

Design UVC Disinfection System on Public Transportation by Optical FEM

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Abstract

The objective of this research paper is to develop a systematic procedure for implementing Ultraviolet-C (UVC) irradiation in a 21-seat minibus, aiming to improve the efficiency of the disinfection system. Utilizing the ANSYS SPEOS[®] optical software, a comprehensive 3D simulation of UVC radiation at 280 nm was conducted, covering the passenger seating area. The simulation's objective was to minimize the number of UVC LED lamps needed within the minibus 21-seat while ensuring a UVC radiation exposure duration of 15 minutes and achieving a log reduction exceeding 1.0 log₁₀ (90%). The simulation determined that a minimum of 9 UVC LED lamps is required for effective disinfection. To validate this simulation-driven approach, Escherichia coli (E. coli) was used as a test medium after actual UVC lamp installation.

Results from the real-installation disinfection process, conducted under optimal parameters, conclusively demonstrated 1.0 log₁₀ (90%) in E. coli and 2.0 log₁₀ (99%) inactivation.

Keywords: UVC Irradiance, Optical Simulation, Cabin, SPEOS[®], Disinfection Efficacy

1. Introduction

Following the Covid-19 pandemic, people are concerned about infection through airborne and contact transmissions (Chow et al., 2023; Morawska & Milton, 2020). Various disinfection methods can be employed to reduce the risk of infection, including chemical methods and UVC irradiance technology (Jinia et al., 2020; Kwok et al., 2021). Among these strategies, Ultraviolet-C (UVC) technology exhibits high disinfection efficacy and has the advantage of being non-consumable and non-thermal during operation.

In the present, a variety of light sources has been used at UVC wavelengths, including mercury-vapor UVC lamps at a wavelength of 254 nm, UVC light-emitting diodes (UVC LEDs) at a wavelength of 280 nm, as well as excimer lamps such as krypton chloride excimer (KrCl) lamps at a wavelength of 222 nm (Gerchman et al., 2020; Pereira et al., 2023). Since UVC-LEDs have clear advantages, such as operating without ozone generation (compared to excimer lamps) and emitting mercury vapor-free light (compared to mercury-vapor UVC lamps) (Pereira et al., 2023), this paper focuses on studying and applying UVC-LEDs at a wavelength of 280 nm for disinfection systems on public transport.

From the literature reviews on the disinfection efficacy of UVC-LEDs at a wavelength of 280 nm that affects SARS-CoV-2, it has been found to achieve efficacious pathogen inactivation of more than 3 log₁₀ (99.9%) under suitable UVC doses of 3.0 mJ/cm² (Cheng et al., 2020).

UVC technology has been implemented for disinfection purposes in a high volume of human contact, such as public buildings and mass transit systems (Bertone et al., 2022; Demeersseman et al., 2023). In Thailand, the tourism industry is of paramount importance and relies heavily on public transport. Accordingly, the use of UV radiation for disinfection has become increasingly prominent, replacing traditional chemical-based methods. This approach has found application in public transportation systems across various countries (Drungilas, Kurmis, Tadzijevas, Lukosius, Martinkenas, et al., 2023). Through comprehensive reviews of previous research, diverse engineering design strategies have emerged, including the deployment of Robot Disinfection, the Autonomous Mobile Robot (AMR) Disinfection system(Camacho et al., 2021), and simulations aimed at assessing the suitability of integrating UVC technology to enhance disinfection efficacy.

In the field of advanced optical simulation, such as UVC-LEDs irradiation, which is useful in industries for visualized design and analysis of invisible irradiance, the Finite Element Method (FEM) is a powerful tool for virtual analysis(Casado et al., 2017; Ye et al., 2021). Numerous FEM studies have simulated and analyzed UVC-LEDs irradiation. These methods can determine the irradiance characteristics under pre- processing conditions with idealized assumptions and curve-fitting methods (M. Keshavarzfathy & F. Taghipour, 2019). Some studies assumed a uniform UV irradiance distribution with an LED suitable for a specific LED model. The curve-fitting method is useful for specific

cases involving meaningful parameters. To estimate the irradiance distribution, the irradiance profile of UVC-LEDs can be represented using curve-fitting. This method assumes a symmetric UV-LED radiation profile that is independent of the azimuthal angle (Majid Keshavarzfathy & Fariborz Taghipour, 2019). The curve-fitting method is useful for specific cases involving meaningful parameters. Therefore, this procedure is acceptable for use in the simulation to optimize the pre-processing parameters of an optical simulation for UV irradiation.

This research aims to establish a systematic procedure for optical Finite Element Method (FEM) to optimize the installation of UVC-LEDs on a 21-seat minibus. The optimized FEM procedure will be coupled with UVC germicidal data. Additionally, the FEM results will be verified for disinfection efficacy against pathogens such as SARS-CoV-2 and E. coli.

2. Materials and Methods

2.1. Light Source Characteristics

UV ray calculations involve solving the Radiative Transfer Equation (RTE) using various numerical methods, with common use of Monte Carlo and Finite-Volume methods. A suggested approach for modeling the radiant energy field of UVC-LEDs considers factors like the actual radiation profile of the UVC-LEDs, media absorption, refraction, reflection interfaces, and internal surface reflection from the walls. In this method, the RTE is simplified by assuming the insignificance of thermal radiation and scattering, along with a constant absorption coefficient (Majid Keshavarzfathy & Fariborz Taghipour, 2019). Radiometry was employed for irradiance measurement, providing a quantitative evaluation of the radiation model. The close agreement

observed between numerical and experimental results highlights the potential of the proposed method for predicting the radiation distribution of UVC-LEDs in a 21-seat minibus.

The behavior of photons within an absorbing, scattering, and emitting medium in space is characterized by a Radiative Transfer Equation (RTE). In a steady-state condition for a monochromatic wavelength, the RTE can be formulated as:

$$s \cdot \nabla I(x, s) + (a + \sigma_s)I(x, s) = aI_b(T) + \sigma_s \int_{4\pi} \Phi(s, s')I(x, s')d\Omega(s') \quad (1)$$

where $I \left(\frac{W}{sr}\right)$ is the radiant intensity, x (m) is the position vector, s is the directional unit vector, $a \left(\frac{1}{m}\right)$ is the absorption coefficient, $\sigma_s \left(\frac{1}{m}\right)$ is the scattering coefficient, $I_b \left(\frac{W}{sr}\right)$ is the black body emissivity function that depends on the medium temperature (T (K)), Φ is the phase function for the in-scattering of photons, and Ω (sr) is the solid angle about the scattering direction vector s'

In this paper, the ANSYS SPEOS® module was used to simulate the optical characteristics of UVC-LEDs at wavelengths of 280 nm. Figure 2 shows the flow chart of the Finite Element Method (FEM) procedure used to determine the essential parameters of the light source model: Radiant Flux (P), Total Angle (θ_T) and Full Width with Half Maximum in X and Y axis (θ_{Fx}, θ_{Fy}). These parameters directly affect the intensity distribution curve.

