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Comparative Efficacy Assessment of Solitary SMD Beaded Ultraviolet-C Light Emitting Diodes for Enhanced Disinfection of High-Touch Surfaces

(Optimization of Surface Disinfection utilizing SMD beaded UV-C LEDs)

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ABSTRACT

Ultraviolet (UV) light-emitting diodes (LED) have gained attention for substituting conventional disinfection methods due to efficiency, environmental benefits, and safety since the early 2000s. Earlier research has investigated high-power UV-disinfection systems employing UV tubes for effectively disinfecting surfaces. However, such systems come with several limitations, including the delicacy of UV tubes, the mercury component, and the larger size of the equipment, requiring trained professionals for handling. Additionally, owing to their larger size, these systems are unable to adequately treat shaded spaces, resulting in insufficient disinfection. Therefore, this study aimed to investigate and compare the efficacy of surface mount device (SMD)-beaded UV-C LEDs against Staphylococcus aureus (S. aureus) bacterium to elucidate the self-reliant disinfection capacity, focusing on achieving peak disinfection efficiency up to 15 cm for treating high-touch regions. Under maximum exposure settings (15 cm, 60 s), a considerable reduction of 1.7-log_{10} inactivation was achieved with KW6565 upon exposure to 0.054 mJ-cm^{-2}, corresponding to an efficiency of 98%. This swift decline led to a reduction in bacterial concentration from the initial level to $1.00x10^8$ CFU/mL. However, the RZX variant necessitated the dose of 0.018 mJ-cm^{-2} to achieve a 1.6-log_{10} inactivation or 97.6% percent reduction under similar exposure settings. The efficacy of both the 4W variants were notably impacted by the UV dose ($p<0.05$) at different distances, compared to the control group, revealing a positive correlation with the bactericidal rate. To conclude, this research substantiated the potential of a 4W UV-LED to establish an enhanced disinfection strategy, particularly for treating shady spaces.

Keywords: Disinfection, UV, LED, Inactivation, Pathogens, Microbes

INTRODUCTION

The rising frequency of multidrug-resistant organisms (MDRO) and hospital-acquired infections (HAI) presents noteworthy challenges for the international community (WHO 2015). To prevent HAI and control the transmission of diseases, there is an increase in research interest in creating novel cleaning and disinfection approaches, with particular attention to near-patient surroundings. Contactless UV irradiation has emerged as a viable disinfection method, offering an alternative to traditional chemical disinfection (Sheikh et al. 2024). UV irradiation has evolved as a possible disinfection technology, providing an alternative to standard chemical disinfection (Sheikh et al. 2024). The most efficient range of UV wavelength for killing bacteria is between 200 nm and 280 nm, classified as short-wave UV-C (Falguera et al. 2011). When subjected to irradiation, there is a significant amount of DNA absorption, which results in the formation of pyrimidine adducts and DNA-protein cross-links. These molecular changes impede DNA transcription and replication, eventually leading to microorganism inactivation (Bintsis et al. 2000; Gayan et al. 2014). Most UV-C-based disinfection systems have used low-pressure (LP) mercury vapour lamps generating UV at a wavelength of 254 nm (Corrêa et al. 2017; Santos et al. 2021; Matin et al. 2018). In recent times, significant advancements have taken place in the field of UV-C LEDs. Contrary to traditional LP mercury vapour lamps, this developing technology can fine-tune its wavelength, optimizing it to the peak of maximal DNA absorption at 265 nm. UV LEDs offer several key benefits over traditional UV lamps, such as being mercury-free, less temperature dependent, not requiring a warm-up period, compact. They can be arranged into various patterns and geometries. This is especially advantageous when disinfecting intricate surfaces, as shading plays an essential part in the effectiveness of microbial inactivation (Chen et al. 2017). Surfaces with sophisticated geometries, such as those found in medical devices, must be disinfected rapidly and cost-effectively using a practical and validated method, mainly when dealing with substantial amounts of microbial contamination.

