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A New Frontier: Photovoltaics and Light-Emitting Diode Technology for Water Disinfection in Remote and Developing Areas

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Abstract

The lack of effective water disinfection in remote and developing areas contributes to the spread of waterborne diseases which claim millions of lives annually. Water sources vary in quality. The water distribution system in some areas is primarily biofilm-fouled water containers which cause contamination. To protect against the latter, advances in Point of Use (POU) technologies are urgently needed.

One POU technology option is ultraviolet (UV) water disinfection which is effective for a wide range of pathogens, consumes no chemicals and leaves no odors, tastes or residues. Recent developments in semiconductor technology have produced UV-C (200-280nm) light-emitting diodes (LEDs), potentially suitable for POU water disinfection.

In this paper, we examine the present state of LED technology and its synergies with PV. Experimental data from a prototype system will be presented which validates the concept. We also explore the cost benefit optimization of LED and power supplies. Parallels between PV pumping and lighting projects and benefits over SODIS will be discussed. It seems quite likely that in the near future, the PV-powered LED-based POU disinfection will be feasible and valuable for clean water supply in remote and regional communities.

1. Introduction

Photovoltaic (PV) powered water pumping and lighting projects have become common in remote and developing areas (Derrick, 1994, Odeh et al., 2006). However, ensuring water is clean is more problematic, in part, due to the use of biofilm-fouled water containers that cause recontamination (Sobsey, 2007).

To address this point-of-use (POU) disinfection is required, with UV disinfection being a promising candidate. UV disinfection operates by directly damaging the DNA of pathogenic microorganisms and inhibiting their reproduction. Different pathogens differ in sensitivity, defined by their 'Action Spectra', examples of which are available in Bolton and Cotton (2008) and Webb and Brown (1979).

Recent developments in light-emitting diode (LED) technology have resulted in the emergence of UV-C (200-280nm) germicidal LEDs which overcome many limitations of traditional UV disinfection (Shur and Gaska, 2010, Khan et al., 2005). These, along with the existing high-volume mass-produced UV-A (315-400nm) and visible LEDs, could realize

affordable PV-based disinfection of water, due to their use of low voltage DC power and insensitivity to intermittent power supply (Aoyagi et al., 2011).

As a result, PV-powered LED disinfection has the potential to provide a sustainable, low-carbon, low-maintenance solution to those in need and open up new markets for PV. However, there are some issues that still need to be resolved, including the optimum combination of LED cost, power supply size and germicidal potential. Such issues, background and other aspects of PV LED-based disinfection are further elaborated in Lui et al. (2014).

This paper reports on key aspects regarding the feasibility and optimization of a PV-powered POU disinfection system based on bench-scale experiments using a range of LEDs.

2. Materials and Methods

2.1. Bench Scale Prototype Disinfection System

The bench scale prototype system consists primarily of LED arrays, current driver circuitry, water containers, and window material. A diagram of the set-up is illustrated in Figure 1.

