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The Potential of Blue Light as a Disinfection Strategy in Indoor Environments

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ABSTRACT

Microbially contaminated objects used in everyday life have been shown to impact human health by harboring infections through direct or indirect contact. For this reason, the development of alternative methods for bacterial elimination that do not lead to resistant microorganisms, large quantities of residues, or human cytotoxicity is warranted. Due to their proven bactericidal power, the use of electromagnetic waves lower than ultraviolet-C radiation would constitute a possible alternative. The main aim of this research was to determine the effect of 462 nm radiation emitted by light-emitting diodes (LEDs) on the most frequent bacteria contaminating everyday objects and surfaces in residential and hospital environments. The rationale behind the selection of this specific frequency within the blue light spectrum, in contrast to previous research exploring the application of higher frequencies, was its safety for individuals' eyes and skin. The findings suggest that the use of low-frequency blue light can be effective in destroying environmental microorganisms stemming from the skin microbiome and mucous membranes, and even fecal bacteria, present in the surfaces of everyday objects such as *inter alia,* mobile phones, remote controls, credit cards, and of which some present high antibiotic resistance.

INTRODUCTION

LED Phototherapy Features

Currently, 80%-90% of the time is spent indoors, especially in homes (Klepeis et al. 2001), in developed countries, as the presence at home ranges from 60% to 90% of the day and 30% of the time is spent sleeping (Borsboom et al. 2016, Hormigos et al. 2018).

Homes, which are the indoor places with the highest exposure, contain the air that is breathed in the majority of the time. According to Wargocki (2016), the indoor atmosphere in a home should promote rest and recovery. However, since poor indoor air quality (IAQ) has detrimental impacts on health, this goal is prevented.

Buildings have become more airtight since the energy crisis of the 1970s, which has caused the emergence of illnesses connected to indoor air quality, such as sick building syndrome (SBS) (Cao et al. 2014). Moreover, studies have shown a connection between ventilation-related air movement in buildings and the spread of infectious diseases (Sanglier et al. 020). Low IAQ also reduces productivity,

which has a considerable negative impact on the economy (Sherman 2008). As a result, since the turn of the century, efforts have been concentrated on striking a balance between energy efficiency and air distribution characteristics, IAQ, and thermal comfort (Chung & Hsu 2001). The advantages of indoor air exchange have been demonstrated in this context. However, it is unclear how much ventilation affects the transmission of infectious diseases (Cao et al. 2014). As airflow rates have no quantifiable impact on health, ventilation rates stipulated in regulations are often established following comfort standards (perceived circumstances) (Wargocki 2015).

Nonetheless, following some techniques can result in a healthy indoor environment by implementing the necessary IAQ improvement strategies, which also include increasing the supply of fresh air, reducing pollution from emission sources, air cleaning, and improving ventilation efficiency (Van Tran et al. 2020), the latter is covered by this study. The distribution of fresh air throughout a space is shown by the ventilation efficiency, providing a qualitative assessment of the effectiveness of the ventilation system. Moreover, it can be utilized as an IAQ indicator if the air supply is of good quality (Chen et al. 2020). The goal of the ventilation system, such as heat removal, contamination removal, cross-infection prevention, or supply of fresh air to the breathing zone, should be taken into consideration when evaluating ventilation efficiency (Zhou et al. 2021).

The breathing zone is defined as the volume of air contained within a hemisphere with a radius of 0.3 m that extends in front of a person's face per ISO 15202-1 (Cao et al. 2014). The midpoint of the imaginary line connecting the ears serves as the hemisphere's center, and the larynx, the top of the head, and that line's intersection create the hemisphere's base. Better or worse, IAQ will be perceived in the breathing zone depending on the flow pattern, and, as a result, depending on the distribution of the age of the air inside a space. As a result of the amount of time spent inside the breathing zone, which results in high exposure, it is vital to evaluate the air quality in the building, particularly in bedrooms (Hormigos et al. 2019).

The use of lamps for therapeutic purposes, i.e., phototherapy and specifically for pathogen elimination, has been known for more than 80 years. The earliest research pointing to the beneficial properties of Ultraviolet (UV) light lamps dates back to 1937 when UV light lamps were used to irradiate classrooms and other school areas to disinfect and sanitize the air to eradicate and prevent the spread of pathogens such as measles, mumps, and chickenpox. Said study provided conclusive findings on the virucidal power of UV light as an effective light therapy (Wells et al.1941), although, at the time, no information was available on its carcinogenic effect in humans.