In the initial step, a UVC-LED light source from W.I.P ELECTRIC was utilized as the model under study. This light source comprised a 12x1 LED array, providing a resolution of irradiation. Figure 2a shows the micro intensity distribution profile of the light source, and it is assumed to follow a Gaussian distribution due to silicone lens, affecting the emission characteristics. To simulate the LED-UVC intensity in SPEOS®,

a surface source with Gaussian distribution is employed, allowing for the adjustment of widespread light emission. The Gaussian distribution exhibits radiant intensity (Figure 2b) and distribution characteristics (Figure 2c). The expression for light intensity can be represented using the formula (Equation 2).

$$I(\theta, \varphi) = \exp\left(-\left(\frac{x^2}{2 \cdot \sigma_x^2} + \frac{y^2}{2 \cdot \sigma_y^2}\right)\right) \quad (2)$$

$$x = \theta \cdot \cos\varphi \quad (3)$$

$$y = \theta \cdot \sin\varphi \quad (4)$$

$$\sigma_x = \frac{FWHM_x}{2\sqrt{2 \cdot \ln 2}} \quad (5)$$

$$\sigma_y = \frac{FWHM_y}{2\sqrt{2 \cdot \ln 2}} \quad (6)$$

Where $I(\theta, \varphi)$ represent the radiant intensity of surface source, σ_x and σ_y represent the standard deviation of the Gaussian distribution along the x-axis and y-axis, respectively.

The second step of the pre-processing simulation is important in this research. Three essential parameters need to be determined through a trial-and-error process using a curve-fitting method. The preliminary input parameters were obtained from the manufacturer's data sheet, as shown in Table 2.

In the third step, the experiment focused on intensity measurement to validate simulation results. The objective was to utilize measurement data for verification. Figure 3a shows a 9 x 9 matrix comprising 81 intensity values arranged on a 1000 x 1000 mm plane (with a resolution of 10x10 mm), depicting a typical intensity distribution curve. For this purpose, a UVC-LED light meter sensor (Linsheng® model 125UV) with a spectral response range of 230 – 315 nm, a resolution of 0.001 W/m², and measuring accuracy of ± 5 μW/cm² was employed. The distance between the light source and the

sensor was set at 400 mm, aligning with the actual conditions of the passenger-seat simulation.

Horizontal illuminance, a prevalent method for illuminance calculation, involves integrating light measurements perpendicular to both the horizontal plane and the sensor surface as shown in Figure 3b. Following the Bouguer law, normal illuminance characterizes light intensity changes with the angle of incidence. Radiometry, a reliable technique, is commonly used for measuring irradiance, quantifying radiant flux incidents on a specific area. These concepts offer crucial insights into light distribution, applicable in diverse fields, from architecture to environmental science. Horizontal illuminance (E) can be expressed using the formula (Equation 7):

$$E = \frac{I(\theta, \varphi) \cos \theta}{l^2} \quad (7)$$

Where E represents the horizontal illuminance, I is the radiant intensity at a specific angle and l is the distance from the light source.

In the fourth step, we will compare the irradiance of simulated data with measured data to assess the pre-parameters, as detailed in the experimental design shown in Figure 4a and utilizing equations 8 and 9. Furthermore, we employ curve-fitting to analyze the data and determine the R-squared value for evaluating the suitability of the parameters. In cases where the simulation results show significant deviation, adjustments will be made to the data to identify parameters that meet the criteria ($R^2 \geq 0.95$).

$$e_{(ij)} = E_{A(ij)} - E_{S(ij)} \quad (8)$$

$$e_{Avg} = \frac{\sum_i \sum_j |e_{(ij)}|}{N} \quad (9)$$

$E_{A(ij)}$ and $E_{S(ij)}$ represent the measured data and simulated data, respectively, of UVC-LEDs at position i on the x-axis and j on the y-axis, $e_{(ij)}$ represents the deviation

between the measured and simulated irradiance at positions i and j , while e_{avg} represents the average deviation in areas i and j .

In the fifth step, the parameters will be adjusted when the simulated irradiance significantly differs from the measured irradiance. The adjustment will prioritize the intensity at the center of the light source, which has the highest irradiance. Each parameter has specific effects on the simulated irradiance: Power input increases the overall intensity, Total Angle enhances the intensity distribution along both the x and y axes but decreases the intensity value, and Full Width at Half Maximum affects the shape of the intensity distribution (Equation 10, 11). The simulated intensity is then compared with the measured intensity until it meets the specified criteria.

$$E_{A(5,5)} > E_{S(5,5)}; (+)P, (-)\theta_T, (-)\theta_{Fx} \text{ or } (-)\theta_{Fy} \quad (10)$$

$$E_{A(5,5)} > E_{S(5,5)}; (-)P, (+)\theta_T, (+)\theta_{Fx} \text{ or } (+)\theta_{Fy} \quad (11)$$

In the sixth step, once the pre-parameters obtained from pre-processing meet specific criteria, we will define the usable region. To enhance result accuracy, this region is determined by recognizing that the high-intensity zone efficiently inactivates pathogens, while excluding the low-intensity region to achieve optimal curve fitting for analysis.

In the seventh step, we will define the optimal parameters using the pre-parameters obtained from pre-processing within the usable region, following equations 10 and 11. The experimental design details are outlined in Table 3. The objective is to determine setting parameters that have an intensity characteristic similar to the actual features of UVC-LEDs at wavelengths of 280 nm. Therefore, this process aims to find the optimal parameters for analyzing the installation layout of UVC-LED lamps on a 21-seat minibus, involving a total of 32 experiments.

