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Design of a Device Based on an LED Matrix for Water Sterilization

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Featured Application: Featured Application: This paper describes the construction of a low-cost, flexible-design device based on encapsulated LEDs, with direct application for water sterilization and scalability potential.

Abstract: The scarcity of potable water emphasizes the urgent need to develop and implement more sustainable treatment technologies, considering both energy consumption and environmental impact. These technologies require effective disinfection systems that avoid the use of chemicals. Innovations in this area, utilizing UV-LED technology, can significantly improve efficiency, reduce costs, and mitigate environmental impacts. This study aimed to evaluate the antimicrobial properties of various encapsulated UV light-emitting diodes (LEDs) to identify the most suitable candidate for constructing an LED array capable of disinfecting large volumes of water. Different devices from various manufacturers, with differing costs and wavelengths, were examined, leading to the selection of the optimal candidate (LED 2) based on its antimicrobial effectiveness and cost-effectiveness. The impact of parameters such as bacterial concentration, sample volume, exposure time, and conditions on disinfection capacity was thoroughly investigated. Exposure to LED 2 resulted in substantial reductions in the viability of bacteria and yeast, demonstrating efficacy even against Clostridium perfringens endospores. Subsequently, an LED array was developed based on these findings and rigorously evaluated for efficacy, confirming its effectiveness as an efficient and environmentally friendly water treatment device.

Keywords: contaminated water; disinfection; LEDs array; microorganism; UV-LEDs

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1. Introduction

Today, it is common to add chemical disinfectants such as bromine, chlorine, iodine, ozone, and chloramines to drinking water. Chlorine, due to its low cost and high sterilization effectiveness, is often the most popular choice. However, chlorine can react with organic matter and form byproducts that may be carcinogenic, mutagenic, cytotoxic, and teratogenic [1,2]. Hence, it is crucial to develop new alternative strategies to eliminate pathogenic microorganisms present in water.

The use of ultraviolet (UV) radiation can be an excellent solution for removing microorganisms from water. It offers several advantages, including the absence of harmful

sterilization byproduct formation, the elimination of the need to add chemicals, and the prevention of the emergence of bacteria resistant to disinfectants [3].

UV radiation spans wavelengths in the electromagnetic spectrum between 200 and 400 nm. This radiation is divided into three regions: UV-A, UV-B, and UV-C. UV-C produces the most efficient sterilization, as its wavelength range corresponds to the peak absorption of nucleic acids (260 nm), resulting in molecular damage leading to cell death [4,5].

Mercury lamps have been widely employed in water sterilization systems, yet they are not deemed the optimal choice, owing to mercury being a toxic element and these lamps having a short lifespan [3]. Alternatively, light-emitting diodes (LEDs) are smaller, stronger, less polluting, and have greater durability [6]. Moreover, they can emit in a narrower wavelength range, allowing us to select the best LED for each application and combine them to treat multiple microbial targets [5].

This study compares the antimicrobial properties of various UV-C LEDs obtained from different manufacturers, with a wide range of prices and different emission wavelengths. To enable their use as water sterilizers, an innovative encapsulation of these LEDs in flexible and transparent polymeric materials was carried out. The device with the best properties was selected to conduct studies on disinfection efficiency against a wide variety of pathogens, including bacteria, yeasts, and bacterial resistance forms (endospores). The influence of parameters such as bacterial concentration, sample volume, or exposure time and conditions on disinfectant capacity was analyzed. This information was used to construct a matrix of encapsulated LEDs whose efficiency was tested in laboratory cultures and environmental samples. The efficiency of this device paves the way for its expansion to practical applications in water treatment.

2. Materials and Methods

2.1. LED Devices

Nine UVC LEDs were selected and evaluated in terms of thickness, cost, and peak emission. Their features are shown in Table 1.

Table 1. Description of the commercial, physical, and cost characteristics of the LEDs used in this study.

Name	Supplier	Code	Size (mm)	High (mm)	Cost (€/unit)	Cost (€/mW)	Emission Peak before Encapsulation (nm)	Emission Peak after Encapsulation (nm)	Emission Peak before Encapsulation (nm)
LED 1	Suntechled (Shenzhen, China)	STSN-60UVC 3535-24	3.50 × 3.50	1.10	1.17	0.234	278 and 397	397	278 and 397
LED 2	Suntechled	STSN-30UVC3939-24	3.90 × 3.90	3.13	2.22	0.111	272	272	272
LED 3	OSRAM (Madrid, Spain)	Oslon UV 3636	3.60 × 3.60	1.80	35.76	0.851	278	278	278
LED 4	Luminus Devices (Sunnyvale, CA, USA)	XST-3535-UV	3.65 × 3.65	2.55	30.14	0.301	280	280	280
LED 5	Inolux (Santa Clara, CA, USA)	IN-C35PUDTDU1	3.45 × 3.45	1.65	7.47	2.49	270	270	270
LED 6	Luminus Devices	XBT-3535-UV-A130 CD270	3.50 × 3.50	2.03	20.39	0.634	276 and 320	276 and 320	276 and 320
LED 7	SETi/Seoul Viosys (Gyeonggi-do, Republic of Korea)	UD5GF1B	3.50 × 3.50	1.20	127.86	36.53	276	276	276
LED 8	QT Brightek (QTB) (Milpitas, CA, USA)	QBHP684E-UV265	3.50 × 3.50	1.59	11.78	4.712	260	260	260
LED 9	QT Brightek (QTB)	QBHP684E-UV265N	3.50 × 3.50	1.59	23.14	2.314	272	272	272