For instance, tabletop equipment used in healthcare is becoming increasingly sophisticated and complicated, making cleaning more expensive and difficult. Since such equipment is frequently utilized in healthcare settings, adequate decontamination before reuse is essential in reducing HAIs. Nonetheless, the disinfection process employing UV LEDs has encountered challenges due to their lower output intensity than conventional mercury and xenon lamps, especially concerning the range of effective disinfection. Prior studies have employed high-powered UV disinfection systems using mercury UV tubes or multiple LED arrays to disinfect high-touch surfaces effectively (Sheikh et al. 2024). Nonetheless, these systems pose inherent dangers due to the fragility of mercury UV tubes. Furthermore, a more significant number of LEDs in the configuration may result in extensive UV radiation, raising concerns over potential detrimental effects on human skin cells and wastage of energy (Chevremont et al. 2012; Matteo et al. 2022; Cheng et al. 2020; Lai et al. 2021; Glaab et al. 2021; Bentancor et al. 2018). Furthermore, these systems' complexity and possible risks highlight the need for safer and more dependable surface disinfection technology. In particular, when it comes to high-touch surfaces, the standalone systems are inadequate in dealing with shady regions, resulting in insufficient disinfection. Overcoming such challenges can be attained through the employment of low-power UV-C LEDs. These compact SMDs can be seamlessly integrated into portable devices, ensuring both efficiency in treatment and a quicker process to reach the necessary UV dose for effective pathogen eradication. Recently, studies (Liang et al. 2021; Ontiveros et al. 2021; Chevremont et al. 2012; Yoram et al. 2020; Sheikh et al. 2021; Tan et al. 2023) have delved into the efficacy of using single LED for high-touch surface disinfection; however, the findings of these investigations delved into the limited treatment range, specifically up to 5 cm. Furthermore, the in-depth discussion concerning the comparative efficacy assessment of two solitary LEDs with nearly identical characteristics has yet to be found in the present literature.

Therefore, the primary goal of this research was to evaluate the self-reliant disinfection efficacy of two solitary UV-C LEDs with nearly similar electrical characteristics. Such characteristics encompass forward voltage (VF): ±12 Volts (V), half-wave width (Δλ): 11 nm, peak wavelength: 275 nm, average reverse current (IR): ±5 μA, radiant flux: ±120 mW, and nearly identical absolute maximum ratings.

The specific focus of this evaluation was to assess their suitability for disinfecting healthcare equipment in practical applications. This entailed examining its capacity to achieve substantial disinfection at an extended range of 15 cm while simultaneously optimizing the duration of treatment, making it safer and more energy efficient. This analysis yielded valuable insights regarding the operational capabilities and distinctive characteristics of these LEDs within the context of decontamination and uniform cleaning in healthcare settings.

METHODOLOGY

EXPERIMENTAL SETUP

DESIGN AND FABRICATION OF EXPERIMENTAL CHAMBER

The disinfection chamber was meticulously designed with CAD software, notably SolidWorks (Dassault Systèmes SOLIDWORKS Corp). Subsequently, a three-dimensional (3D) chamber model was developed to avoid any external light interference and fabricated using a 3D printer (Ender 3 Pro, Creality, China).

UV LIGHT SOURCES

The study utilized two solitary UV-C LEDs for the two distinctive experimental batches, producing light at a peak wavelength of 275 nm. The LEDs were installed in the upper section of the 3D chamber, with their emission focused downwards. Prior to the experiments, emission spectroscopy analysis was conducted by using spectrometer (HR4000-Vis-NIR, Ocean Optics, Inc, USA) to accurately evaluate the actual wavelengths of both UV-C sources (KW6565, Boya Technology, China and RZX, OTdiode, Shenzhen Trillion Auspicious Lighting Co. Ltd, China) as illustrated in Figure. 1. To maintain a consistent illumination, a 12 V direct current (DC) power supply was employed to operate these LEDs, delivering a continuous current of 300 mA during the entire treatment.