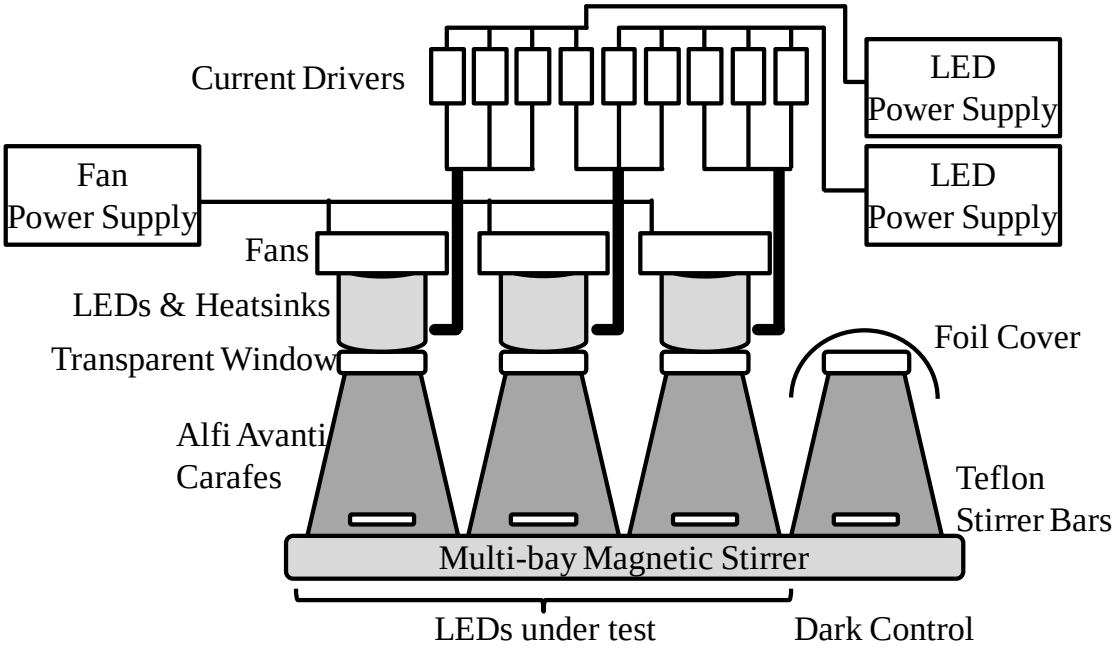


Figure 1. System Diagram

2.1.1. LED Arrays

A variety of commercial LEDs were used to construct low power arrays which aimed to achieve disinfection over periods of up to 6h (Table 1). The size of the LED arrays are constrained by cost, and reasonable power consumption (up to 35W) and thermal output/heat dissipation for a POU system.

Table 1. LED Array Configuration

Wavelength (nm)	Quantity, Vendor & Model of LEDs	Price (AU$)
270	5 x Sensor Electronic Technology Inc. UVTOP270TO39FW	1168
310	3 x Sensor Electronic Technology Inc. UVTOP310TO39FW	768

365	2 x LED Engin Inc. LZ1-10U600 1 x LED Engin Inc. LZ4-40U600-0000	246
455	7 x Cree XTEARY-02-0000-000000N04	33
525	3 x LED Engin Inc. LZ4-40G100-0000	102

Each of the arrays, except the 270nm and 310nm arrays, were mounted to a Fischer Elektronik SK 584/50 SA 1K/W round heatsink using thermal conductive compound, with additional cooling provided by a 120mm fan.

2.1.2. Power Supply

To mimic small PV units electricity was supplied by a pair of Manson HCS-3102 benchtop power supplies. Current driver units were built depending on the LED array requirements:

- For the 270nm and 310nm arrays, an On Semiconductor NSI45020AT1G 20mA linear regulator was used with all LEDs in a series string. The power supply was configured to provide 36V.
- For the 430nm array, an XP Power LDU2430S1000 DC-DC 1000mA LED Current Driver Module was used, with the power supply set to provide 28V.
- For all other wavelength arrays, an XP Power LDU2430S700 DC-DC 700mA LED Current Driver Module was used, with one LED package per channel, and the power supply set to provide 28V.

Multiple current driver modules were run from each power supply with the loading kept below 50% maximum current to ensure output current regulation.

2.1.3. Other Components

A number of Alfi Avanti 1.3L vacuum carafes with reflective glass inserts were used as proxies for water containers. The liquid within the flasks was stirred using teflon coated magnetic stirrer bars and a multi-bay stirrer unit. Protection against liquid contact was provided by polished quartz round windows for 270nm and 310nm LEDs, and round UV-transmissive Perspex® windows for other wavelengths (transmission >95%).

2.2. Inactivation Experiments

A stationary phase culture of *E. coli* K12 was prepared by inoculating a typtone soya agar slope and incubating for 24 hours at 35°C. Sterile 1 L volumes of 0.05M NaCl solution were pH adjusted to 7.6 ± 0.1, and inoculated to approximately 10^6 organisms/mL. The solutions were transferred to the vacuum carafes with clean teflon magnetic stirrer bars. Windows were positioned on the containers' mouths, followed by LED arrays and cooling fans.

The LEDs and stirrers were operated for up to six hours per run. Liquid samples were extracted, using a glass Pasteur pipette over the course of each experiment. For initial screening experimental runs, the drop-plate counting method (triplicate samples) was used. For repeat experiments, a spread-plate method was used where liquid was serially diluted (phosphate buffered saline) and spread plated on tryptone soya agar plates. All plates were incubated for 24 hours at 35°C before colony counting to determine the numbers surviving. One container per experiment was used as a dark control.

Inactivation as a function of LED power output was determined from the experimental data and plotted as $\log_{10}$ reduction, where one $\log_{10}$ is a 90% reduction, 2-log is a 99% reduction, and so on. The fluence (otherwise known as dose, represented as mJ cm^{-2}) was determined by

dividing the optical input power by the largest cross-sectional area of the flask (130mm diameter). As the water is continuously stirred, all of the liquid would receive this average level of fluence. Only data from the spread-plate runs have been plotted, as the drop-plate runs were used to provide confirmatory (above/below a given log reduction level) data. At all points, the drop-plate runs agreed with the data yielded by the spread-plate runs.

