimeter card developed by Atlantic Ultraviolet company[106].

ACKNOWLEDGMENTS

Emerson Roberto Santos, main author of this work, would like to thank and dedicate the article for his father, PhD Antonio Padua Santos (*in memoriam*), who died by Covid-19, all other people that died and all people that worked or that are working at the front line (doctors and nurses, mainly) with this terrible disease.

The authors thank the Instituto de Astronomia, Geofísica e Ciências Atmosféricas of Universidade de São Paulo, by the ozone monitor and spectroradiometer.

The authors also thank the Escola Politécnica of Universidade de São Paulo, Engenharia Metalúrgica e de Materiais and Instituto de Energia e Ambiente of Universidade de São Paulo, for measurements, equipment and facilities.

AUTHOR'S CONTRIBUTION

Conceptualization, Data curation, Formal analysis, Methodology, Validation, Visualization, Writing – review & editing: Junior ECB; **Conceptualization, Data curation, Formal analysis, Methodology, Validation, Visualization, Writing – review & editing:** Santos ER; **Data curation, Formal analysis, Writing – original draft:** Vendrami JA; **Funding acquisition, Software, Resources, Supervision:** Hui WS; **Validation, Visualization, Writing – review & editing:** Duarte AC.

FUNDING

Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES)
http://doi.org/10.13039/501100002322
PNPD Project N° 02998/09-2.

DATA AVAILABILITY STATEMENT

Data are available in a data repository. Vendrami JA. Filmes de PEDOT:PSS irradiados com UV-Ozônio em tempos distintos [undergraduate thesis]. São Paulo: Faculdade de Tecnologia da Zona Leste; 2015.

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