2.2. Encapsulation Procedure

Ethylene tetrafluoroethylene (ETFE) films (NOWOFLON ET 6235 Z, Nowofol, Siegsdorf, Germany) were utilized for both the top and back layers (150 µm thick). Ethylene vinyl acetate (EVA) was selected as the lamination material; specifically, a 125 µm-thick EVA film (Photocap® 15420P/UF, Specialized Technology Resource, STRE, Llanera, Spain) was employed. Optimal adhesion between ETFE and EVA was attained through corona treatment of ETFE. Encapsulations were conducted utilizing lamination equipment (P.Energy Company L036A, Padova, Italy) at a processing temperature of 140 °C, with a vacuum cycle of 4 min and a pressure cycle of 8 min. The encapsulation structure consisted of: ETFE + EVA + LED + EVA + ETFE. Initially, LEDs were encapsulated individually, followed by the design of a prototype incorporating the most suitable LED in terms of cost and efficiency. To ensure uniform UV light emission throughout the prototype, LED strips were welded in series, maintaining consistent distances between each LED in all directions.

2.3. Optical Characterization and Degradation Tests

To assess and compare the optical performance of various commercial LEDs, a characterization was conducted using UV-NIR spectrophotometric measurements. This was achieved using a fiberoptic spectrophotometer (AvaSpec2048-USB2, Avantes, Apeldoorn, Netherlands), which provided spectra within the wavelength range of 200 nm to 1100 nm. The LEDs were powered by a current-regulated power supply. Qualitative spectra, representing UV light emissions, were acquired before and after encapsulation for each commercial LED (Table 1).

Additionally, to investigate potential degradation due to moisture exposure, tests were conducted underwater, in a volume of 5 L and at a depth of 20 cm, lasting for 700 h.

2.4. Microorganisms and Culture Conditions

The microorganism species utilized in this study were clinical isolates obtained from the Hospital Universitario Central de Asturias. *Escherichia coli*, *Klebsiella pneumoniae*, *Enterococcus faecalis*, and *Salmonella enterica* were cultured in brain heart infusion (BHI) broth (Gibco-Thermo Fisher Scientific, Waltham, MA, USA) at 37 °C in a shaking incubator. *Clostridium perfringens* was cultivated in tryptic soy broth (TSB) (Thermo Fisher Scientific, Waltham, MA, USA) under anaerobic conditions generated by an AnaeroGen system (Oxoid, Basingstoke, UK) within Brewer anaerobic jars. *Candida albicans* and *Saccharomyces cerevisiae* were grown in Sabouraud broth (Difco, Detroit, MI, USA) at 28 °C in a shaking incubator.

2.5. Effect of LEDs on Water Temperature

The effect of LEDs on water temperature was measured using a thermometer in 10 mL of deionized distilled water in contact with different LEDs at the following time intervals: 0 min, 1 min, 2 min, 4 min, 8 min, 16 min, 32 min, 64 min, 90 min, 2 h, 3 h, and 6 h.

Following the construction of an array of LEDs, their effect on temperature was assessed by placing the thermometer inside a flask containing 1 L of deionized distilled water, and measuring the temperature at the following intervals: 0 min, 1 min, 2 min, 4 min, 8 min, 16 min, 32 min, 64 min, 90 min, 2 h, 3 h, and 6 h.

2.6. Effect of LED Exposure on Microorganism Viability

To compare the antibacterial capacity of the different LED devices tested, *E. coli* was used as a control. Cultures of *E. coli* in exponential phase were washed 10 times by centrifugation with deionized distilled water and diluted in 10 mL of water to reach 5×10^3 colony-forming units (CFU) per milliliter. At this point, the cells were exposed to the LEDs for different periods of time, under both static and stirring conditions. Dilutions were then plated on solid BHI medium plates, and after overnight incubation at 37 °C, the colonies obtained were quantified. After selecting LED 2 as the best option to build a disinfection prototype, its effect on different species of bacteria and yeasts was analyzed

following a similar protocol. The effect on yeasts was carried out similarly, but using Sabouraud medium instead of BHI.

To obtain *C. perfringens* endospores, cultures were washed by 10 centrifugations with distilled water, and finally resuspended in distilled water. Under these stringent conditions, vegetative cells disappeared from the culture and were replaced by endospores. Viability tests were carried out by culturing dilutions of endospores on McConkey agar in a manner analogous to that used for vegetative cells.

2.7. Effect of Microbial Concentration on the Efficiency of Exposure to LED 2

Cultures of the different bacteria were washed by 10 centrifugations with deionized distilled water and serially diluted to reach concentrations of 5×10^3, 5×10^4, 5×10^5, 5×10^6, 5×10^7, and 5×10^8 CFU/mL in a volume of 10 mL. Subsequently, the dilutions were exposed to UV radiation for 5 min with and without stirring. Finally, viable bacteria were quantified as described previously.