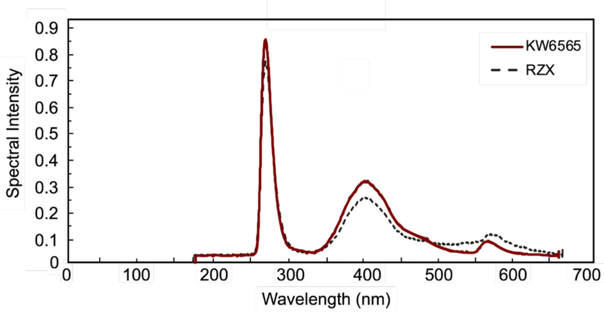

FIGURE 1. Emission spectroscopy analysis performed with the HR4000-Vis-NIR spectrometer (Ocean Optics, Inc., USA)

IN-VITRO BACTERIAL DISINFECTION TESTING

BACTERIAL CULTURE

Previous studies have classified S. aureus as the most prevalent bacteria found on various medical equipment and electronic device surfaces, contributing significantly to the rise in nosocomial infections (Katsuse et al. 2017; Ulger et al. 2009; Yao et al. 2022; Missri et al. 2019). Therefore, Gram-positive *S. aureus* (ATCC 15442) bacteria were chosen for this investigation. The decision to work with *S. aureus* was motivated by several key considerations. First and foremost, it is a recognized pathogen frequently associated with HAI and has been extensively studied in the context of disinfection (Katsuse et al. 2017; Ulger et al. 2009; Yao et al. 2022; Missri et al. 2019; Perl et al. 1998; Ford et al. 2021; Ananda et al. 2022; Bondurant et al. 2020). Therefore, we aimed to establish a consistent and controlled experimental framework, facilitating a more precise assessment of UV-C LED efficacy using single bacteria. For culture, a level II biosafety cabinet (1300 series A2, Thermo Fisher Scientific) was used that provided a sterilized working environment. The culturing was initiated with bacterial streaking, which involved a loop to transfer bacterial cultures onto nutrient agar plates. Consequently, these streaked bacterial cultures were incubated for 24 h at 37°C using a laboratory incubator (PSI-50D, Tech Lab Protech, Malaysia) to encourage growth. The turbidity of these bacterial suspensions was meticulously compared to a 0.5 McFarland standard, ensuring that a standardized bacterial concentration of 1 x 10^8 cells/mL was achieved. These standardized bacterial suspensions were gently swabbed onto agar plates to initiate the disinfection tests. The samples were then subjected to UV exposure using various set of parameters.

MULTI-FACETED ASSESSMENT OF BACTERIAL DISINFECTION

COLONY FORMING UNIT (CFU)

A serial dilution technique was employed to determine the impact of both the UV-C LEDs on the viable colony count of treated bacteria. The method permitted the quantification of enduring bacterial colonies post-treatment. Visible colonies produced post-incubation were suspended in 15 mL of sterile phosphate buffer saline (PBS) solution and were steadily dispersed through systematic stirring with the help of a cell spreader. Subsequently, 1 mL of this suspension was extracted and transferred to sterilized micro-test tubes. Later, serial dilution was carried out by transferring 0.1 mL of the bacterial suspension to successive test tubes containing 0.9 mL of fresh sterile saline solution. The contents of these tubes were vigorously mixed with the help of a vortex mixer. This iterative process was repeated until an 8-fold dilution of the original bacterial suspension was attained. Later, 30 μL of the diluted suspension was extracted with a micropipette and was applied to freshly prepared nutrient agar plates.

The plates were again incubated at 37°C for 24 hours under controlled conditions. Viable colony quantification was obtained by manually counting colonies falling within 20 to 300 colonies per plate. To determine the number of viable colonogenic bacteria, equation (1) was employed.

$$\frac{CFU}{mL} = \frac{No. of\ colonies\ counted}{Vol\ of\ suspension\ plated\ x\ DF} \quad (1)$$

LOG INACTIVATION

The evaluation of the bacterial reduction for samples subjected to both the UV LEDs treatments was carried out through a two-step process. The CFU logarithm of the irradiated samples (final CFU) was divided by the CFU logarithm of the untreated samples (initial CFU), as depicted in Equation (2).

$$Log\ Reduction = Log_{10}\left(\frac{Initial\ CFU}{Final\ CFU}\right) \quad (2)$$

Consequently, the calculated log inactivation values were translated into inactivation efficiencies using equation (3).

$$\eta = \left[1 - \left(\Sigma \frac{CFU_{UV\text{-}ON}}{CFU_{UV\text{-}OFF}}\right)\right] x\ 100\% \quad (3)$$

Where,
CFUuv-on: CFU/mL of irradiated samples,
CFUuv-off: CFU/mL of non-irradiated samples.