2.2. Optimizing Light Source Installation in Minibus 21 seats

In determining the optimal number of light sources for installation on the 21-seat minibus, our initial step involves creating a model of the minibus, using the dimensions of a typical minibus employed. The case study design, outlined in Figure 4a, investigates UVC-LED intensity on the minibus, divided into three sections: the front zone, middle zone, and rear zone. Fixed positions for the front and rear zones include two lamps installed above the driver and passenger seats, and one lamp in the middle of the rear seat row. We will explore three scenarios, each with lamps placed along the longer length of the minibus: 9 lamps, 11 lamps, and 13 lamps.

Meshing strategically optimizes computational resources by targeting specific geometric regions, thereby enhancing result granularity through the subdivision of the model into manageable blocks, typically triangular shapes, within CAD software. This focused computational approach is particularly beneficial in simulations where the interpretation of incoming rays involves numerous intricately meshed components.

In the evaluation of LED-UVC irradiance within a 21-seat minibus, the essential requirement is the incorporation of a 3D irradiance sensor. To use the 3D irradiation must convert internal objects within the minibus by using the Facet function in ANSYS SPEOS®, with the Max edge length parameter set to 2 mm. This specific configuration aims for high detail, allowing for a reduction in the maximum edge length to enhance mesh surface intricacy.

As a preliminary step, we'll prioritize seats in zones based on the volume of human contact. Priority zone 1 has the highest human contact volume, while priority zone 2 comes next (see Figure 4b). Figure 4c shows the dimensions of the preliminary model, and we aim to simulate the intensity on seats for determining the installation positions of

lamps. The goal is to minimize the number of UVC lamps in the 21-seat minibus while achieving a sufficient UVC Dose to inactivate the pathogen within a 30-minute exposure time.

The disinfection efficacy was evaluated through logPFU ratio following equation 12. The infectious titer reduction rate following equation 13 (Inagaki et al., 2020).

$$\log\text{PFU} = \log_{10} \left(\frac{N_t}{N_0} \right) \quad (12)$$

$$\text{activate reduction} = \left(1 - \frac{1}{10^{\log\text{PFU}}} \right) \times 100 \quad (13)$$

Where N_t is PFU count after exposure by UV-irradiance and N_0 is initial PFU count.

3. Result and Discussion

3.1. Result of Lights Source Characteristics Analysis

In the pre-processing study, optimal pre-parameters were power input 0.2W, total angle 70°, FWHM 55°, and 60° in x and y respectively. The high irradiance usable region between 30 - 70cm in X and Y axes (Figure 5a and 5b). Deviation occurred in low irradiance outside the Confidence Interval, but R^2 met criteria ($R^2 > 0.95$) (Figure 5c). For accuracy, focus on usable region due to its best curve fitting in high irradiance. Most values fell within the specified range (95% Confidence Interval) (Greenland, 2004), with an R^2 value of 0.977 (Figure 5d).

After defining the usable region on a plane, the UV irradiance will be analyzed within this boundary (Figure 6). In the parameter study, it is observed that the center of the plane commonly exhibits the highest UV irradiance, with a continuous decrease depending on the Full Width at Half Maximum (FWHM) of each axis. The result shows the average deviation of comparison data ranged from 7.65% to 16.01%. The optimal parameters with the lowest average deviation are Power Input, Total Angle, and FWHM in X and Y axes, set at 0.2 watt, 65°, 50°, and 60°, respectively, as shown in Figure 7. These parameters will be applied to simulate the light distribution of LED-UVC inside a 21-seat minibus.

3.2. Result of Intensity Distribution on minibus 21 seats

In the initial intensity distribution (Figure 8a), seat pads and armrests show UV irradiance between 0.20 - 0.40 W/m², back seats and headrests range from 0.10 - 0.30 W/m², and 0.10 - 0.90 W/m², respectively. In the UV irradiance on priority zone 1 (seat pad and armrest) within a 21-seat minibus across scenarios. In Scenario 1, the average irradiance is 0.139 W/m², ranging from 0.103 W/m² to 0.166 W/m² (Figure 8b). For Scenario 2, the average irradiance is 0.177 W/m², with values ranging from 0.170 W/m² to 0.185 W/m² (Figure 8c). In Scenario 3, the average irradiance is 0.220 W/m², with a range from 0.103 W/m² to 0.166 W/m² (Figure 8d).

In the analysis of disinfection scenarios for *E. coli*, achieving a 3 log₁₀ (99.9%) reduction requires minimum irradiance durations of 859, 673, and 541 seconds, reaching a UV dose of 119 J/m² (Cheng et al., 2020). For SARS-CoV-2, a 3 log₁₀ (99.9%) reduction demands minimum irradiance durations of 217, 170, and 136 seconds, reaching a UV dose of 30 J/m² (Minamikawa et al., 2021) in scenarios with 9 lamps, 11 lamps, and 13 lamps, respectively (Figure 9).

Concerning cost analysis, UVC-LEDs at a wavelength of 280 nm cost approximately 10,000 THB per lamp. So, for each scenario, the investment cost is 90,000, 110,000, and 130,000 THB, respectively, excluding modification and installation costs.

The disinfection efficacy target is to inactivate bacteria and viruses on the minibus surface within 15 minutes. Therefore, based on simulation results, choosing 9 UVC-LED lamps is sufficient for pathogen reduction of more than 90% (D₉₀). Additionally, if we aim to reduce the disinfection cost while maintaining a high efficacy target, Scenario 1 with 9 lamps appears to be a cost-effective choice due to its lower investment cost of 90,000 THB compared to 110,000 THB for Scenario 2 and 130,000 THB for Scenario 3,

To validate the installation layout of UVC-LEDs at wavelengths of 280 nm in scenario 1 for sufficient surface irradiance in disinfection, *E. coli* bacteria will be employed. Since the high biosafety hazard associated with SARS-CoV-2 and the requirement for specialized equipment, testing for SARS-CoV-2 will be conducted in a laboratory to validate disinfection efficacy. Samples of *E. coli* will be strategically placed inside the minibus at various irradiance intensities as shown in Figure 8.

The results as show in Tables 5, in the irradiance duration 15 minutes, the UV dose reaching to 125 J/m^2 , the inactivation of the *E. Coli* more than $4.00 \log_{10}$ (99.99%) in 7 of 10 positions overall the minibus, in the irradiance duration 30 minutes, the UV dose reaching to 250 J/m^2 , the inactivation of the *E. Coli* more than $4.00 \log_{10}$ (>99.99%) in 9 of 10 positions overall the minibus. The lowest inactivation was 96.50% on the back passenger seat pad. Overall, in all positions prioritized in the bus, pathogen inactivation more than $1.00 \log_{10}$ (90%)

For the SARS-CoV-2 virus, the UVC-LED lamp was positioned 15 cm above the SARS-CoV-2 plate. The inactivation results are summarized in Table 6. Achieving a UV dose of 50 J/m^2 in 8 seconds, resulting in a disinfection efficacy of $2.84 \log_{10}$ (99.86%). A UV dose of 100 J/m^2 is reached in 16 seconds, ensuring a disinfection efficacy more than $4.00 \log_{10}$ (99.99%).