2.8. Influence of Volume on the Efficiency of Exposure to LED 2

Cultures of the different microorganisms in exponential phase were washed 10 times by centrifugation with deionized distilled water and diluted to reach 5×10^3 CFU/mL. Subsequently, volumes of 10, 20, 40, 80, 160, and 320 mL of these suspensions were exposed to UV radiation for 5 min with and without stirring. The remaining viable bacteria were quantified as in the previous sections. This test was also conducted using *E. coli* at a concentration of 5×10^8 CFU/mL.

2.9. Antibacterial Activity of the LED Array Prototype

Cultures of *E. coli* were washed and resuspended at a concentration of 5×10^3 CFU/mL in 1 and 5 L of water, respectively. These suspensions were then exposed to UV irradiation using the prototype LED array for varying durations. The experiments were conducted under both static and stirring conditions. The surviving bacteria were quantified using methods outlined in previous sections. Furthermore, this test was extended to include a mixture of all bacteria in a 1:1 ratio, suspended in 5 L of water, and subjected to the same experimental conditions.

To assess the prototype's effect on an environmental sample, water samples were collected from the Piles River (Gijón, Spain), an urban natural environment with high contamination [7]. Samples of 5 L of river water were exposed to UV irradiation produced by the LED array prototype for different durations, under both static and stirring conditions, and the surviving viable microorganisms were quantified as in previous sections. The river water was not filtered before UV-C LED exposure. The assays were conducted under both aerobic and anaerobic conditions, for which an atmosphere generator system was used to maintain anaerobiosis. BHI medium was used under aerobic conditions, while TSB medium was used under anaerobic conditions.

3. Results

3.1. The Thermal Effects Generated by the LEDs Are Inadequate for Bacteria Elimination

All the LEDs used in this study caused water heating, although the observed pattern depended on each specific device. The least effect was produced by LEDs 6 and 8, increasing the temperature by around 3 °C. On the other hand, LEDs 3 and 4 increased it by approximately 30 °C. The remaining LEDs analyzed produced intermediate increases. In no case did the temperatures rise enough to compromise the viability of the microorganisms, ruling out the possibility of heat sterilization (Figure 1).

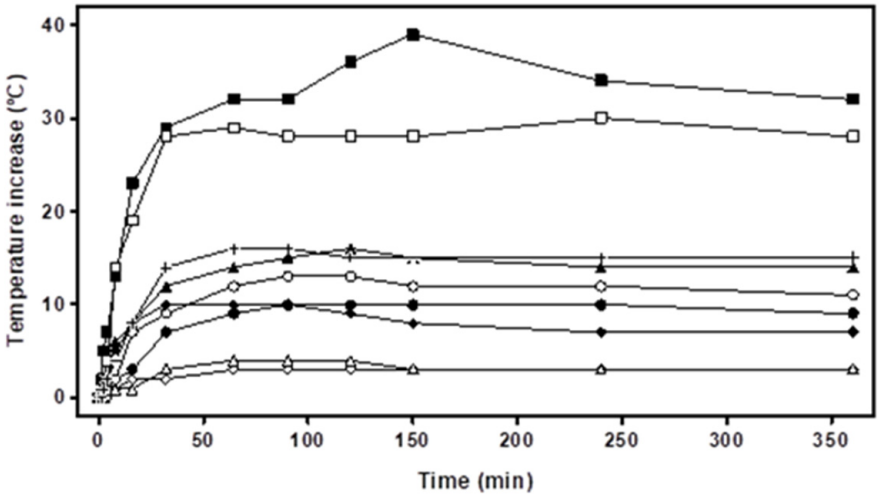


Figure 1. Effect of various LEDs in water temperature. Water heating of LED 1 (●), LED 2 (○), LED 3 (■), LED 4 (□), LED 5 (◆), LED 6 (◇), LED 7 (▲), LED 8 (△), and LED 9 (+).

3.2. The Influence of the Different LED Types on E. coli Viability

Under static conditions, all tested devices demonstrated the ability to completely sterilize the material, albeit with varying efficiencies. LED 1 required 180 min for the total elimination of viable bacteria, while LEDs 4, 5, 7, and 9 required 40 min and LED 3 required 20 min. LEDs 2, 6, and 8 exhibited the highest effectiveness, achieving sterilization in 10, 5, and 7 min, respectively (Figure 2). When tests were conducted under stirring conditions, the efficiency of the devices improved across the board. LED 1 achieved 100% mortality in 120 min, LED 4 in 40 min, and LED 2 in 2 min. LEDs 3, 5, 6, 7, 8, and 9 accomplished sterilization in less than 1 min (Figure 2). Based on its exceptional antibacterial activity under both static and stirring conditions, LED 2 was selected for further studies. Additionally, its relatively low cost (EUR 2.22/unit) positioned it as a highly competitive option for application in prototypes designed for disinfecting large volumes of water.