QUANTIFYING UV-C DISINFECTION EFFICACY ON PETRI DISH

To assess the bacterial disinfection index (BDI), we calculated the product of the disinfection percentage (D) that occurred on the petri dish upon exposure to varied time durations and distances, the area of disinfection (A) in cm^2, and the total area of the Petri dish (dA) in cm^2, using equation (4):

$$BDI = D\ x\ \frac{A}{dA} \quad (4)$$

Where,
D is the disinfection percentage,
A is the area in cm^2
dA is the total area of a petri dish

This equation allowed us to represent the bacterial inactivation level within the designated treatment region of the total petri dish. A higher BDI number indicated more efficient disinfection, whereas a lower value indicated less effective disinfection. This quantitative technique offered a reliable means of measuring the efficacy of our disinfection procedure in a controlled laboratory setting. It also aided in evaluating how effectively the disinfection performed in lowering bacterial contamination within the specific treatment region of the petri dish relative to the whole area (50.26 cm^2).

STATISTICAL ANALYSIS

The treated data was subjected to a statistical analysis. The one-way analysis of variance (ANOVA) was conducted using GraphPad Prism software (v6.01, GraphPad Software Inc., CA) to identify the level of significance difference between the data obtained with the KW6565 variant and the data obtained with RZX variants independently.

RESULTS AND DISCUSSION

INACTIVATION OF *S. AUREUS*

The post-irradiation analysis revealed circular disinfected regions of varying sizes on the agar surface, corresponding to the irradiation exposure from both the UV-C LED sources. These observations indicated the suppression of bacterial growth. Notably, at 5 cm, substantial differences in inhibitory regions were observed. However, prolonged irradiation and extended distances resulted in the development of more significant regions; in contrast, several untreated colonies were infrequently observed within the disinfected region when the samples were irradiated with RZX. Across all UV-C parameters, bacterial samples subjected to KW6565 consistently exhibited more significant inhibitory regions. Mainly, at the exposure distances of 10 cm and 15 cm, the KW6565 variant effectively eradicated the majority of bacterial growth, leaving behind a few isolated colonies on the edges of agar plates. However, as exposure distance and time were increased, the growth of bacterial isolates was further reduced. Subsequently, the presence of a few isolated residual colonies was observed at the maximum exposure time (60 s) and the farthest distance (15 cm). On the other hand, several untreated isolated *S. aureus* colonies were observed on the samples treated with the RZX variant. The visual evidence validated that the degree of bacterial suppression depended on the distance and duration of applied irradiation, underscoring the significance of both parameters.

VIABLE COLONY COUNT

According to CFU analysis (Figure 2), KW6565 UV LED consistently exhibited superior disinfection capabilities over the RZX variant. For instance, at a distance of 5 cm, the bacterial concentration was swiftly reduced from the initial level of 5.20 x 10^9 CFU/mL to 2.55 x 10^9 CFU/mL in 10 s irradiation, requiring a dose of 0.025 mJ-cm^{-2}. The dose-time relationship was evident as longer exposure duration at this distance led to even more significant reductions, reducing the bacterial concentrations to 2.23 x 10^9 CFU/mL and 2.00 x 10^9 CFU/mL upon exposure to the dose of 0.075 and 0.15 mJ-cm^{-2}, following 30 s and 60 s of irradiation, respectively. A similar trend was noticed at distances of 10 cm. After irradiating for 10 s, the bacterial concentration was reduced to 3.70 x 10^8 CFU/mL. In comparison, 30 s and 60 s of irradiation advanced to further reduction, reaching a concentration of 1.20 x 10^8 CFU/mL and 7.50 x 10^7 CFU/mL, requiring 0.048 and 0.096 mJ-cm^{-2} of dose, respectively. Lastly, at a maximum exposure distance, the bacterial concentrations were reduced to 4.06 x 10^8 CFU/mL, 1.50 x 10^8 CFU, and 1.00 x 10^8 CFU, corresponding to 10, 30, and 60 s of exposure, respectively.

