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# Enhanced Irradiance Levels using Synergistically Engineered Monochromatic Wavelength Ultraviolet-C Arrays Configuration

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**Abstract:**
Contamination in healthcare environment poses risk of microbial transmission to healthy people. Recently, conventional ultraviolet (UV) technologies, particularly low-pressure mercury lamps have caught researcher's attention for disinfection. Nonetheless, drawbacks such as hazardous components, limited lifespan, warm-up time, maintenance and fragility have driven researchers to delve into light emitting diode (LED) technologies as an appealing alternative. However, due to the diminishing intensity exhibited by LEDs over extended distances, prior studies primarily focused on short-distance investigations. Consequently, the phenomenon remained insufficient owing to the limited exploration in this field. Furthermore, frequently investigated LEDs in ambient settings, potentially created a gap in completely understanding the capability for irradiance attainability. Hence, this study aimed to overcome this limitation by evaluating the effectiveness of UV-C LEDs with synergistic arrangements within an enclosed chamber, offering optimum settings for examining irradiance performance. The analyzed recorded data aimed to identify trends in emission performance over different distances (5 to 60 cm), providing insights into how the arrangement of LEDs could influence irradiance output. The study unveiled that the synergistic effects of 6, 8, and 10-LED, when strategically engineered, significantly contributed to enhanced intensity. Notably, 10-SEMW LEDs exhibited a remarkable ability to maintain significant irradiance levels across extended distances. This was evident in the range between 0.037 and 0.016 $mW.cm^{-2}$ observed at 5 and 60 cm, respectively. In conclusion, the findings stress the importance of strategically arranging LEDs in a synergistic configuration to achieve optimal irradiance levels across a diverse range of spatial parameters for effective long-range disinfection.
**Keywords:** Ultraviolet-C; Irradiance; Synergy; Disinfection

## 1. Introduction

Within the scientific literature, the growing prevalence of multidrug-resistant organisms (MDROs) and the growth in hospital-acquired infections (HAIs) are serious concerns with global consequences (1). Compelling evidence suggests that the infectious agent is transmitted by contact with objects or surfaces contaminated with it (2). Transmission of bacteria can occur through a variety of routes, including direct transfer from infected or colonized patients and the hands of healthcare workers. Furthermore, objects in close contact to patients are more vulnerable to contamination, and these infections frequently result in higher levels and rates of bacterial infection. Interestingly, bed rails, bed surfaces, supply carts, over-bed tables, and IV pumps are some of the surfaces that healthcare workers (HCW) handle more often (3).

To reduce the danger of infection and prevent cross-contamination through the touch of others hands, disinfection practices aim to eliminate the majority or all harmful bacteria (4). This is why standard cleaning and disinfection procedures are often combined, carried out once a day on general wards, as well as in focused actions as soon as surfaces get contaminated with blood or other bodily fluids (5). Nowadays, it's essential to disinfect tabletop electronics on a daily basis due to their growing use in healthcare. However, chemical disinfectant-based disinfection processes may not be the best choice for disinfecting electronic medical equipment due to the hypersensitivity of such equipment (6). While it is widely acknowledged that UV lamps are efficient in eliminating hazardous microorganisms, there are various drawbacks of using them. Notably, the fragile and mercury component of the lamps, which could be hazardous, and short lifespan, making them less durable. Furthermore, the fact that they require a predetermined period of warm-up time before operating at their


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best efficiency aids with practical challenges even further (7, 8). Due to the limitations of conventional UV lamps, a new type of UV technology, UV light-emitting diodes (UV-LEDs) has emerged as a substitute. Because of the numerous advantages they offer such as utilizing remarkably efficient energy, eliminating the need for warm-up time, and boasting an exceptionally extended lifecycle, UV-LEDs are becoming more and more recognized as an extremely significant replacement for traditional UV lamps (9).