2.3. LED Array Outputs

2.3.1. Dominant Wavelength

Characterization of dominant wavelength was achieved by powering LEDs at room temperature (21°C) for <1 s then recording the spectrum using an Ocean Optics S2000 fibre-optic spectrometer and OOIBase32 software. The wavelength corresponding to the peak reading was recorded as the dominant wavelength, and the difference in wavelength between bins with half of the peak reading was recorded as the full width at half maximum (FWHM).

2.3.2. Output Power

The array output power of the LEDs were determined by reading the manufacturer-provided test report data for 270nm and 310nm LEDs, and by consulting datasheets for all LEDs except 430nm where no data was available. Verification of the output power was performed using the dual-integrating sphere method with a Perkin-Elmer 150mm Integrating Sphere, a set of 2mm and 3mm aperture plates and an Ocean Optics FOIS-1 Integrating Sphere. The spectrometer above was calibrated using an Ocean Optics DH-2000 Deuterium/Halogen Calibration Light Source.

3. Results and Discussion

3.1. LED Dominant Wavelength

The results are summarized in Table 2. Due to the array construction, some LEDs were not measured independently but with the whole array as a unit.

Table 2. Measured LED Dominant Wavelength and Full Width at Half Maximum

Wavelength (nm)	**Measured Dominant Wavelength (nm)**			**Full Width at Half Maximum (nm)**		
	Sample 1	**Sample 2**	**Sample 3**	**Sample 1**	**Sample 2**	**Sample 3**
270	272.39 (whole array)			9.90 (whole array)		
310	311.45 (whole array)			10.17 (whole array)		
365	370.31	368.58	366.85	10.04	9.69	9.34
455	448.41 (whole array)			20.01 (whole array)		
525	521.16	522.49	521.81	35.12	34.12	35.12

Table 2 illustrates the variation in commercially available LEDs. The nominal wavelength is often the shortest wavelength for that particular model, actual wavelength is often longer. The manufacturer also maintains a tolerance on their wavelength measurements. In array units, poor matching of LEDs will increase the apparent FWHM.

It also illustrates that LED light sources are not truly monochromatic, and will put out significant energy up to 15nm either side of the dominant wavelength. At wavelengths at the boundaries of semiconductor material systems, the output spectral distribution can show asymmetry, as illustrated in Figure 2.

This may be important as the action spectra for pathogens feature significant plateaus and dips, and variable performance could result if the dominant wavelengths of different batches of the same type of LED straddle these variations.