4. Conclusions

In conclusion, we have identified Scenario 1, utilizing 9 lamps, as the most effective configuration for the public transport disinfection system. This setup demonstrated inactivation efficacy against *E. coli* and SARS-CoV-2, achieving a 3 log₁₀ (99.9%) reduction within a 15-minute exposure duration. This decision is grounded in a careful balance between disinfection efficacy and cost considerations.

To ensure the practical effectiveness of the disinfection system, we validated the inactivation efficacy against *E. coli* and SARS-CoV-2. The minimum inactivation efficacy observed for *E. coli* was 1.46 log₁₀ (96.5%) at a UV dose of 125 J/m², and for SARS-CoV-2, it was 2.84 log₁₀ (99.86%) at a UV dose of 50 J/m². This thorough approach gives confidence in the proposed disinfection system to establish a safe and pathogen-free environment in public transport.

5. Acknowledgments

This research was supported by Thailand' PMU-C in the future motility sector.

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<https://doi.org/10.1016/j.fm.2014.08.015>

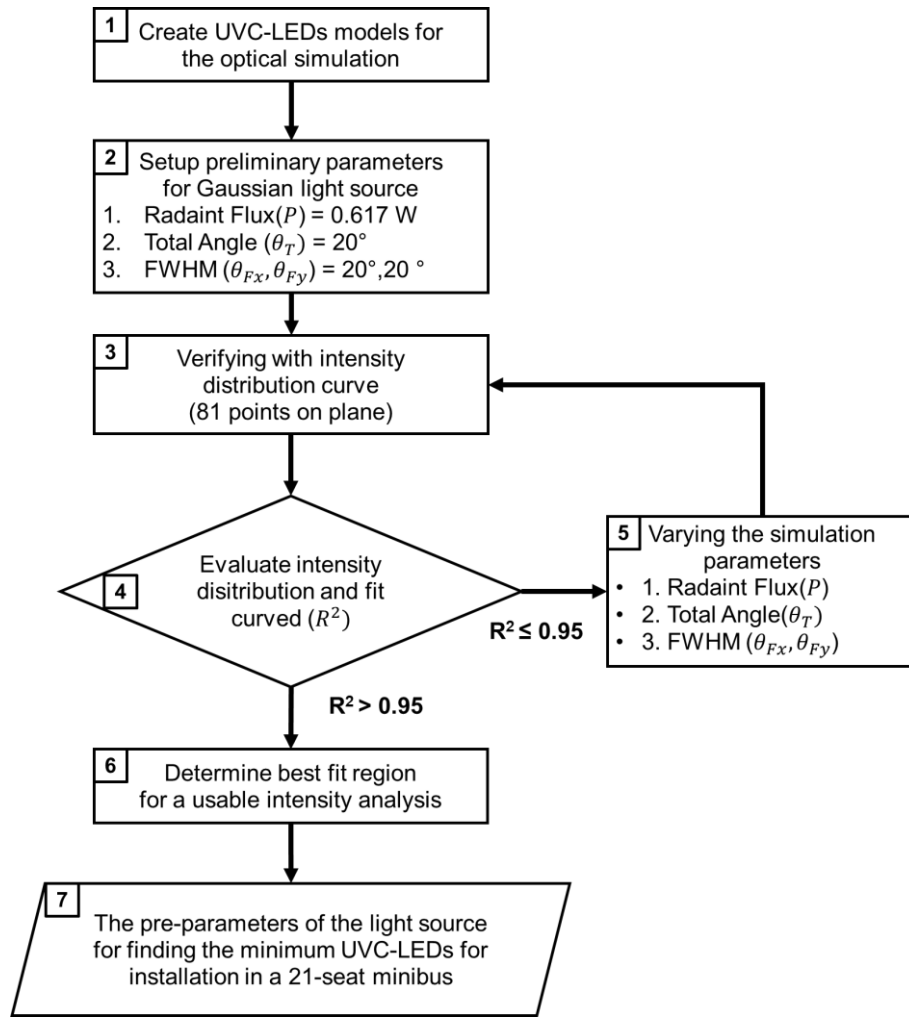


Figure 1 Methodology for defining the light source characteristics of LEDs-UVC

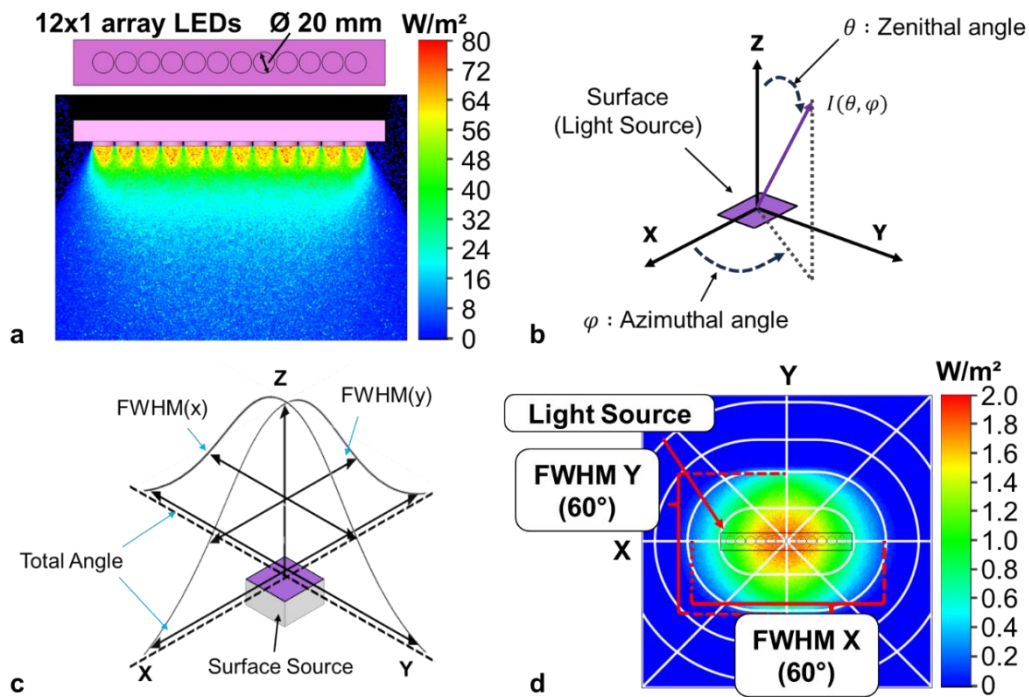


Figure 2 Light source properties, a) The micro-intensity distribution of 12x1 array LEDs module, b) Gaussian distribution laws, c) The emission profile of the light source of asymmetric Gaussian and d) The intensity profile of asymmetric Gaussian on surface sensor at total angle 60° and FWHM 60° in x-axis and 60° and y-axis