These LEDs have potential as adaptable and effective surface disinfection alternatives, predominantly for shorter treatment distances (10, 11). However, recent studies necessitated multiple LED sources and extended treatment durations to elevate the overall effective dose (12 – 14). This conventional method, often deemed unsuitable for clinical settings due to its time-consuming nature, allows little leeway for extended periods. This limitation is primarily attributed to the lower intensity of LEDs, hindering their capacity for disinfection across extended distances. In its essence, the quantitive assessment of irradiance holds immense importance in bactericidal treatments, as it directly influences the effectiveness of the treatment by calculating the overall dose, a product of time and irradiance, expressed in $mW.cm^{-2}$ or $\mu W.cm^{-2}$. Therefore, determining the right irradiance becomes essential in achieving the intended rate of inactivation, measured in dose ($mJ.cm^{-2}$) (15).

Furthermore, as per previous literature, the efficacy assessment by employing multiple LEDs has taken place in an open or ambient environment, which may not have fully demonstrated the true potential of the light source due to external light interference. This raises questions about the precise achievability of irradiance over specified distances, particularly by using low-power LEDs. Moreover, the inactivation achieved through the sequential or randomized arrangement of these LEDs might have derived additional benefits from a synergistically arranged setup. The strategic deployment of LEDs in such manner could potentially result in heightened and improved inactivation outcomes, as emphasized in the study (16, 18), the feasibility of achieving good intensity uniformity is underscored by strategically arranging multiple light sources in close proximity and right position. Hence, this study aimed to overcome such limitations by quantifying irradiance over extended distances by assessing the potential of LEDs within an enclosed chamber, facilitating a precise examination of irradiance intensity across specified distance intervals ranging between 5 and 60 cm. Within this controlled environment, potential external light interference was eliminated, ensuring a comprehensive understanding of optimized intensity levels using synergistically engineered with monochromatic wavelength (SEMW) UV-C LEDs with 275 nm peak emission. This methodology not only expanded upon previous research but also filled existing gaps in comprehending the necessary criteria essential for optimizing an irradiance particularly for long-range disinfection.

## 2. Methods and Materials

### 2.1 Section of LED

In navigating the diverse landscape of UV-C LEDs, the essential task of choosing the most suitable LED variant hinged on its capacity to deliver elevated intensity. Since aluminum nitride (ALN) is considered as a promising semiconductor material for use as a substrate in high-power, high-frequency electrical and optoelectronic devices with lower losses and higher withstand voltage than gallium nitride (GaN) LEDs (17), this study utilized multiple 275 nm ALN-based LEDs encompassing varying package sizes and power ratings (Figure 1). Once acquired, a thorough evaluation was conducted to determine their synergistic influence on irradiance by blending them in at-least four different arrangements. Since, irradiance is reported to be effectively enhanced by strategically arranging UV-C LEDs which requires meticulous consideration of the spatial arrangement of the LEDs to ensure greater efficiency in providing enhanced intensity (18), each arrangement was assessed in at-least four distinct manners to evaluate the cumulative effects of irradiance at different distances. During the initial phase of the study, testing comprised a combination of four identical LEDs arranged in four distinct configurations to identify the maximum irradiance. This was done to examine the peak irradiance from each specific arrangement. However, the cumulative irradiance achieved from the 4-LED configuration was found to be insufficient, with a noticeable decrease in irradiance observed after a specified distance. In response to this, the study advanced by incorporating an additional two LEDs, resulting in a 6-LED setup. Consistent evaluation methodologies were applied to assess irradiance output within four distinct arrangements. Unpredictably, synergistic effects were observed, yielding an augmented irradiance output in conjunction with a particular arrangement. This streamlined arrangement was subsequently chosen for further investigation. The similar systematic approach was employed for setups with 8 and 10-LEDs consequently.

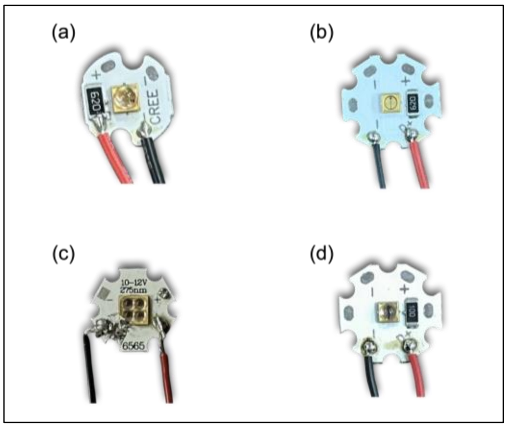

Figure 1. Different variants of ALN-based 275 nm UV-C LEDs.