Since its inception, phototherapy has evolved considerably. The increasing number of multidrug-resistant bacterial strains, together with the difficulty of obtaining new antibiotics, have rendered novel microbial control techniques essential. One of the strategies that has since demonstrated potential for pathogen destruction is the use of light-emitting diode (LED) lamps or light systems, which, in addition to being low cost, have a low environmental impact [16] and do not pose a health hazard for humans and animals (Angarano et al. 2020, Gillespie et al. 2017).

LEDs emit light because of the flow of electric current through two semiconductors, whose material determines the light emission wavelength (Prasad et al. 2019). The bactericidal effect of LEDs is due to the presence of endogenous photosensitizers (EPs), such as porphyrin-containing cytochromes, ubiquinones, or flavin-containing enzymes (Kim et al. 2021), which are commonly found on the inner membrane of the bacterial cell. The excitation of EPs, i.e., the release and transfer of an electron into an oxygen molecule for EPs stabilization, takes place when these are irradiated by a certain wavelength of light. This change of charge at the molecular level is responsible for the appearance of Reactive Oxygen Species (ROS) such as superoxide anion, hydroxyl radicals, and hydrogen peroxide, which damage bacterial structural components such as DNA, RNA, lipids, and proteins (Kim & Kang 2021, Angarano et al. 2020).

Exposing different foods to 405 nm LED light has been previously shown to reduce their pathogenic bacterial load. Moreover, Li et al. (2018) found a considerable decrease of *Salmonella* spp. and *Listeria monocytogenes* present in fresh ready-to-eat salmon, and Kim et al. (2017) obtained analogous results with *Salmonella* spp. in fresh fruit. In like manner, the load of *Escherichia coli 0157:H7* on the surface of dried fruits was found to lessen after LED light exposure (Lacombe et al. 2016). Despite the lower antibacterial efficacy of LED light compared to other methods, e.g., high-temperature heating or UV or ionizing radiation, low-energy photons avoid material degradation or tissue damage while also not compromising food quality.

The need to control microbial contamination in hospital environments gave rise to research assessing the effect of LED light on bacteria frequently found in those settings, such as methicillin-resistant *Staphylococcus aureus*, and obtaining antibacterial levels similar to that of laser light (Masson-Meyers et al. 2015). Additionally, the technology has been considered for potential medical use, entailing wound decontamination (McDonald et al. 2011) and sterilization of tissue matrices such as collagen (Smith et al. 2009).

Most existing studies have based their research on lamps with peak emission at 405 nm, whose oxidizing power can induce skin and retina damage. Thus, the present research adopted a wavelength of 462 nm, which does not present the oxidizing power of wavelengths closer to Ultraviolet-A (UVA) and hence does not incur any damage at high intensity (Wang et al. 2007, ICNIRP 2013, Roehlecke et al. 2013, Lawrence et al. 2018).

One of the primary environments affecting quality of life has been identified as the residential indoor environment (QoL). The relationship between home indoor environment and quality of life is complex. Nevertheless, studies often focus on a small number of residential environmental elements and their impact on QoL (Rajagopalan & Goodman 2021). Consequently, based on the results of the home environment and health survey, the purpose of this study is to determine the correlations between the overall residential interior environment and quality of life, as well as how such associations can be altered by various confounding factors. The findings indicated that participants' top cited home environmental concerns were thermal issues. Even after adjusting for age, sex, education, smoking, drinking, number of residents per household, and other factors, there was a statistically significant correlation between the increase in physical/mental health conditions and the decrease in reported frequency of residential environmental problems, including thermal, indoor air quality, lighting, acoustics, hygiene, safe and security environment (Vardoulakis et al. 2020). After controlling for confounding variables, it was discovered that coupled home environmental issues such as temperature and humidity, thermal environment and air quality/noise/mold, air quality and noise, and fall and wet had substantial combined effects on physical/mental health. This study tried to unravel the intricate connections between indoor living conditions and quality of life, which would serve as a foundation for developing QoL-improving measures (Marć et al. 2019).