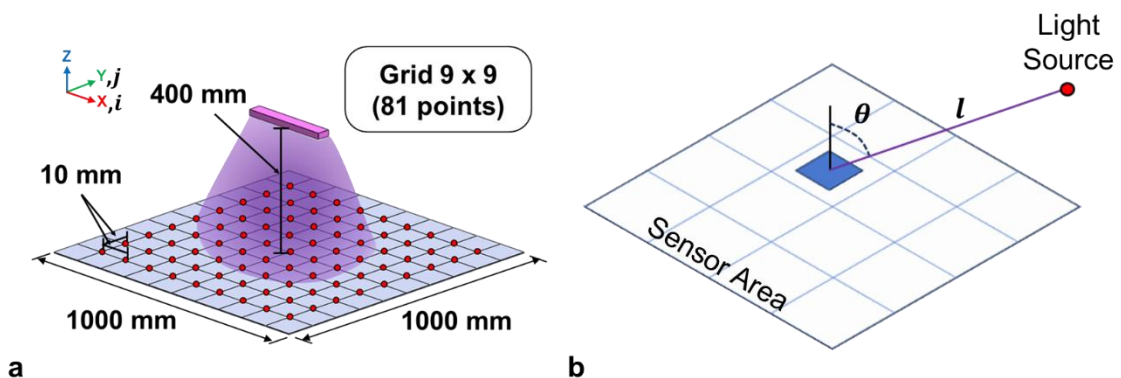


Figure 3 a) Experimental design for measuring of UVC-LEDs module, and b) Horizontal illuminance for measuring irradiance.

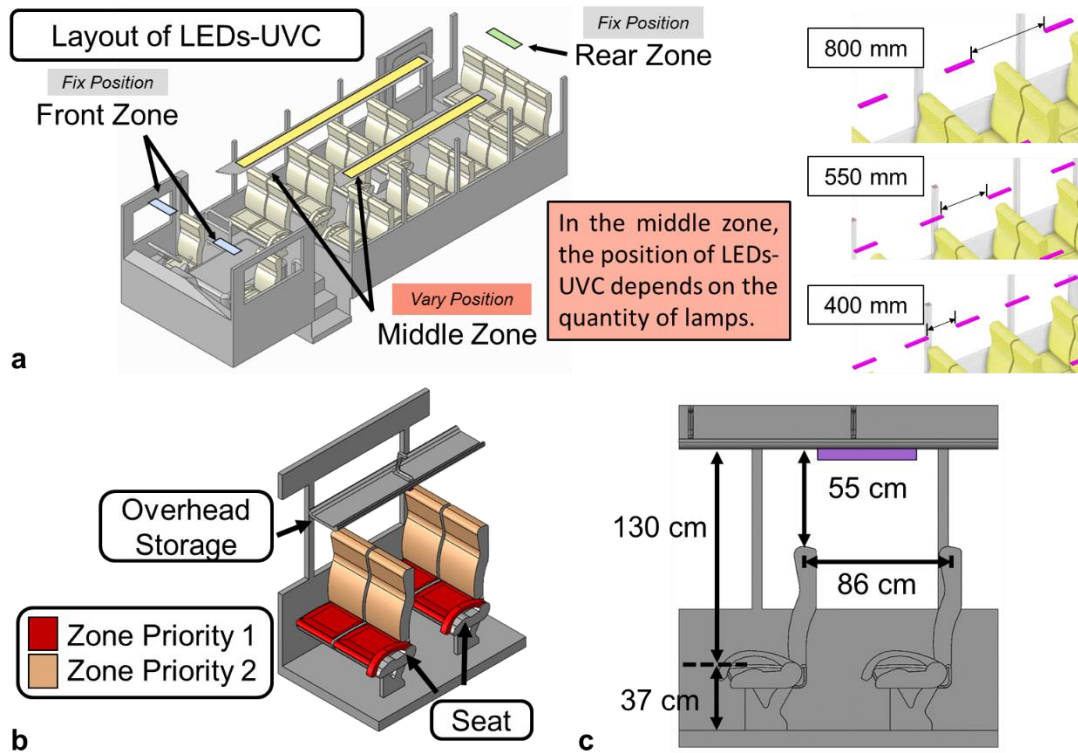


Figure 4 Light Simulation in 21-seats minibus a) Minibus model for light simulation, b) Preliminary intensity distribution and c) Preliminary dimension