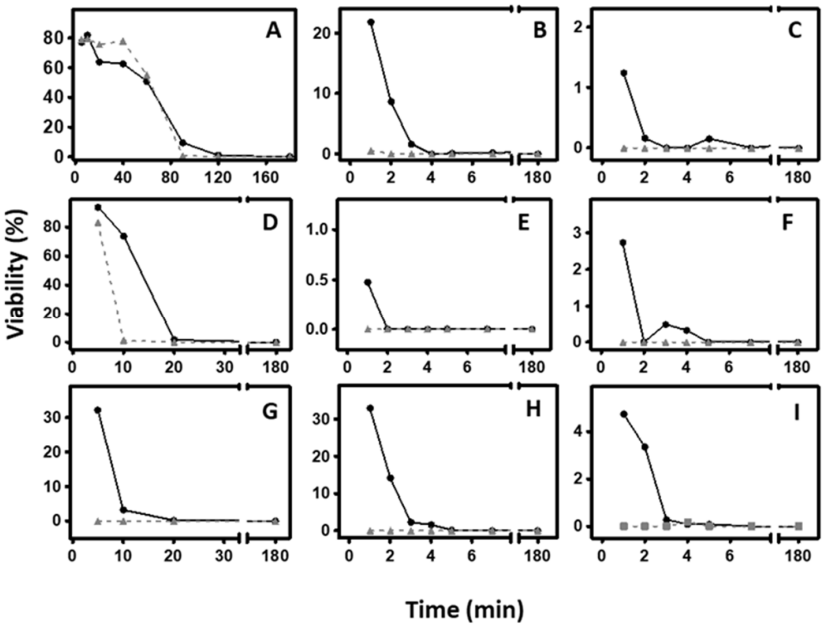


Figure 2. Influence of the different LEDs tested on *E. coli* viability. (**A**–**I**) Results of LEDs 1 to 9, respectively. Tests were conducted under static conditions (black, solid lines) or with stirring (gray, dashed lines). All tests were performed in triplicate.

3.3. LED 2 Exhibits Efficacy in Eradicating Both Vegetative Microorganisms and Resistant Cellular Forms

The effect of LED 2 was tested on suspensions of different pathogenic bacteria in water, including vegetative cells of *K. pneumoniae*, *E. faecalis*, *S. enterica*, and *C. perfringens*, as well as spores of *C. perfringens*. When tests were conducted under static conditions, viable vegetative cells were completely eliminated in 40 min and spores in 120 min (Figure 3A–E). Stirring increased the efficiency of the procedure, achieving 0% viability with 1 min of treatment in *K. pneumoniae* and *E. faecalis*, with 2 min in *S. enterica*, and with 1 and 5 min for the vegetative and resistant forms of *C. perfringens* respectively (Figure 3A–E). In the case of yeasts, it took 90 min and 120 min to kill *S. cerevisiae* and *C. albicans* under static conditions, but less than 40 and 5 min, respectively, under stirring (Figure 3F,G).

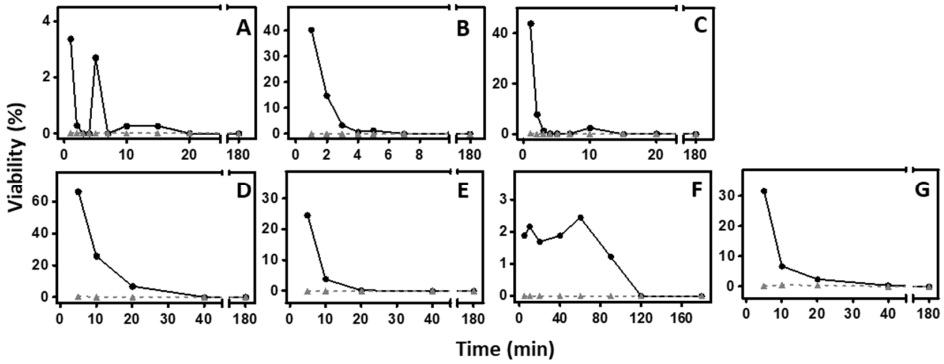


Figure 3. Effect of LED 2 on the viability of different microorganisms. (**A**), *K. pneumoniae*; (**B**), *E. faecalis*; (**C**), *S. enterica*; (**D**), *C. perfringens* (vegetative cells); (**E**), *C. perfringens* (spores); (**F**), *C. albicans*; (**G**), *S. cerevisiae*. Tests were carried out under static conditions (black, solid lines) or with stirring (gray, dashed lines). All tests were performed in triplicate.

3.4. The Impact of Bacterial Concentration and Sample Volume on the Sterilization Efficacy of LED 2

To determine the limits of LED 2 sterilizing capacity against increasing concentrations of microorganisms, these were progressively increased by five orders of magnitude, from 5×10^3 to 5×10^8 CFU/mL. Under static conditions, an increase in levels of surviving viable microorganisms related to the concentration used was observed, although the increases were dependent on each bacterial species (Figure 4). However, when tests were conducted under stirring conditions, the sterilization efficiency experienced a drastic improvement, with viability close to zero even at the highest concentrations (Figure 4).