The research of Haraldstad et al. (2019) in the fields of biomedicine, social science, clinical medicine, and health services must now take quality of life (QoL) into account as a significant health outcome metric. The World Health Organization (WHO) recognized environmental factors as the primary drivers of quality of life (QoL) (Skevington et al. 2004). Without a doubt, the residential indoor environment is acknowledged as one of the most significant environmental factors. People spend roughly 66% of their time in residential structures on average (Zhang et al. 2021). Because of restrictions on outside activities, this percentage is especially greater during the COVID-19 epidemic. This statistic alone demonstrates the necessity of researching how residential indoor environments affect quality of life.

Over the past ten years, there has been a rapid advance in the recognition and comprehension of the impact the home indoor environment has on health. Numerous studies have examined the relationship between indoor environmental factors (primarily indoor air pollutants, noise, lighting, and comfort factors) and adverse health outcomes, including mortality (Ma et al. 2020), respiratory issues (Raju et al. 2020), allergy (Svendsen et al. 2018), sleep disturbance (Ricketts et al. 2022), lung cancer (Caracci et al. 2021), mental health (Zhang et al. 2023) and cardiovascular disease (Xia et al. 2021), has been developed. QoL might thus be thought of as "the missing measurement in health." The WHO defines QoL (1998) as "individuals' impressions of their situation in life in relation to their objectives, aspirations, standards, and worries and in the context of the culture and value systems in which they live."

Also, the increase in life expectancy over the previous century has caused a change away from considering health in terms of survival (mortality), leading to an emphasis on being disease-free and, more recently, an emphasis on quality of life (QoL) (McDowell 2006). That underlines even more how crucial it is to incorporate QoL into environmental health research.

Although the home indoor environment has been frequently discussed for its major impact on QoL, quantifying the relationship between them remains a significant problem. Some examples could clarify this: Environmental exposure that occurs on multiple occasions and simultaneously is common in residential indoor environments. For instance, data from numerous international surveys revealed that multiple risk factors, including noise, indoor air pollution, thermal issues, moisture and mildew, water quality, and the lack of daylight, commonly affected the home indoor environment (Ormandy 2009). The body of research on the relationships between indoor air quality, the temperature environment, sound, and light is also expanding. Interactions might change the home's occupants' ability to live in a comfortable and healthy atmosphere (ASHRAE 2011).

Also, to advance the research, it is proposed to take into account the convective effects caused by people's presence and the way they breathe when evaluating the airflow patterns inside an enclosure (Moreno-Rangel et al. 2018).

Bacterial Pathogenicity

Hospital-acquired infections brought about by direct or indirect contact with everyday surfaces and objects have been extensively studied (Suleyman et al. 2018). The survival of common bacteria indoors on the individual's skin and mucous membranes, as well as microorganisms in bioaerosols from plants, the air, and the soil, facilitates the

acquisition of infections, especially in immunocompromised and hospitalized individuals (Kumar & Ison, 2019, Kurizky et al. 2020). Patients undergoing oncological or immunosuppressive treatments are also more susceptible to community-acquired pathogens, making microbial elimination or reduction in their usual environment advisable.

The genus *Pseudomonas aeruginosa* and *Acinetobacter* spp. stand out among the environmental microorganisms most frequently linked to colonization and indirect disease transmission through contact with contaminated objects, e.g., mobile phones, computer keyboards, and doorknobs (Isaacs et al. 1998, Borer et al. 2005, Malta et al. 2020). With a high survival rate on inanimate surfaces, these can form biofilms with high tolerance to disinfecting agents and, therefore, promote pathogen transmission by hands and medical equipment, in turn reaching at-risk individuals (Yang et al. 2020, Angarano et al. 2020). The clinical relevance of biofilm formation lies in its multiple drug resistance in hospital settings, as well as its potent pathogenicity in nosocomial infections (Olu-Taiwo et al. 2020, Malta et al. 2020). LED illumination was shown to increase the sensitivity of *Pseudomonas aeruginosa* biofilms to antibacterial agents, such as chlorhexidine and benzalkonium chloride, thus facilitating their inactivation and elimination (Yang et al. 2020).

By the same token, common human gut colonizing bacteria such as *Escherichia coli* and *Enterococcus*, or those present on mucous membranes, e.g., *Staphylococcus aureus* and *Streptococcus pyogenes,* persist in their environment for long periods, allowing it to spread through direct or indirect contact and potentially originate infectious outbreaks (Dancer 2008, Yoon et al. 2009, Kramer & Assadian 2014, Kanamori et al. 2016). Their high antibiotic resistance rates pose treatment challenges by narrowing the therapeutic options available (Lakhundi & Zhang 2018).