Following to an extensive evaluation, the 4 W LED variant (RZX-SL6868, ShenZhen Trillion Auspicious Lighting Co., Ltd) with a package size of 6.8 mm x 6.8 mm (as depicted in Figure 2) was reported to exhibit heightened irradiance intensity and outperformed other variants as a function of varied exposure distances. As a result, this particular variant emerged as the most suitable choice for further investigation. The electrical and optical characteristics of RZX-SL6868 are demonstrated in Table 1.

Table 1. Electrical and optical characteristics of RZX-SL6868 SMD LED as provided by manufacturer.

| Parameters | Values |
|---|---|
| Radiant flux (mW) | 120 mW |
| Peak wavelength (nm) | 270 nm |
| Forward voltage ($V_F$) | 14 V |
| Reverse current ($I_R$) | 5 μA |
| Viewing angle | 60º |

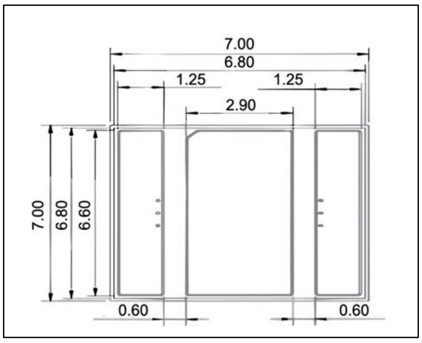


Figure 2. Package size of RZX-SL6565 SMD LED.

## 2.2 Analysis of Emission Spectrum

Despite the fact that the UV-LEDs were obtained from reliable sources and the accompanying datasheets quantified their wavelengths with tolerances, the necessity for precision led to the authentication of these values prior to investigation. As a result, before commencing with the study, the emission spectra of this specific variants was examined under spectrometer (shown in Figure 3). In general, a detailed emission spectroscopy investigation predominantly relies on the spectrometer, an equipment designed to provide insight into radiation strength across wavelengths. Therefore, the analysis was carried out by using high-resolution spectrophotometer (HR4000-Vis-NIR, Ocean Optics, Inc, USA) to precisely measure the actual wavelengths of the UV-LED sources, ensuring a precise groundwork for the following experimental trials.

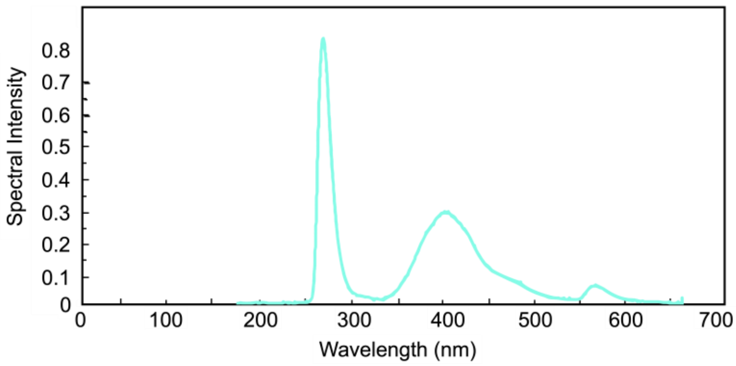


Figure 3. Package size of RZX-SL6565 SMD LED.

## 2.3 Experimental Setup

The experimental setup for this investigation initiated with the configuration of the UV lamp, which entailed the integration of circuitry within a lamp head. In the subsequent step, the LEDs were meticulously installed within the LED panel housing, and as an additional precaution, they were covered with heat sinks to address potential challenges associated with heating. To address concerns regarding overheating, three DC fans were integrated within the lamp head, positioned to face the LEDs. The circuitry for all configurations was intentionally designed to withstand thermal conditions during up to 3600 s of treatment operation. This underscored the significance of thermal management, ensuring adequate surface area and cool air circulation to facilitate the dissipation of heat from the LEDs. The lamp head, housing the LED assembly, featured a maximum curvature diameter of around 18 cm and a depth measurement of 12 cm, as illustrated in Figure 4. The LED housing was deliberately affixed at the farthest point, precisely located at a distance of 8 cm from the base and 4 cm from the highest point within the reflector's head. This arrangement facilitated optimal UV irradiation through effective reflection and placement, ensuring the efficacy of the experimental setup.