On the other hand, the disinfection efficacy of RZX LED was evident with considerable dissimilarities with comparably lower dose values in the extent of bacterial reduction compared to KW6565. At 5 cm, RZX reduced the bacterial concentration to 3.93 x 10^9 CFU/mL upon exposure to the dose of 0.013 mJ-cm^{-2} after irradiating for 10 s, with less potential for disinfection compared to KW6565. However, the reduction was less pronounced in contrast to KW6565. Subsequently, RZX reduced the bacterial concentrations to 3.20 x 10^9 CFU/mL and 2.50 x 10^9 CFU/mL when irradiated for 30 s and 60 s. RZX also exhibited a similar trend of increasing bacterial reduction with longer exposures, preserving a degree of efficacy even at greater distances. For instance, at 10 cm, the concentration was reduced to 6.76 x 10^8 CFU/mL, 5.06 x 10^8 CFU/mL, and 3.15 x 10^8 CFU/mL following 10, 30, and 60 s of irradiation requiring a 0.012, 0.036 and 0.072 mJ-cm^{-2} of dose, respectively. Ultimately, at 15 cm, the bacterial concentrations were further reduced to 7.85 x 10^8 CFU/mL, 4.22 x 10^8 CFU/mL, and 1.20 x 10^8 CFU/mL.

In conclusion, both KW6565 and RZX exhibited an effective bacterial disinfection capability, particularly at a maximum exposure duration of 60 s at 10 and 15 cm. However, KW6565 consistently outperformed RZX LED, yielding slightly higher reductions in CFU within the same treatment period. Overall, the disinfection efficacy notably depended on the distance between the LED source and the sample, the dosage and the viewing angle, which significantly impacted close range. Moreover, longer exposure times resulted in more favorable CFU values, validating the importance of dosage in LED-based disinfection strategies.

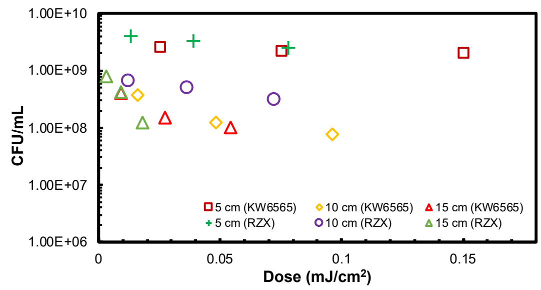

FIGURE 2. CFU Analysis of Bacterial Samples Treated with KW6565 and RZX UV-C LEDs

INACTIVATION CHARACTERISTICS

The results established a correlation among bacterial reduction, inactivation efficiencies and the dose required for effective bacterial reduction under various exposure conditions (as illustrated in Figure 3 and Figure 4). Particularly, a significant difference at $p < 0.05$ was found between the data obtained across 5, 10 and 15 cm for both LED variant (as depicted in Figure 3a,b), demonstrating importance of considering distance and a viewing angle when choosing a light source. Moreover, when utilizing the KW6565 LED at a proximity of 5 cm with a 10-s exposure duration, the bacterial load exhibited a reduction of 0.3-log_{10} inactivation upon receiving a dose of 0.025 mJ-cm^{-2}, corresponding to a disinfection efficiency of 50.90% (Figure 3a). Extending the exposure duration to 30 s and administering a dose of 0.075 mJ-cm^{-2} where the reduction value remained same at 0.3-log_{10} inactivation. Nevertheless, the resulting inactivation efficiency was elevated, reaching at 57.1% (Figure 4). Conversely, the overall disinfection efficiencies attained from both the variants were comparable ($p > 0.05$), with only exception of the 5 cm distance, attributable to differences in the viewing angle. Subsequently, at a maximum duration of 60 s, 0.4-log_{10} inactivation was achieved upon exposure to 0.15 mJ-cm^{-2}, corresponding to a 61.5% efficiency rate. In contrast, RZX variant required 0.013, 0.039 and 0.078 mJ-cm^{-2} of dose to reduce the bacterial burden by a factor of 0.1, 0.2 and 0.3-log_{10} inactivation, respectively. At this shortest distance, comparably lower inactivation efficiencies were reported as 24.4%, 38.4%, and 51.9% across all exposure durations (Figure. 3b). Similarly, at a 10 cm distance, KW6565 required 0.016, 0.048 and 0.096 mJ-cm^{-2} of dose to achieve a 1.1, 1.6 and 1.8-log_{10} inactivation upon exposure to 10, 30 and 60 s of irradiation, respectively. Contrastingly, RZX LED variant was able to achieve only 0.8, 1.0 and 1.2-log_{10} inactivation, corresponding to the inactivation efficiencies of 87.0%, 90.3% and 93.9% under similar exposure durations, respectively (Figure. 3b). Lastly, at maximum distance of 15 cm, considerable amount of bacterial reduction was achieved by KW6565 variant for all exposure durations in comparison to RZX, requiring 0.009, 0.027 and 0.054 mJ-cm^{-2} of dose to achieve 1.1, 1.5 and 1.7-log$_{10}$ inactivation, respectively. In comparison to this, RZX variant could only reduce the bacterial burden by a highest factor of 1.6-log$_{10}$ inactivation across maximum treatment span of 60 s, attaining 97.6% efficiency rate at 0.018 mJ-cm^{-2}. This demonstrated that even if LEDs have the same electrical properties and require the same amount of power to operate, the effectiveness and capacity to disinfect might vary depending on the viewing angle and the variant itself.