The overarching aim of this research was to determine whether radiation far removed from UVA, specifically blue light at a wavelength of 462 nm, displays bactericidal power for personal and everyday objects. On the assumption that the bactericidal power is confirmed, the authors would proceed to test the reduction or elimination of the microbial load on small surfaces, objects, or devices for everyday and clinical use.

MATERIALS AND METHODS

462 nm blue LED lamps were used and placed at a distance of 1.5 cm from the sample. When switched on, their temperature was 28°C, while the ambient temperature of the laboratory neared 26°C. The bacterial suspensions were placed on Parafilm under the lamps.

The microorganisms employed in the research were retrieved from the culture collection of the Microbiology Section of the Faculty of Pharmacy at CEU San Pablo University. The Gram-positive bacteria were the genus *Staphylococcus aureus*, *Enterococcus faecalis*, and *Streptococcus pyogenes,* while the Gram-negative bacteria were *Escherichia coli*, *Pseudomonas aeruginosa* and *Acinetobacter baumannii.*

All microorganisms were stored at 20°C in a freezer in the microbiology laboratory. The *Streptococcus pyogenes* samples were cultured in blood-agar medium, the *Enterococcus faecalis* samples in Slanetz-Bartley agar, the *Staphylococcus aureus* samples in Baird-Parker agar, and the *Escherichia coli, Pseudomonas aeruginosa*, and *Acinetobacter baumannii* samples in nutrient-agar media. All media were provided by OXOID. The experimental light exposure was carried out in a laminar flow cabinet. Drops of 200 µl volume containing bacterial suspensions in saline solution were placed on Parafilm inside the cabinet, under the LED light beam at 1.5 cm from the emitting source. The LEDs, whose characteristics were described in section 3, functioned continuously for one to four hours. Non-irradiated control samples were additionally prepared under the same conditions. The bacterial suspensions were adjusted according to the 0.5 McFarland turbidity Standard. To prevent sample desiccation, 105 µL and 90 µL of saline solution were added to the irradiated and control samples, respectively, every hour. All experiments were performed in triplicate.

The irradiated bacterial samples and their respective controls were collected every hour and diluted 10,000-fold by means of two successive 1/100 dilutions in saline solution. Subsequently, 100 µl were taken and spread following the Drigalski-spatula technique on the agar plates mentioned in section 3.2. After a 24-hour incubation period in an oven at 37°C, the colony-forming units (CFUs) were counted. The Student's t-test was performed to determine the differences between the irradiated and the non-irradiated samples.

RESULTS

A significant reduction in CFUs was obtained within the first hour of exposure for the *Staphylococcus aureus* and *Streptococcus pyogenes* ($p>0.01$) samples and from the second hour of exposure ($p>0.05$) for the *Enterococcus faecalis* sample (Table 1). Two hours of exposure were necessary for reaching the sterilization of the *Streptococcus pyogenes* sample, while three hours were required for the inactivation of the *Staphylococcus aureus* and *Enterococcus faecalis*, slightly longer than the 80 minutes reported in previous research (Maclean et al. 2009). A possible

explanation for this discrepancy may lie in the disparate characteristics of the lamps used in the studies. The present research employed a blue light lamp with a peak emission wavelength of 462 nm and an irradiance of 3.01 $mW.cm^{-2}$, whilst Maclean et al. (2009) used a lamp peaking at 405 nm with an irradiance of 10 mW/cm^{-2}. Although the distance between the LEDs and the sample was somewhat smaller in our testing procedure (1.5 cm versus 2 cm implemented in the latter), the different emission powers could be an explaining factor for the gap between the two studies' findings.

As for the experiments with the Gram-negative bacteria, a noteworthy reduction in CFUs was yielded within the first hour of exposure for the *Escherichia coli* sample, within two hours for *Acinetobacter baumannii,* and three hours for *Pseudomonas aeruginosa* (Table 2). None of the samples attained full bacterial eradication, including after four hours of irradiation. These outcomes are in line with those of Maclean et al. (2009), who found a 4-log reduction of CFU as a result of two to four hours of blue light exposure. The present study observed a lesser reduction in Gram-negative bacteria, which could also be attributed to the different emission powers of the lamps. Table 1 shows the effect of blue light therapy on Gram-positive bacteria. A significant impact is shown * p>0.05* and ** p>0.01** in the Student's t-test of the irradiated samples versus controls at each hour of exposure. Table 2 shows the effect of blue light therapy on Gram-negative bacteria. A significant impact is shown * p>0.05* and ** p>0.01** in the Student's t-test of the irradiated samples versus controls at each hour of exposure.