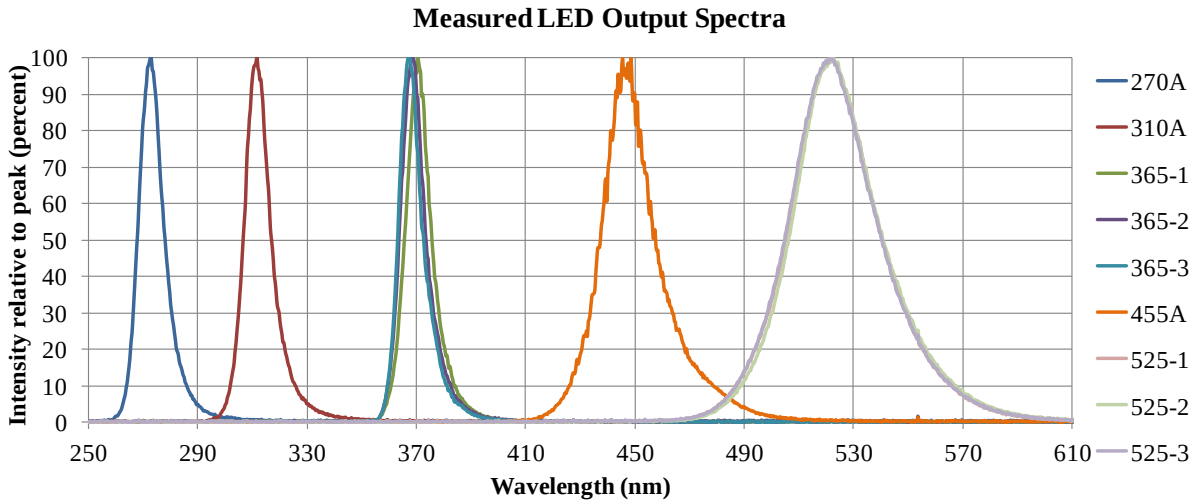


Figure 2. Measured LED Output Spectra

3.2. LED Input and Output Power

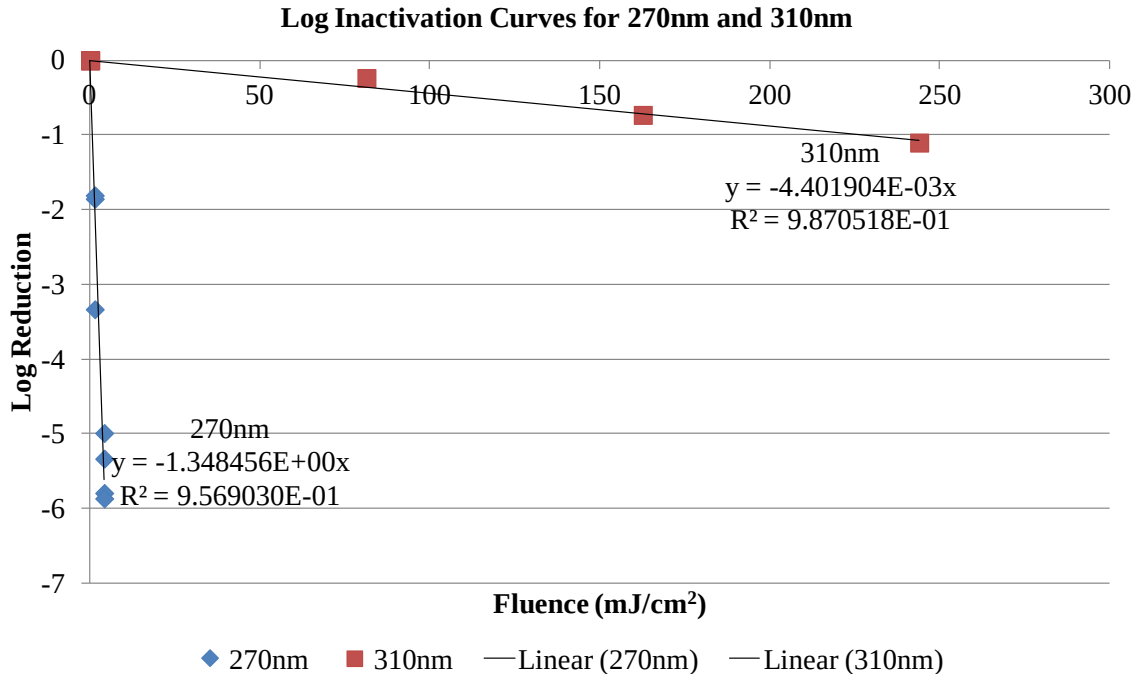
The LED input and output power is summarized in Table 3. The range of powers for each LED unit can be significant. Only the UVTOP series of LEDs were provided with a test report indicating measured power. For LEDs within the visible region, radiometric power values were not provided and were converted from lumens (with some level of error). Additionally, as each LED varies in its forward voltage at operating current, the power consumption is also subject to slight variation.

An attempt was made to verify the typical figures provided, however, precise estimation proved challenging. Reasons included calibration light source and integrating sphere port fraction uncertainties and accuracy of reflectance data for Spectralon. As an interim measure, reported typical optical power has been used to estimate inactivation.