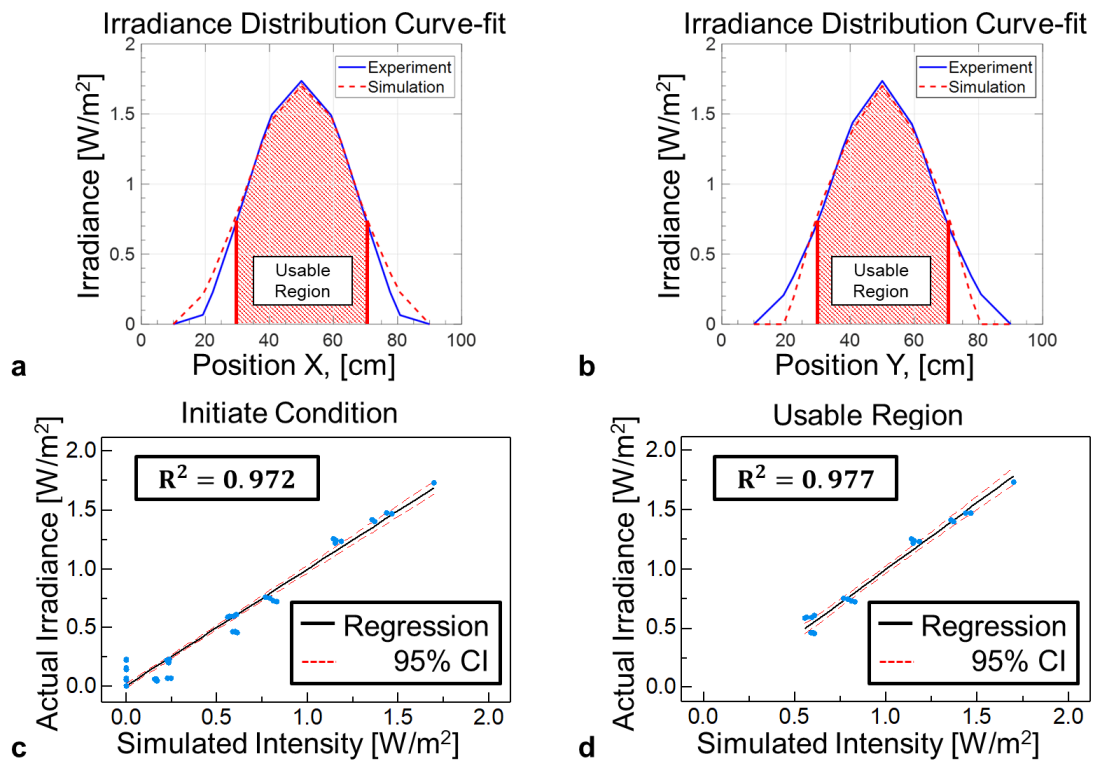


Figure 5 Comparison of actual and simulation results, a) Irradiance curve-fit in X axis, b) Irradiance curve-fit in Y axis, c) Regression of irradiance comparison on plane (81 points) and d) Regression of irradiance comparison on usable region (21 points)

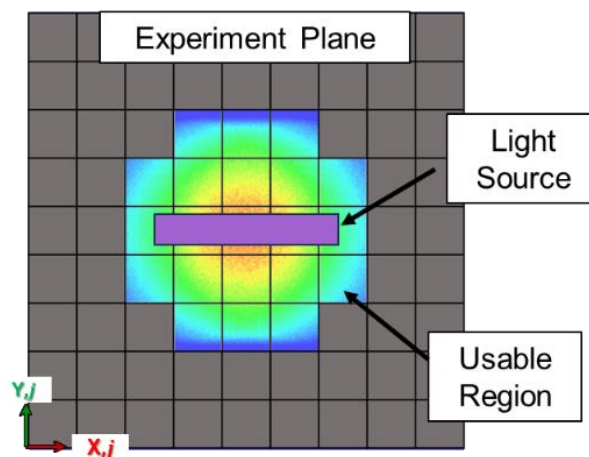


Figure 6 Light irradiance on plane in usable region

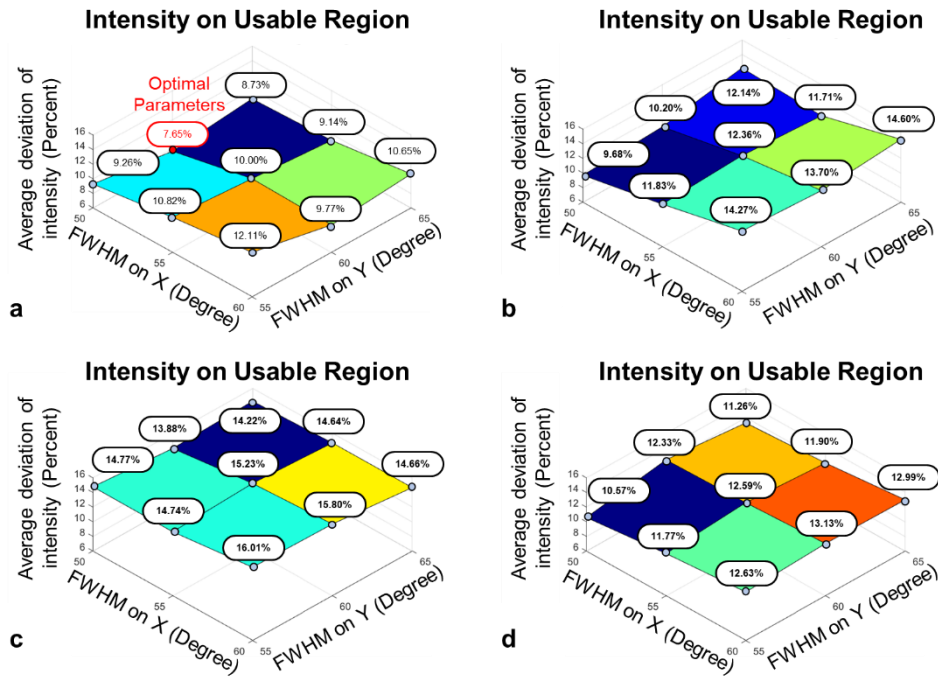


Figure 7 The average deviation usable region, (a) P = 0.2 watt, $\theta_T = 65^\circ$, (b) P = 0.2 watt, $\theta_T = 70^\circ$ (c) P = 0.22 watt, $\theta_T = 65^\circ$, (d) P = 0.22 watt, $\theta_T = 70^\circ$