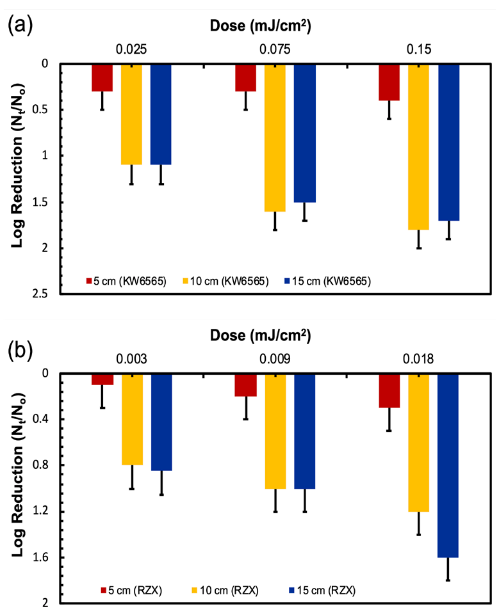

FIGURE 3. Dose-Dependent Logarithmic Reduction of Bacterial Load in Response to UV-C LED treated by: (a) KW6565 UV-C LED Treatment and (b) RZX UV-C LED Treatment

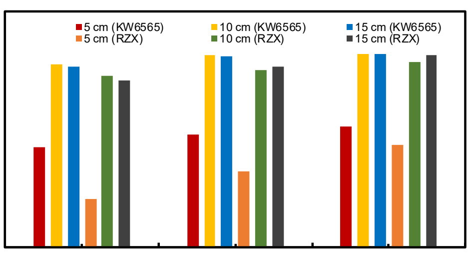

FIGURE 4. Dose-Dependent Inactivation efficiencies of Bacterial Load in Response to UV-C LED treated by KW6565 and RZX LED variant

DISINFECTION EFFICACY ON PETRI DISH

In this study, the Bacterial Disinfection Index (BDI) was employed as a quantitative measure to assess the extent of bacterial suppression across the surface of a petri dish. The BDI values (as depicted in Figure 5) quantified the level of disinfection achieved about the entire petri dish area, which was measured at 50.26 cm². This approach aimed to provide a comprehensive evaluation of the spatial effectiveness of UV-C irradiation in suppressing bacterial growth. Our study also showed a noteworthy finding, where it seems that the treatment with both the sources (KW6565 and RZX) did not significantly differ, corresponding to the BDI values in all the treated samples ($p > 0.05$). However, the BDI achieved at 5 cm distance was less pronounced due to the difference of viewing angles that led to variation in coverage.