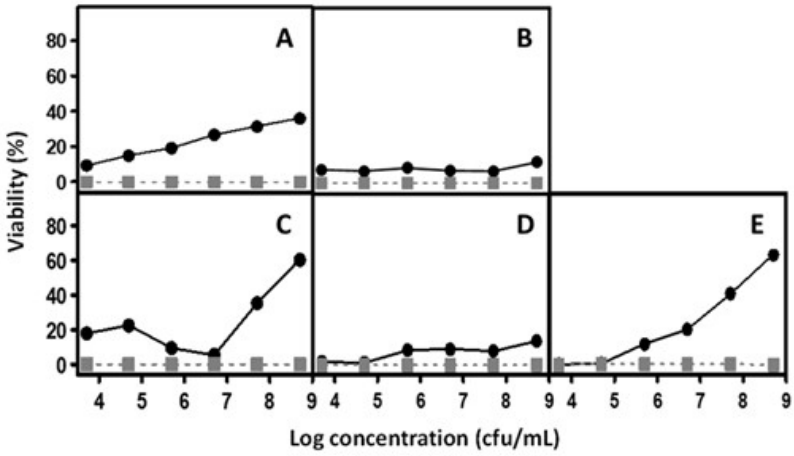


Figure 4. Influence of bacterial concentration on the sterilizing capacity of LED 2. (**A**), *E. coli*; (**B**), *K. pneumoniae*; (**C**), *E. faecalis*; (**D**), *S. enterica*; (**E**), *C. perfringens*. The tests were conducted for 5 min under static conditions (black, solid lines) or with stirring (gray, dashed lines). All tests were performed in triplicate.

The experiments described up to this point were conducted by placing each LED unit in a volume of 10 mL of water. To explore the limits of the device's sterilizing capacity, tests were performed using each bacterial species at a concentration of 5×10^3 CFU/mL in increasing volumes up to 320 mL. Under static conditions, the volume increase resulted in an increase in the number of viable microorganisms, following patterns dependent on each bacterial species. Conversely, the same series of tests conducted under stirring conditions showed total mortality for all microorganisms (Figure 5).

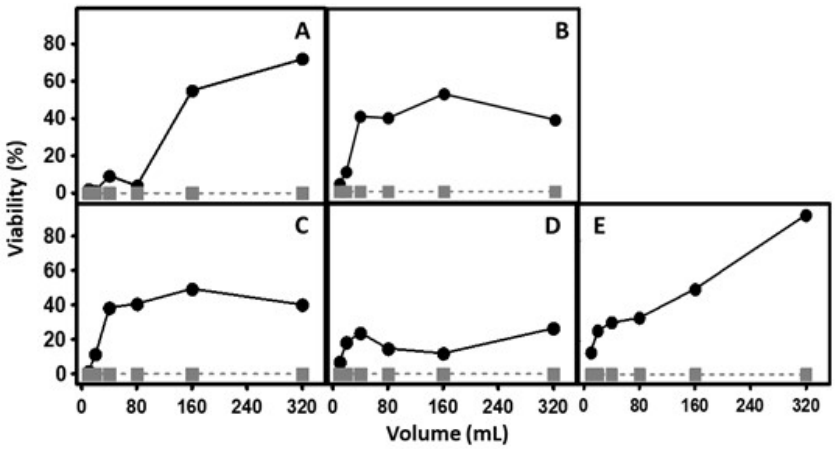


Figure 5. Influence of sample volume on the sterilizing capacity of LED 2. (**A**), *E. coli*; (**B**), *K. pneumoniae*; (**C**), *E. faecalis*; (**D**), *S. enterica*; (**E**), *C. perfringens*. Tests were carried out under static conditions (black, solid lines) or with stirring (gray, dashed lines). All tests were performed in triplicate.

Using *E. coli* at a very high concentration (5×10^8 CFU/mL), the sterilizing capacity was explored in the same range of sample volumes. The results showed partial mortality dependent on the volume when tests were carried out under static conditions, but total mortality in volumes up to 80 mL when agitation was used in the tests. Under these latter conditions, mortality was also very high in larger volumes, with only 8% viable at 320 mL (Figure 6).

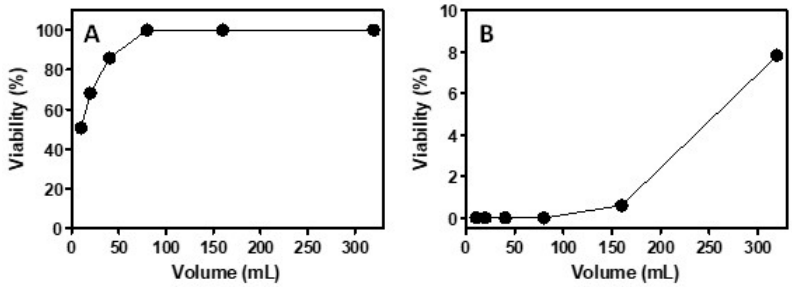


Figure 6. Influence of the volume of a suspension of *E. coli* at 5×10^8 CFU/mL on the sterilizing capacity of LED 2. (**A**) Test carried out under static conditions. (**B**) Test carried out in stirring. All tests were performed in triplicate.