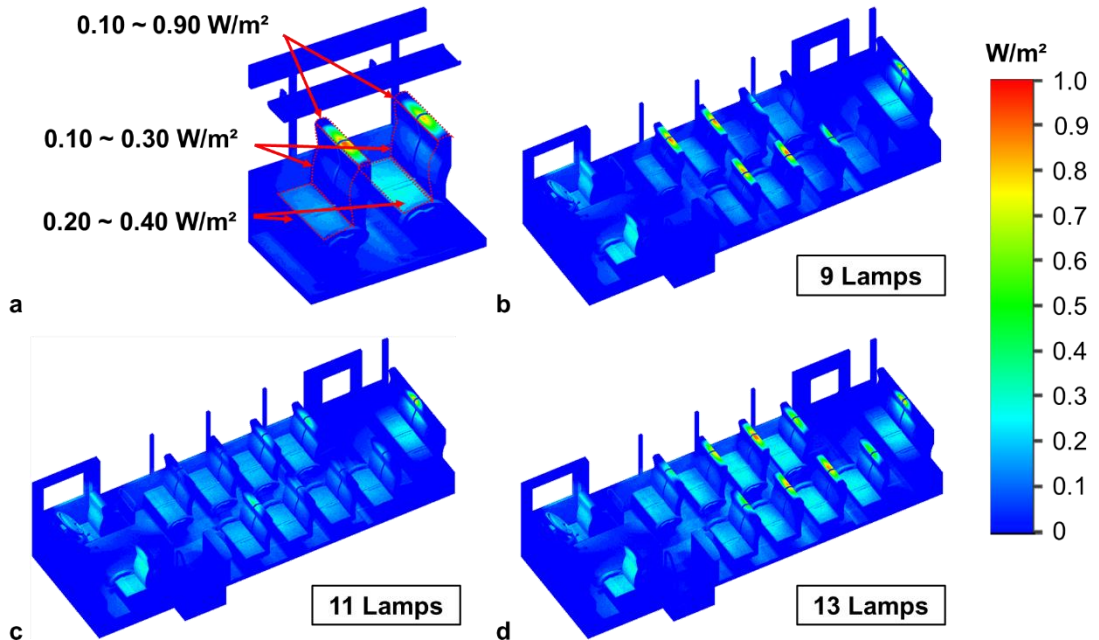


Figure 8 The intensity distribution of simulation, a) Preliminary on 2 seats (b) 9 lamps in minibus (c) 11 lamps in minibus (d) 13 lamps in minibus

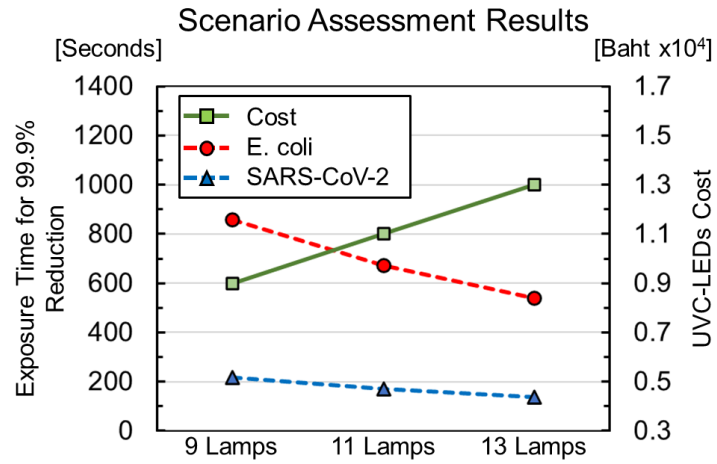


Figure 9 Cost and minimum exposure time analysis for 99.9% inactivation of SARS-CoV-2 and E. Coli in each scenario

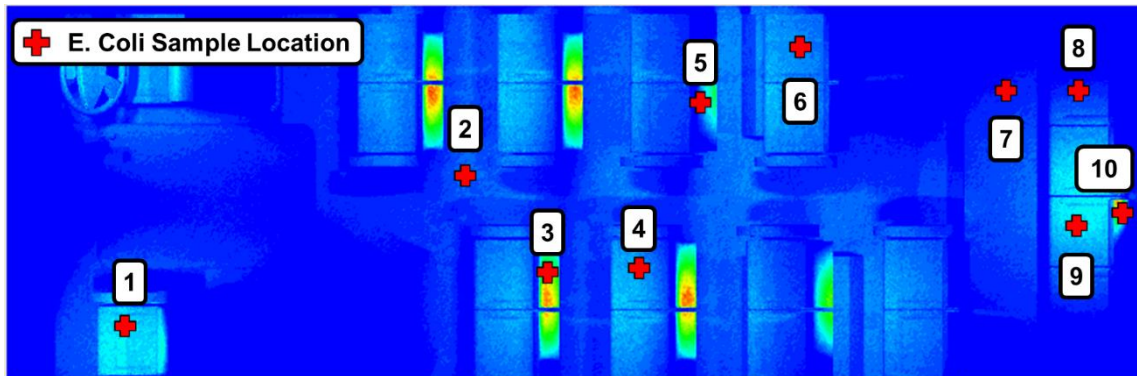


Figure 10 Schematic of scenario validation using Escherichia coli.

Table 1 Exploring UVC Lamps efficacy and Applications of UVC Technology

	Name	Condition	Results	Highlights	
UVC Disinfection Efficacy	Excimer lamps KrCl (222 nm)	Bacteria	UVC dose and exposure time	<ul style="list-style-type: none"> Reduced harm to human skin and eyes Safety to use Ozone Generation (Kitagawa et al., 2021; Yin et al., 2015) High efficiency Low cost Mercury-vapor (Ma et al., 2021; Sesti-Costa et al., 2022) No Ozone Production Application flexibility High efficiency (Inagaki et al., 2020; Minamikawa et al., 2021; Trivellini et al., 2021) 	
		E. coli O157:H7	dose: 75 mJ/cm ²		2.81 log ₁₀
		Virus			
	Mercury-vapor UVC (254 nm)	SARS-CoV-2	dose: 0.1 mJ/cm ²		0.94 log ₁₀
			dose: 3 mJ/cm ²		2.52 log ₁₀
		Bacteria			
	LEDs-UVC (255-280 nm)	E. coli	dose: 6 mJ/cm ²		4.00 log ₁₀
		Virus			
		SARS-CoV-2	dose: 1.3 mJ/cm ²		1.00 log ₁₀
		dose: 10.4 mJ/cm ²	4.00 log ₁₀		
	Virus				
	SARS-CoV-2	dose: 37.5 mJ/cm ²	3.00 log ₁₀		
		dose: 3.0 mJ/cm ²	3.00 log ₁₀		
		dose: 8.31 mJ/cm ²	3.00 log ₁₀		
UVC Technology applications	Far-UVC Excimer lamps (222 nm)	A 12 m long M3 city bus	Optimal disinfection is achieved when the far-UVC light source targets the seat with a UVC Dose of 2 mJ/cm ²	Disinfection time: <ul style="list-style-type: none"> 38.1 min (2 lamps) 20.6 min (4 lamps) Energy required: <ul style="list-style-type: none"> 111.3 Wh (2 lamps) 109.8 Wh (4 lamps) 	<ul style="list-style-type: none"> Robotic lamp positioning and lifting/lowering system. Far-UVC disinfection system installed. Passenger Detection (Drungilas, Kurmis, Tadzijevas, Lukosius, Sapalas, et al., 2023)
	UVC Lamp (254 nm)	Tests conducted in an enclosed laboratory	Efficient UVC disinfection robot design, path optimization, real-time application prospects.	Improved A-star Algorithm with NN sorting: search path length 36.45 m in search time 0.038 sec	<ul style="list-style-type: none"> Real-time map-based path planning Potential applications in various robot domains (Wang et al., 2022)
	UVC-LEDs	Access card reader, bookshelf, and toolbox are in the building	Develop a high-performance disinfection robot with UVC-LEDs for targeted zone disinfection.	E. coli 99% reduction	<ul style="list-style-type: none"> High flexibility Online trajectory planning from integrated interface (Ma et al., 2022)
Simulation Analysis for UVC Irradiation	UV-LEDs (255 nm)	The difference between model and experimental irradiance values	At a 4 cm distance from LEDs (8 LEDs)	<ul style="list-style-type: none"> The variation in the large area is less than 20%. The small section exhibits a 20-40% variation. 	Curve-fitting method (Bowker et al., 2011)
	UV-LEDs (275 nm)		At a 4 cm distance from LEDs (4 LEDs)	<ul style="list-style-type: none"> The majority of the variation in the area is less than 10% Most of the remaining area had under a 20% difference. 	
	UV LEDs (260 nm)		Triiodide formation	Flowrate: 109 mL/min; 30 LEDs Flowrate: 109 mL/min; 25 LEDs Flowrate: 190 mL/min; 30 LEDs Flowrate: 190 mL/min; 25 LEDs	