DISCUSSION AND CONCLUSIONS

The development of alternative disinfection methods has led to consider the potential of a raft of biological techniques as the use of bacteriophage therapy (Lin et al. 2017), i.e. bacteria-killing viruses, bacteriocins, i.e. antimicrobial peptides produced by bacteria that are active against other strains of the same or related species, and physical methods such as the use of low-frequency electromagnetic radiation as an alternative to Ultraviolet-C light or ionizing radiation, which poses a danger to human health (ICNRP 2013).

The thermal environment, indoor air quality, acoustic environment, lighting environment, hygiene environment, safety environment, and security environment conform to the healthy home environment as described by the WHO (2018) and Harvard T.H. Chan School of Public Health. (J.G. Allen et al. 2017).

The results obtained suggest that blue light therapy does not bear an equal effect on all bacteria types, similar to what happens with chemical disinfectants. Specifically, blue light exhibited a diminished bactericidal effect on the Gram-negative bacteria tested when compared to Gram-positive ones, which is aligned with previous research (Maclean et al. 2009, Moyano et al. 2020). This mismatch in efficacy could be due to Gram-positive and Gram-negative bacteria having different endogenous porphyrin compositions, with a concurrent impact on bacterial photoinactivation and elimination levels (Guffey & Wilborn 2006, Kim et al. 2017, Hessling et al. 2017). Numerous studies have

Table 1: Effect of blue light therapy on Gram-positive bacteria. Med.: Mean value of log CFU, SD: Standard deviation.

	Staphylococcus aureus				*Streptococcus pyogenes*				*Enterococcus faecalis*			
	Control		Irradiated		Control		Irradiated		Control		Irradiated	
Hours	Med.	SD	Med.	SD.	Med.	SD	Med.	SD	Med.	SD	Med.	SD
0	6,9	0,01	6,9	0,01	6,8	0,6	6,8	0,6	5,9	0,8	5,9	0,8
1	6,79	0,02	6,62*	0,04	5,2	1	2,45**	0,7	5,55	1	4,06**	1,2
2	5,51	0,02	3,12**	0,03	4,1	0,9	0**	0	4,4	1	2,61**	0,3
3	5,1	0,02	0**	0	3,03	1,1	0**	0	3,9	0,4	0**	0
4	4,7	0,02	0**	0	2,21	1	0**	0	3,2	0,5	0**	0

Table 2: Effect of blue light therapy on Gram-negative bacteria. Med.: Mean value of log CFU, SD: Standard deviation.

	Escherichia coli				*Acinetobacter baumannii*				*Pseudomonas aeruginosa*			
	Control		Irradiated		Control		Irradiated		Control		Irradiated	
Hours	Med.	SD	Med.	SD	Med.	SD	Med.	SD	Med.	SD	Med.	SD
0	6,9	0,6	6,9	0,6	6,5	0,8	6,5	0,8	5,5	0,8	5,5	0,8
1	6,6	0,5	3,8**	0,4	5,9	1	5,2	0,9	5,1	0,5	4,4	0,6
2	5,4	0,4	2,8**	0,5	5,7	0,4	4,6*	0,6	4,6	0,4	4,1	0,6
3	5,1	0,2	2,1**	0,5	5,3	0,7	3,93**	0,4	4,11	0,6	2,9*	0,7
4	4,9	0,3	1,4**	0,5	4,9	0,5	3,51**	0,7	3,66	0,7	1,12**	1,1

established the correlation between the efficacy of bacterial photoinactivation at different wavelengths to the endogenous porphyrins that bacteria can synthesize or to the different precursors of porphyrin synthesis that can be used as photosensitizers (Hessling et al. 2017).

Residents often consider thermal issues to be more significant than other environmental factors, including sound, light, and indoor air quality (Dimitroulopoulou 2012). This study also shows a substantial correlation between the rise in physical and mental health issues and the decline in reported thermal problem frequency. These results were consistent with other research that revealed relationships between thermal variables such as dry bulb temperature, radiant temperature, humidity, air speed, and mental/physical well-being. (Jingyi et al. 2021)

According to a number of studies, particularly those conducted in the winter, more than one-third of people reported experiencing indoor air quality issues that may be related to CO_2 (37%), HCHO (53%), and TVOC (40%) (Huang et al. 2018).