3.5. Design of LED Matrix Prototype

An LED matrix prototype was developed to be immersed directly in water for sterilization purposes. The objective was to create a lightweight and flexible device capable of emitting UV-C light uniformly. Flexibility enables its insertion into any container without the need for specific designs beyond size. As previously mentioned, LED 2 was chosen as the optimal candidate for constructing the matrix prototype due to its bactericidal properties and low cost. The device was engineered to sterilize water volumes of up to 5 L, utilizing 18 LEDs with a sterilization capacity of 277 mL each. Flexible LED strips with

a 33.3 mm LED spacing were utilized, soldered in series, and encapsulated as described earlier. The prototype had final dimensions of 300 mm × 200 mm (Figure 7). The encapsulation conditions designed allowed the devices to pass the degradation test successfully under humidity exposure. There was no delamination of the assembly, and the LED strips functioned perfectly, confirming that there were no water leaks inside.

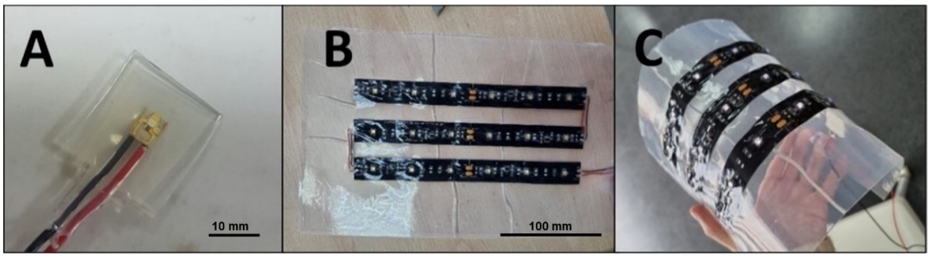


Figure 7. Design of LED matrix prototype. (**A**) Individually encapsulated LED; (**B**) prototype displaying the encapsulated LED array; (**C**) prototype demonstrating its flexibility.

3.6. Assessment of the Sterilizing Capacity of the LED Matrix Prototype

The determination of the effect of the device on the heating of 1 L of water showed a limited increase, reaching 6 °C after 6 h of exposure. The sterilizing capacity induced by the UV radiation of the device on *E. coli* was measured using 1 and 5 L of water. Under static conditions, no viable bacteria were detected in 1 L in less than 5 min, but 20 min was required for 5 L, whereas under agitation, less than 5 min was needed in both cases (Figure 8A,B). When the effect on a mixture of *E. coli*, *K. pneumoniae*, *E. faecalis*, *S. enterica*, and *C. perfringens* was tested in a volume of 5 L, no viable bacteria were detected in less than 5 min under aerobic and agitation conditions (Figure 8C).

The sterilizing capacity of the LED matrix was tested against a sample of urban river water with high levels of microbial contamination. Under static conditions, anaerobic microorganisms were eliminated within 60 min of exposure, whereas aerobic ones required 90 min (Figure 9A,B). However, under agitation, aerobic and anaerobic microorganisms were completely eliminated in 10 and 5 min, respectively (Figure 9C,D).

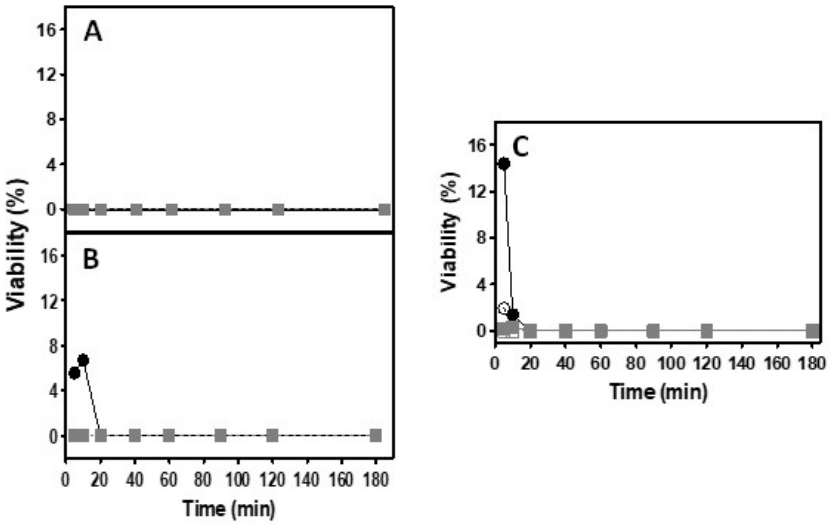


Figure 8. Influence of LED matrix prototype on bacterial viability. (**A**) Influence of LED matrix on *E. coli* viability in 1 L of water. (**B**) Influence of LED matrix on *E. coli* viability in 5 L of water. Tests were carried out under static conditions (black, solid lines) or with stirring (gray, dashed lines). (**C**) Influence of LED matrix on *E. coli*, *K. pneumoniae*, *E. faecalis*, *S. enterica* and *C. perfringens* in 5 L of water, in both aerobic and anaerobic atmospheres. Static and aerobic conditions (black circles); static and anaerobic conditions (white circles); stirring and aerobic conditions (gray squares); stirring and anaerobic conditions (white squares). All tests were performed in triplicate.