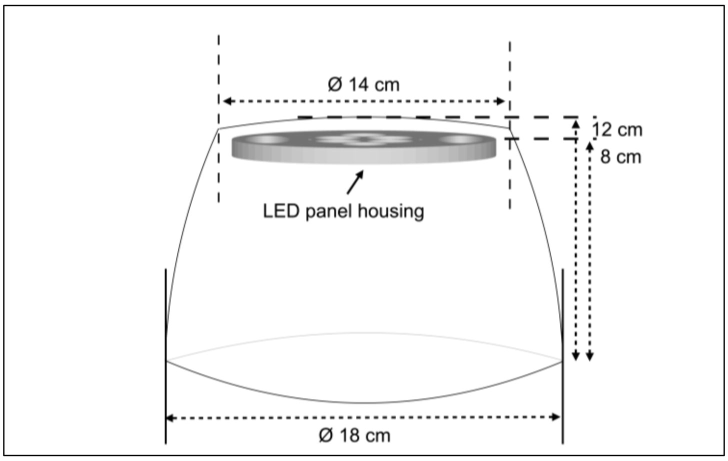


Figure 4. Illustration and dimension of lamp-head incorporating LED panel housing.

Furthermore, LEDs, synergistically coupled in 6, 8, and 10 arrangements were mounted within the LED panel housing each time to validate the placement, ensuring the proper functioning prior to the following assessment. Nonetheless, for the assessment of solitary LED, the source was meticulously mounted directly beneath the chamber encompassing the dimensions of (220 x 30 x 50 cm) (Figure 5), ensuring adequate alignment to the center. Following that, the circuitry was systematically installed within the lamp head and tested several times prior to the actual assessment. Before beginning the exposure testing phase, each SEMW LED arrays were operated at 300 mA for approximately 10 min with the goal of identifying and addressing  any potential malfunctioning or overheating issues.

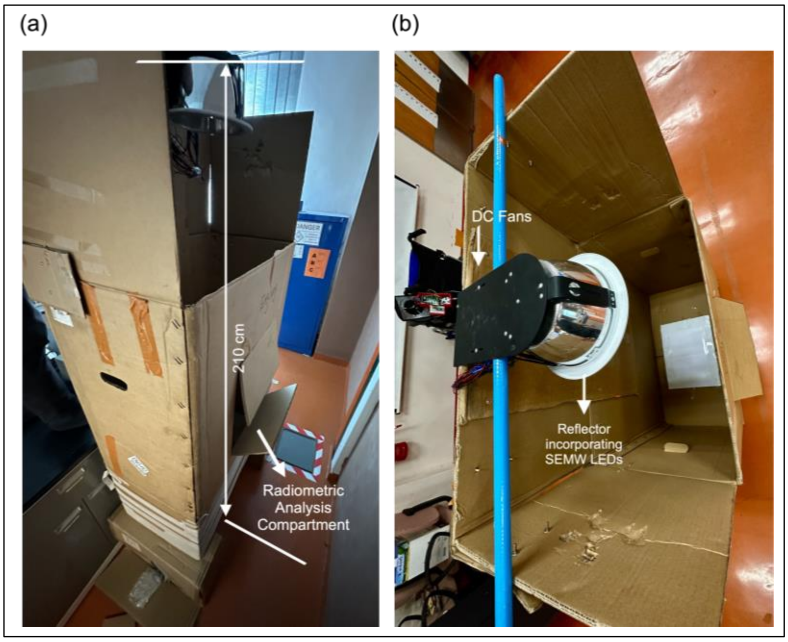


Figure 5. Visualization of experimental setup preceding tests, (a) overall dimension of testing chamber and (b) illustration of components incorporated within the chamber.