Table 1 Exploring UVC Lamps efficacy and Applications of UVC Technology

Table 2 The preliminary parameters for SPEOS[®] pre-processing

Parameters	Value
Light Source Type	Surface type
Material Reflectance	20 %
Irradiance Sensor Type	3D - Irradiance
Radiant Flux(P)	0.617 W
Total Angle (θ_T)	20°
FWHM (θ_{Fx})	20°
FWHM (θ_{Fy})	20°

Table 2 The preliminary parameters for SPEOS[®] pre-processing**Table 3 Light source parameters and levels**

Parameters	Level-1	Level-2	Level-3
Power Input: Radiant Flux (W)	0.2	0.22	-
Total Angle (θ_T)	65	70	-
FWHM in X (θ_{Fx})	50	55	60
FWHM in Y (θ_{Fy})	55	60	65

Table 3 Light source parameters and levels

Table 4 Light source parameters and experiment result

No.	Radiant Flux (W)	Total Angle (°)	FWHM _X (°)	FWHM _Y (°)	e _{Avg}
1	0.20	65	50	55	9.26%
2	0.20	65	50	60	7.65%
3	0.20	65	50	65	8.73%
4	0.20	65	55	55	10.82%
5	0.20	65	55	60	10.00%
6	0.20	65	55	65	9.14%
7	0.20	65	60	55	12.11%
8	0.20	65	60	60	9.77%
9	0.20	65	60	65	10.65%
10	0.20	70	50	55	9.68%
11	0.20	70	50	60	10.20%
12	0.20	70	50	65	12.14%
13	0.20	70	55	55	11.83%
14	0.20	70	55	60	12.36%
15	0.20	70	55	65	11.71%
16	0.20	70	60	55	14.27%
17	0.20	70	60	60	13.70%
18	0.20	70	60	65	14.60%
19	0.22	65	50	55	14.77%
20	0.22	65	50	60	13.88%
21	0.22	65	50	65	14.22%
22	0.22	65	55	55	14.74%
23	0.22	65	55	60	15.23%
24	0.22	65	55	65	14.64%
25	0.22	65	60	55	16.01%
26	0.22	65	60	60	15.80%
27	0.22	65	60	65	14.66%
28	0.22	70	50	55	10.57%
29	0.22	70	50	60	12.33%
30	0.22	70	50	65	11.26%
31	0.22	70	55	55	11.77%
32	0.22	70	55	60	12.59%
33	0.22	70	55	65	11.90%
34	0.22	70	60	55	12.63%
35	0.22	70	60	60	13.13%
36	0.22	70	60	65	12.99%

Table 4 Light source parameters and experiment result

Table 5 The disinfection of E. Coli bacteria through UVC-LEDs 280 nm over 15-minute and 30-minute duration.

Time of exposure (minute)	No.	Sample Code	Antivirus activation		
			CFU/ml	Log reduction	% Reduction
15 (UV dose 125 J/m ²)	1	Position 1	1,300	5.30	> 99.9%
	2	Position 2	1,500	5.24	> 99.9%
	3	Position 3	8	7.51	> 99.9%
	4	Position 4	1,500	5.24	> 99.9%
	5	Position 5	1,900,000	2.14	99.27%
	6	Position 6	240	6.03	> 99.9%
	7	Position 7	1,000,000	2.42	99.62%
	8	Position 8	9,100,000	1.46	96.50%
	9	Position 9	260	6.00	> 99.9%
	10	Position 10	240	6.04	> 99.9%
30 (UV dose 250 J/m ²)	1	Position 1	1,200	5.34	> 99.9%
	2	Position 2	1,300	5.30	> 99.9%
	3	Position 3	3	7.94	> 99.9%
	4	Position 4	15	7.24	> 99.9%
	5	Position 5	1,500	5.24	> 99.9%
	6	Position 6	1,600	5.21	> 99.9%
	7	Position 7	1,900	5.14	> 99.9%
	8	Position 8	4,600,000	1.75	98.23%
	9	Position 9	190	6.14	> 99.9%
	10	Position 10	170	6.19	> 99.9%

Positive Control at 15 min is 260,000,000 (2.6E+08)

Table 5 The disinfection of E. Coli bacteria through UVC-LEDs 280 nm over 15-minute and 30-minute duration.

Table 6 The efficacy of SARS-CoV-2 virus disinfection within a laboratory through the UVC-LEDs 280 nm

UVC Device	UVC dose target (J/m ²)	Time of exposure (Second)	Virus titer (pfu/mL)	Antivirus activation	
				Log reduction	% Reduction
LEDs-UVC (280 nm)	50	8	$4.33 \times 10^3 \pm 3.28 \times 10^3$	2.84	99.86
	100	16	$< 10^2$	≥ 4.4	$\geq 99.99^*$
Untreated (Control)	-	1785.7 (≈ 29.8 min)	$2.25 \times 10^6 \pm 1.15 \times 10^5$	-	-

*Virus was not detected at the limit of detection

Table 6 The efficacy of SARS-CoV-2 virus disinfection within a laboratory through the UVC-LEDs 280 nm

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