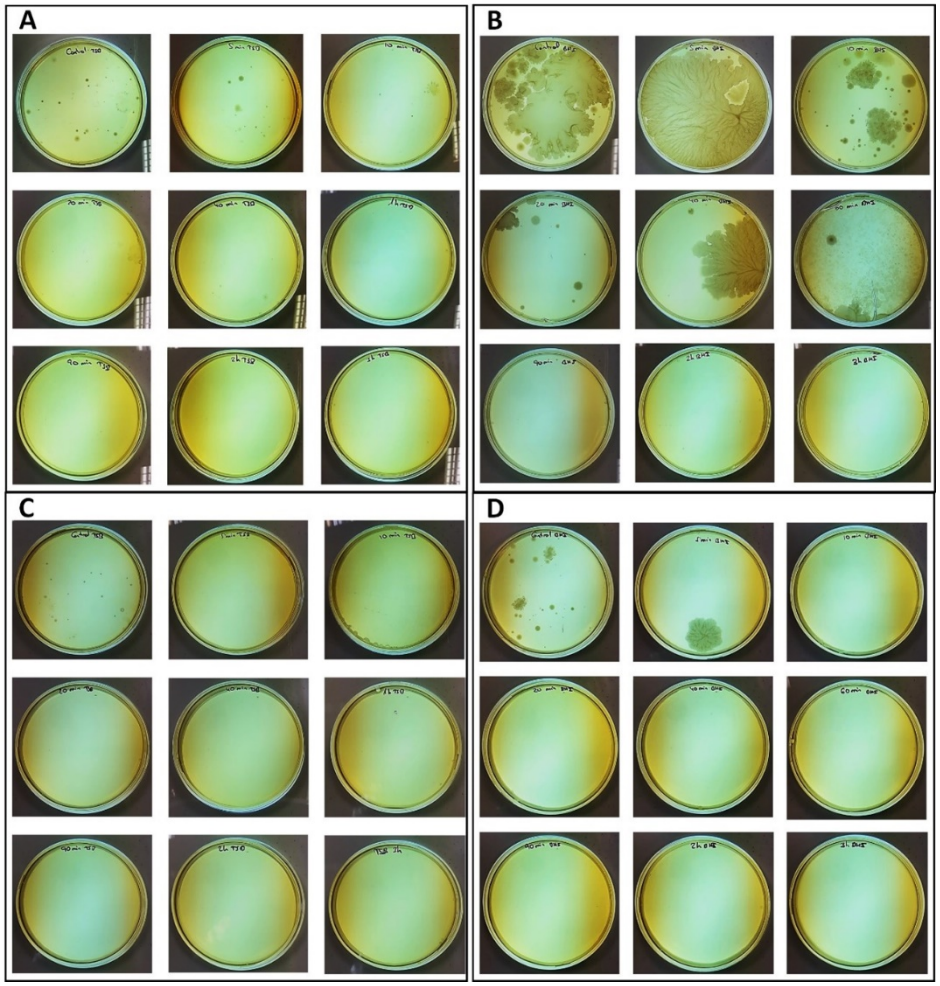


Figure 9. Effect of LED array prototype on microorganism viability in 5 L of river water. (**A**,**C**) Effect on anaerobic microorganisms. (**B**,**D**) Effect on aerobic microorganisms. (**A**,**B**) Trials conducted under static conditions. (**C**,**D**) Trials conducted under stirring. In all cases, exposure times (from left to right and top to bottom) were: control, 5, 10, 15, 20, 40, 60, 90, and 120 min.

4. Discussion

The aim of the present study was to design a flexible, low-cost, and easily integrated device that incorporates UV LED technology within polymers capable of direct contact with water for sterilization purposes. To achieve this, polymers such as ETFE and EVA were chosen for their suitable properties as encapsulants for UV LEDs. ETFE was selected for its lightweight and flexible nature, which does not degrade or yellow under UV radiation. On the other hand, EVA was chosen for its transparency and high adhesion properties. The ability to easily configure an array of LEDs to match the required dimensions and geometry for specific applications represents an advantage over traditional standard UV disinfection systems.

Initially, different encapsulated LEDs obtained from various manufacturers were tested to identify the best candidate for the application. Since the goal was to measure the antibacterial properties of UV rather than heat-induced death, the heating produced by the different devices was determined. It is known that non-sporulating bacteria die above 50 °C, whereas spore-forming bacteria require at least 100 °C [8]. The results showed that the LEDs used did not generate sufficient heat to produce a sterilizing effect.

Several studies have analyzed the removal of viable microorganisms caused by UV light [9,10]. LED devices have also been described as more cost-effective than other options, such as the use of mercury lamps [5,11]. To study the sterilizing capacity of LEDs, *E. coli*

suspensions were employed, as this microorganism serves as an indicator of pathogenic bacteria and fecal contamination, making it a good measure of water quality [12].

The assays conducted in this work demonstrated that all the LEDs used could produce total microorganism death, although there were notable differences in their respective efficiencies. LEDs 6, 8, and 2, under agitation conditions, yielded the best results, with the first two capable of completely eliminating viable bacteria in less than 1 min and the third in less than 2 min. In the absence of agitation, the times required for sample sterilization increased significantly. The decrease in bacteria survival capacity under agitation conditions has been described [13] and has been attributed to the homogenization of the average irradiation distances achieved under these conditions [14]. The price per unit of LED 2 was EUR 2.22, while those of LED 9 and LED 6 were 530% and 918% more expensive, respectively (EUR 11.78 and EUR 20.39). This efficiency-price ratio led to the selection of LED 2 as the best candidate for the project.