### 2.4 Radiometric Analysis

The precise measurement of UV light intensity was essential in this study for evaluating the disinfection competencies. Various approaches were considered in this study, ranging from theoretical mathematical models to actual equipment utilization such as radiometers. For this study, radiometer was chosen for computing irradiance intensity. The irradiance meter (LS123, Portable UV Power Meter, China) was chosen to obtain precise and reproducible measurements, notwithstanding its high cost, which limits their widespread utilization. This particular radiometer had a maximum capacity of measuring up to 40,000 µW/cm$^2$ and was designed to measure irradiance within the UV-C spectrum range of 260 - 400 nm. For the measurement, the sensor was strategically placed beneath the UV source in accordance with the established protocol set by the manufacturer. As per irradiance measuring standards, a measuring scale was utilized to measure irradiance (in mW.cm$^{-2}$) precisely at various distances, which signified the power per unit area obtained from the light which was emitted using equation (1).

$$E(\vec{x}) = \lim_{\substack{d(S)\to 0 \\ \vec{x}\in S,\ S\subseteq P}} \frac{\Phi_i(S)}{\mu(S)} = \frac{d\Phi_i}{dS} \quad (1)$$

## 3. RESULTS AND DISCUSSION

### 3.1 Radiometric Assessment of Solitary LED

According to the analysis performed using solitary LED (as depicted in Figure 6). The irradiance was measured to be 0.0025 mW.cm$^{-2}$ from a nearest distance of 5 cm. This observation signified that the intensity generated by a single LED at the nearest distance measured 0.0025 milliwatts within a one-square-centimeter region. As the distance was increased to 10 cm, the declining trend was observed, reporting value at 0.0016 mW.cm$^{-2}$. The irradiance decreased with increasing distance from the LED, indicating the light's dispersion over a greater surface area. Notably at 15 cm, the irradiance dropped to 0.0009 mW.cm$^{-2}$. The measured irradiance adhered to the inverse square law, indicating that it decreased in proportion to the square of the distance from the light source. The swift reduction in irradiance with increasing distance further demonstrated the predictable behavior of light propagation. In conclusion, the results provided insightful information on the relationship between irradiance values and the distance from a single LED.

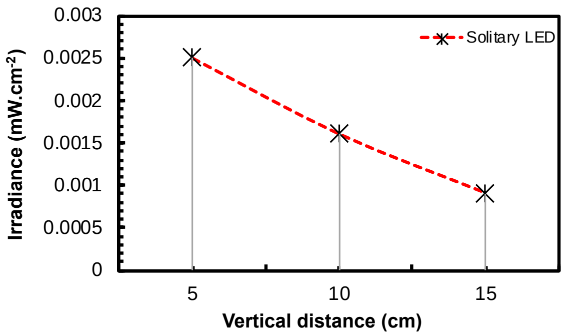


Figure 6. Illustration amplitude of 275 nm solitary LED as function distance.

### 3.2 Radiometric Assessment of SEMW LEDs

#### 3.2.1 Synergetic Enhancement of Irradiance: A Multi-LED Configuration Approach

The irradiance level for synergistically arranged LEDs across various distances measured were notably higher compared to the outcomes acquired from a single LED as depicted in Figure 7. For instance, at 5 cm, the 6-SEMW LEDs provided heightened irradiance of 0.02511 mW.cm$^{-2}$ compared to the single LED (Figure 7a), which registered 0.0025 mW.cm$^{-2}$. This produced intensity confirmed the potential microbial inactivation through a 10-s exposure, generating a dose of 0.2 mJ.cm$^{-2}$, aligning with the findings of Kim, D *et al* (19), who demonstrated that a dose of 0.2 mJ.cm$^{-2}$ was effective in inactivating *Escherichia coli* (*E. coli*), *Staphylococcus aureus* (*S. aureus*), and *Listeria monocytogenes* (*L. monocytogenes*). This signified the synergistic impact of the combined 6-SEMW LED configuration, emitting notably higher intensity within the measured region at the closest distance. Furthermore, at a distance of 10 cm, irradiation of 0.011 mW.cm$^{-2}$ was reported, which was higher than the value of 0.0016 mW.cm$^{-2}$ attained by solitary LED. The similar trend was further reported as distances were increased, with the 6-SEMW LEDs constantly demonstrating higher irradiance levels across all measured distances. Notably, at farthest distance of 60 cm, the irradiance was recorded to be 0.0003 mW.cm$^{-2}$, demonstrating lower yet attainable dose over a treatment period of at least 150 s, potentially by achieving a dose of 0.045 mJ.cm$^{-2}$. This aligned with the study conducted by P. Li et al (20), who observed a 3-$\log_{10}$ reduction in bacterial burden upon exposure to dose of 0.529, 0.0943, 0.0882, and 0.048 mJ.cm$^{-2}$, which was effective in mitigating the airborne pathogens.