According to Spengler et al. (2001), temperature and humidity can directly affect both physical and mental health. Blue light excited endogenous porphyrins result in ROS and free radicals, which are responsible for non-specific damage to different structural components of the bacteria, e.g., proteins, the plasma membrane, and genetic material. Protoporphyrin IX, a very abundant endogenous photosensitizer in *Staphylococcus aureus* located in the cytoplasm, is catalyzed by ferrochelatase, which is the terminal cytoplasmic enzyme of the heme biosynthetic pathway involved in iron incorporation (Kim et al. 2017). According to the previous research, in addition to causing DNA damage, ROS inhibits the enzyme ATPase, as well as the activity of other pumps such as the phosphoenolpyruvate (PEP): carbohydrate phospho-transferase system (PTS) (glucose uptake pump). More recently, Kim & Kang (2021) suggested that damage also occurs at the plasma membrane level with the loss of respiratory activity when exposed to blue light wavelengths.

Other molecules susceptible to induce bacterial photoinactivation by means of ROS production are flavins. A previous study conducted by Plavskii et al. (2018) on *Staphylococcus aureus* and *Escherichia coli* evidenced that the photosensitization of endogenous porphyrins and flavins occur most effectively under 405 nm light and 445 nm, respectively. Reducing the microbial load on objects and surfaces minimizes the risk of cross-infection. Most chemical disinfectants do not sterilize nor completely eradicate microorganisms, so on that level, blue LED therapy would not fall behind conventional ones. Its main drawback, however, lies in the time necessary for significant bacterial decrease, which averages two hours. It would be interesting for future work to examine whether repeated irradiation at 15-min or 30-min intervals could increase the bactericidal power of blue light, as obtained by Masson-Meyers et al. (2015) in their experiments with *Staphylococcus aureus*.

On the other hand, Gillespie et al. (2017) and Mori et al. (2017) state that pulsed light can be as effective as continuous light since only one photon is needed for porphyrin excitation. Bacteria do not absorb photons while the molecule is in an excited state, so the use of continuous light would convey a rapid saturation and loss of the latter. Conversely, pulsed light would allow for energy savings whilst obtaining analogous effects. According to certain investigations by Wu et al. (2020), high noise levels were strongly linked to less thermal comfort than usual thermal conditions. Noises tend to increase the intensity of interior odours and lower perceived air quality (Sarigiannis 2014). Additionally, it aims to evaluate how the air is distributed while taking into account factors like the quality of the indoor air and occupant behaviour, as well as energy efficiency standards (Domínguez-Amarillo et al. 2020).

The use of LED light as a disinfectant in the food industry and hospital environments for material disinfection and wound treatment (McDonald et al. 2011) led the authors to assess its antibacterial activity on the most frequent bacteria contaminating everyday objects and surfaces in residential and hospital settings. On the proviso that its efficacy was confirmed, we would proceed to develop a series of lamps capable of sterilizing the surfaces most susceptible to microbial contamination, such as *inter alia,* lift buttons, switches, doorknobs, push-buttons, washbasins, and toilets. Due to the nature of these surfaces, the safety of prolonged use of the disinfecting light was a necessary condition, namely for eyes and skin. Furthermore, to avoid toxic effects brought about by the external photosensitization of microorganisms, no chemical compound susceptive to radiation-induced alteration should be used.

The use of said type of lamps in households and public places could positively impact the consumption of chemicals currently used for the same purpose, which would lower the production of these compounds and packaging and, in turn, decrease energy consumption and single-use plastic waste.

LED luminaires emitting longer wavelengths in the blue light spectrum, such as those used for the present experimental research, may take longer to inhibit pathogens in contact surfaces than those with shorter wavelengths but provide the advantage of being innocuous to the skin and eyes of people even near the emitting source.

Direct 642 nm blue LED irradiation significantly reduced the populations of Gram-negative bacteria and completely eradicated Gram-positive ones tested after three hours of exposure.

Further analysis should be carried out using higher-power blue lamps in pulsed or continuous mode to analyze their impact on exposure time reduction and the elimination of Gram-negative bacteria.

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