To study in detail the effect of UV radiation from LED 2 on bacterial viability, three basic parameters were evaluated: time, concentration, and sample volume. Sanitary criteria to ensure the safety of drinking water for human consumption determine the analysis of certain microbiological parameters, including the viability of *E. coli*, *Enterococcus*, and *C. perfringens*, the latter including both vegetative forms and resistance spores [15]. This study also included two pathogens, *S. enterica* and *K. pneumoniae*. In all cases, LED 2 was able to affect bacterial viability, although the time needed to achieve this effect depended on each species, with *C. perfringens* being the most resistant, while *K. pneumoniae* and *E. faecalis* were easily eliminated. These results are consistent with previous descriptions that established the influence of time, concentration, and volume on microorganism viability [4,16]. *C. perfringens* is a facultative anaerobe capable of producing endospores, allowing it to survive in adverse conditions such as extreme temperatures and lack of nutrients, which hinders its elimination [17,18]. In this regard, LED 2 also showed its effectiveness against endospores, successfully eliminating them in less than 5 min under agitation.

Although the presence of pathogenic yeasts in aquatic environments has recently raised concerns about their impact on human health [19], the risk of waterborne fungal infections is a less studied aspect. The results of this study showed that LED 2 was able to eliminate *C. albicans* and *S. cerevisiae* with great efficiency, particularly under stirring. *C. albicans* was more resistant under static conditions, whereas *S. cerevisiae* showed less sensitivity under agitation. These results were consistent with previous studies indicating that inactivation kinetics depend on the yeast strain, among other factors. Cellular adhesion to particles or suspended surfaces and the formation of aggregates that protect cells can diminish the bactericidal efficacy of radiation. Additionally, the structural characteristics of each strain may influence the LED effect [20].

Parameters required for drinking water typically refer to a bacterial concentration of 0 CFU/100 mL. For this reason, it is necessary to develop a method that can sterilize high concentrations of bacteria and large volumes of water. To analyze the effect of concentration on bacterial viability after UV radiation exposure, bacterial cultures were irradiated at different concentrations for 5 min, under both stirring and static conditions. The results showed a decrease in efficiency with increasing concentrations of microorganisms under static conditions, but high efficiency under stirring, even at the highest concentrations.

The effect of parameters such as bacterial concentration and water volume on sterilizing capacity was also analyzed. The use of microbial concentrations ranging from 5×10^3 to 5×10^8 CFU/mL showed species-dependent effects under static conditions, but nearly total mortality at all concentrations under stirring. Regarding volume, total sterilization was achieved at bacterial concentrations from 5×10^3 up to at least 320 mL, and up to 80 mL at concentrations as high as 5×10^8 CFU/mL. These results are consistent with previous studies showing that surface area and volume influence the bactericidal properties of LEDs because they are related to the radiation distance [4,21].

With the information obtained, a prototype was constructed using an array of LED 2. The design was flexible to allow adaptability to containers and integrated a total of 18 LEDs,

with dimensions of 300 × 200 mm. The goal was to sterilize volumes of up to 5 L of water. The device proved capable of sterilizing bacterial mixtures in laboratory conditions in less than 5 min under stirring. As a final test, it was tested against an environmental sample of contaminated water, yielding results dependent on exposure time and stirring, but achieving total sterilization of the samples. These results align with the described fact that the antibacterial effect is dependent on volume and exposure time [22]. An operational suggestion on how to apply the agitation device in a practical application is shown in Supplementary Figure S1.

According to their manufacturers, a useful lifespan of approximately 25 years is guaranteed for the polymers utilized in encapsulating the prototype. EVA was specifically selected for its favorable plastic properties, high adhesion, and exceptional transparency, which may diminish due to degradation from prolonged exposure to solar radiation. ETFE, on the other hand, is lightweight, flexible, and resistant to degradation or yellowing under extreme environmental conditions or UV radiation. Over time, there may be a risk of adhesion loss and delamination between the different layers. Nevertheless, leak tests on the prototypes have been conducted by immersing the assembly in water for 1000 h, during which both the encapsulation and LEDs continued to function flawlessly. Therefore, the device's useful lifespan would align with that of the LED itself.

5. Conclusions

In conclusion, this work has described the antibacterial effect of different encapsulated LEDs suitable for immersion in water. This property was studied using different conditions, such as exposure times, bacterial concentrations, water volumes, and stirring, concluding that LED 2 was the best candidate due to its efficiency and low cost. The design of a flexible matrix integrated with LED 2 proved to be an effective alternative for eliminating both aerobic and anaerobic microorganisms from contaminated water in short periods of time. Additionally, stirring conditions significantly enhanced the antimicrobial effect of UV radiation, underscoring the importance of this parameter in optimizing LED sterilization protocols. These results highlight the sterilizing effectiveness of a low-cost polymer-encapsulated design, flexible for easy adaptation to any container, and based on an array of LEDs that enable uniform UV light emission and straightforward adjustment to the required size and geometry.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/app14135635/s1. Figure S1: Example of a tank with the device centered, illuminating UV in both directions.

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