Upon positioning the LED sources in proximity to the sample at a distance of 5 cm and subjecting it to an irradiation of 10 s, KW6565 achieved a BDI score of 23.49, depicting the extent of the disinfected area on a petri dish spanning 50.26 cm2, an outcome significantly more efficacious in contrast to RZX (Figure. 5), achieving a BDI of 7.37 only under similar conditions. The values attained at the shortest distance by KW6565 LED were notably higher than those of the RZX variant. This can be attributed to their differing viewing angles, where KW6565 features a broader viewing angle of 60^{o}, while RZX holds a narrower angle of 30^{o}. This discrepancy predominantly affected the exposure's nearest proximity (5 cm). As the duration remained consistent at 10 cm for both variants, KW6565 exhibited substantial results, yielding a BDI score of 82.31, whereas RZX's BDI was measured at 62.82. Hence, upon increasing the distance of the source from the sample, the discrepancies in BDI values of both sources gradually diminished, resulting in more comparable outcomes. This pattern persisted when the LED source was positioned at 15 cm and exposed for 10 s, with KW6565 exhibiting a striking score of 92.1, signifying a level of disinfection approaching completeness. At the same time, RZX achieved a comparable BDI of 84.9. With an extended exposure duration of 30 s, KW6565 continued to outperform with a BDI score that stood at 31.08, 88.8, and 97.11 for distances of 5, 10 and 15 cm, respectively. On the other hand, RZX achieved comparatively lower BDI scores of 14.99, 77.19, and 91.8 at similar exposure settings. Subsequently, a 60 s exposure duration further emphasized KW6565's enhanced disinfection performance, with BDI scores reaching 43.89, 98.5, and 98.0 for all the distances. However, RZX's could achieve 29.20, 93.9, and 97.6 for the corresponding distances, indicating that while RZX exhibited substantial improvement in response to extended exposure duration, KW6565 retained a consistent performance in achieving higher BDI scores.

The analysis found that the overall antimicrobial effect of the KW6565 and RZX sources was relatively comparable against the tested organism regardless of the variation in the viewing angles (*$p > 0.05$*) across all measured distances. However, a significant alteration was observed in the samples when compared to untreated (controlled) samples (*$p < 0.05$*). However, KW6565 comparably outperformed RZX in achieving slightly elevated BDI scores. Consequently, these findings validate the preference for KW6565 as the ideal UV source for enhanced bacterial disinfection under diverse conditions of proximity and exposure duration.

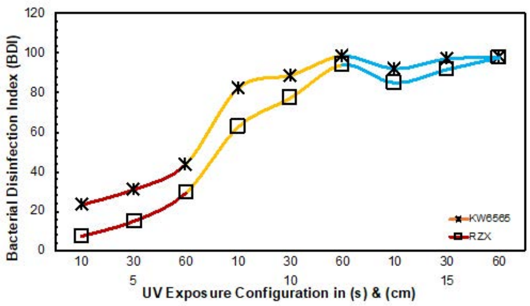

FIGURE 5. Illustrates the Bacterial Disinfection Index (BDI) across diverse exposure settings, delineating disinfection efficacy per 50.26 cm² of a petri dish, with a KW6565 and RZX LED variants as the light sources

CONCLUSION

This research proposes a practical disinfection approach for treating high-touch surfaces or close-range objects within the healthcare facility. The main emphasis of this study centers on the disinfection of close-range surfaces, particularly those associated with medical equipment or tabletop devices. This focus is essential due to the limitations observed in the traditional UV system when addressing shaded regions which is left untreated. Despite persistent challenges, notably in addressing issues like insufficient treatment in shady areas and potential skin cell damage resulting from elevated radiation levels, this comparative investigation presents a revolutionary approach for achieving enhanced disinfection using the solitary SMD-beaded UV-C LED. From the rigorous evaluation and comparative antibacterial efficacy assessment, the study validates the ability of 4W UV-C LED to provide effective treatment within a 15 cm range, particularly in healthcare settings. The results indicate that both KW6565 and RZX UV-C LEDs maintained disinfection efficiencies of over 97%, confirming their potential as a practical disinfection tool for eradicating microorganisms within a distance of up to 15 cm. In conclusion, the results suggest that 4W LEDs offer a viable solution for achieving enhanced microbial decontamination in healthcare.

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DECLARATION OF COMPETING INTEREST

None.

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