The incorporation of two more LEDs in the 8-SEMW configuration resulted in a significant increase in irradiation levels when compared to the 6-SEMW LED (as illustrated in Figure 7b). These additional LEDs appeared to work synergistically, producing more efficient and enhanced irradiance levels. This was validated by consistently observing higher irradiance values across all measured distances, indicating an increased capacity for delivering elevated irradiation intensity to the targeted areas. The synergistic effects became more apparent when examining irradiance values at shorter distance. For instance, at 5 cm, the 8-LEDs setup could achieve an irradiation value of 0.032 mW.cm$^{-2}$, which was notably higher than the 6-SEMW LEDs. This demonstrated that the synergy among the eight LEDs resulted in a more focused and intense output, particularly at close ranges. This positive impact of the synergistic effects persisted across longer distances by consistently maintaining higher irradiance levels. The heightened performance underscored the imperative of acknowledging the collective impact of multiple LEDs within a configuration. This accentuated the potential to amplify intensity through meticulous design and collaborative synergies within an LED array. Understanding and leveraging these synergistic effects has practical consequences for a variety of applications, including optimizing disinfection systems with greater efficiency and efficacy. This concordance between the observed values and the study by P. Li et al (20) reinforced the continuing significance of radiant energy in the inactivation process of pathogens. The results highlighted the sustained need for efficient delivery of energy, particularly evident at the furthest distance of 60 cm. These findings contributed valuable insights to our understanding of the intricate relationship between radiant energy, distance, and the effectiveness of pathogen inactivation mechanisms. This underscored the prominence of considering both the duration of exposure and the required radiant energy to efficiently inactivate pathogens in various settings, contributing valuable insights to the field of pathogen control and mitigation.

The irradiance measurements for a 10-SEMW LEDs arrangement at varying distances further provided useful insights regarding the synergistic impression. For instance, at a distance of 5 cm, the irradiance acquired was 0.03724 $mW.cm^{-2}$, which was observed to be slightly higher than the previously discussed 6 and 8-SEMW LEDs (Figure 7c). The elevated irradiance level indicated that the incorporation of two additional LEDs into the setup had a positive impact on the reported irradiance. As the distance was extended up to 10 cm, the irradiance remained stable at 0.03027 $mW.cm^{-2}$. This sustained level of irradiance demonstrated the 10-SEMW LEDs' ability to provide intense light across moderate distances. Advancing further, at a distance of 15 cm, the recorded irradiance was reported to be 0.02677 $mW.cm^{-2}$, which declined to 0.01621 $mW.cm^{-2}$ at 60 cm. When compared to prior arrangements, the 10-SEMW LEDs demonstrated a significant ability to maintain high irradiance levels along all measured distances. The ten LEDs in this arrangement appeared to work together synergistically to produce enhanced and steady intensity output. Understanding these tendencies and optimizing multi-LED designs can have a substantial impact on applications requiring precise control and distribution of light intensity.

Resultingly, these findings indicate a consistent trend of decreasing irradiance with increasing distance for each LED arrangement. However, it is crucial to recognize that limitations associated with this trend could be mitigated by extending the treatment duration, ultimately resulting in higher dose values. Moreover, this comparative analysis unveiled potential synergy effects by strategically combining multiple LEDs. These findings underscored the significance of LED arrangement in optimizing irradiance levels, providing valuable insights for the applications requiring precise and efficient doses for inactivating various harmful microorganisms. The findings further resonate with the conclusions drawn in Bollanti's study (21), which highlighted the feasibility of achieving uniform irradiation through the synergistic arrangement of multiple light sources in close proximity. This idea was substantiated by the outcomes derived from the examined 6-SEMW, 8-SEMW, and 10-SEMW arrangements, illustrating the collaborative impact of purposefully designed configurations in attaining improved and uniformly distributed irradiance levels across different distances.

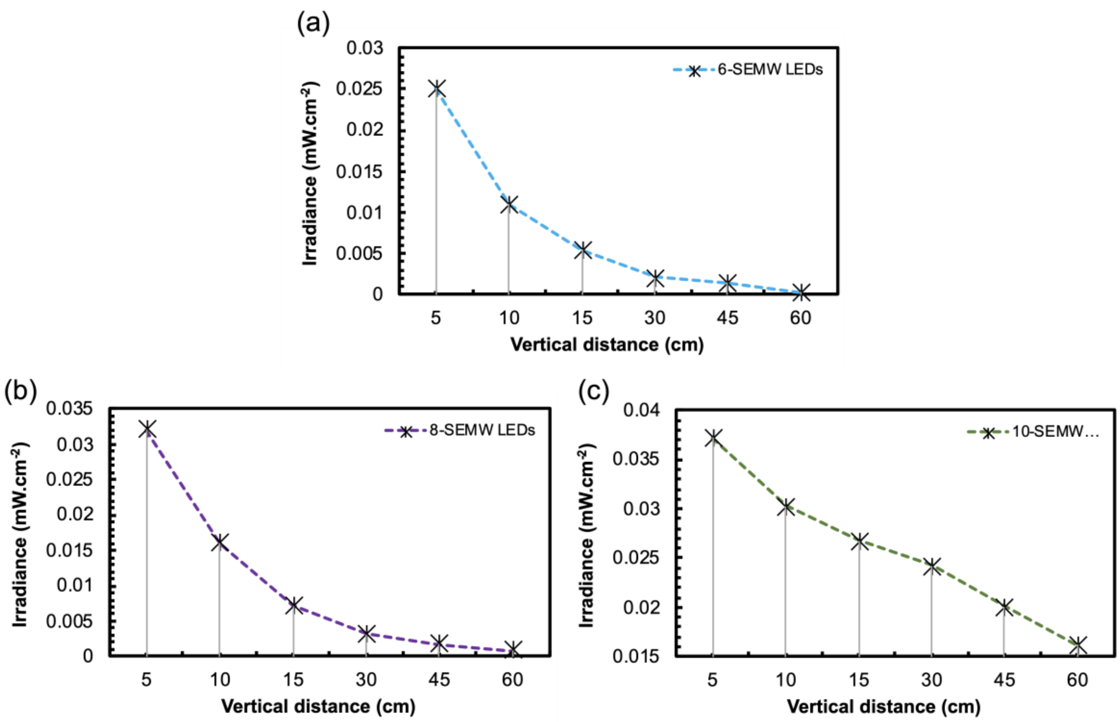


Figure 7. Comparative Analysis of Irradiance Levels: Synergistic Impact of: (a) 6 SEMW LEDs, (b) 8 SEMW LEDs, and (c) 10 SEMW LEDs at varying vertical distances.

## 4. CONCLUSION

In conclusion, this work meticulously evaluated the irradiance performance of variable LED combinations, ranging from single to 10-SEMW LEDs, at diverse set of distances within a controlled chamber setting. The results showed a clear trend demonstrating that the strategic arrangement of multiple LEDs contributes to an improved and uniform irradiance intensity, achieving a substantial capacity to maintain significant irradiance levels across the longest distance of 60 cm. This highlights the synergistic impact achieved by utilizing higher number of LEDs working in synergy. These findings make a significant contribution to the ongoing discourse about the optimization of UV-LEDs disinfection applications that require enhanced intensity over extended distances to attain the required dose, such as for the development of high and low-touch disinfection systems, requiring precise controlled irradiance intensity. The results of this study provide convincing proof of the synergistic impact which is essential for achieving optimal and consistent irradiance levels across varying spatial extents.

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**CONFLICT OF INTEREST**

The authors declare no conflict of interest.

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