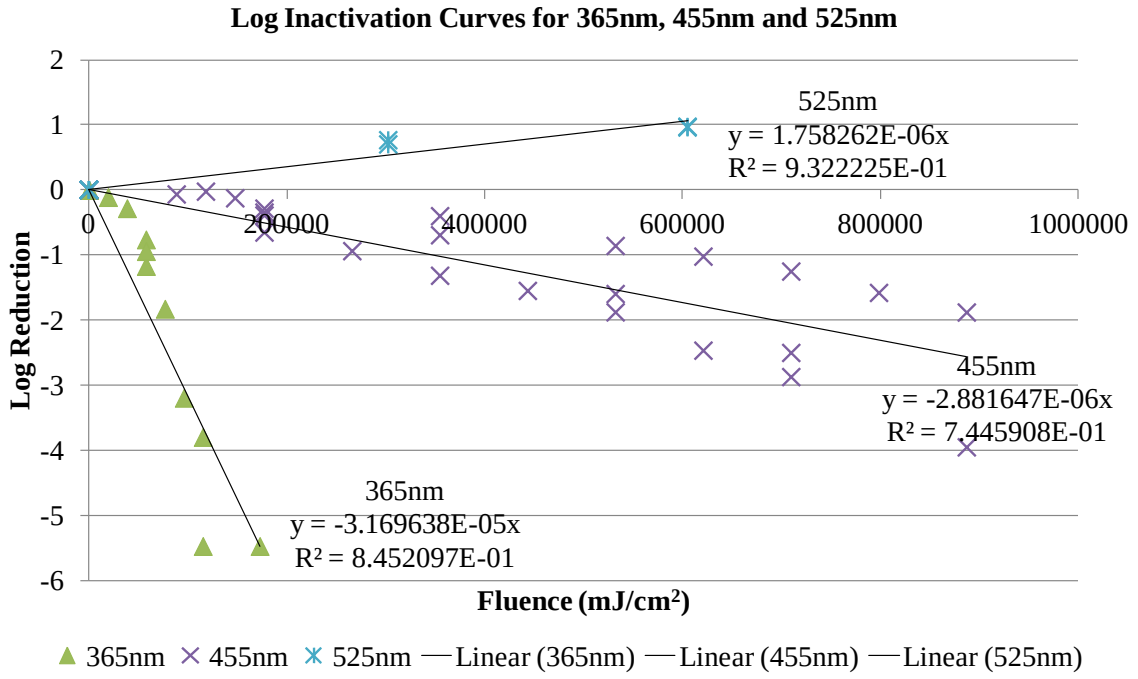
Table 3. LED Array Power

Wavelength (nm)	Optical Power Range (mW)	Typical Optical Power (mW)	Typical Electrical Input Power (W)	Electrical Efficiency (%)	Lifetime (hours to a percentage of initial output)
270	2.4 - 4.0	3.069 (manufacturer tested)	0.552746 (manufacturer tested)	0.56	250 to 50%
310	1.08 - 1.80	1.499 (manufacturer tested)	0.302603 (manufacturer tested)	0.50	5000 to 50%
365	1068 - 3420	2120	17.22	12.31	Not Specified
455	Not Specified	6545	15.043	43.51	>60500 to 90%
525	2757 - 5379	3719 (from lumens)	30.24	12.30	65000 to 70%

3.3. *Log_{10} Inactivation versus Fluence (Dose)*



(a)



(b)

Figure 3. Log Inactivation Curves

Figure 2a illustrated how bacteria are much more sensitive to 270nm and 310nm as compared with 365nm though 310nm radiation did not result in useful disinfection within the six hour period due to the relatively low output power of the diodes compared to bacterial sensitivity. Successful (> 3 log_{10}) reduction was achieved within six hours for 270nm and 365nm, with borderline inactivation (2.6 log_{10}) for 455nm. For the visible wavelength of 525nm disinfection was below the detection threshold, and appears to be reversed likely due to the final division of bacteria from beginning of the experiment (i.e. no true growth).

3.4. Sizing and Cost Sensitivity - LED Arrays versus PV Modules

The power consumption of the LED arrays ranges from 0.3W to 33W. As the better performing LED arrays cost AU$200 to AU$1200, the cost of energy appears much less important than the PV outlay (~AU$1/Wp). However, the power consumption will have a direct bearing on the sizing of batteries and balance of system costs, and thus lower-consumption UV-C (200nm-280nm) LEDs may still be preferable.

The power consumption of the LED arrays is similar to the power consumption of water pumps and lighting, thus similar system designs can be utilized. A parallel between water pumping demands and disinfection demands is apparent, as disinfection can be useful during the daytime without any storage of energy by short term storage of disinfected water. Flow-based disinfection systems utilize low-flow water pumps, a mechanical motor-based load, with identical load-based challenges of best driving motors for water pumping (Mokeddem et al., 2011). An additional challenge is introduced, in the need to match a more complex load including the LEDs. Integration of disinfection with water pumping appears to be possible.

A more sophisticated POU disinfection system which disinfects water on demand would involve battery storage and LEDs, which mimics the requirement of PV lighting deployments in collecting energy through the daytime for use at other times. The power consumption of fluorescent lamps commonly ranges from 8w to 38w which is similar to LED requirements. Existing LED-focused lighting designs (Ye et al., 2010, Vieira and Mota, 2010) may be adaptable for driving UV LEDs by redesigning for the required voltage and current.

3.5. Comparison with SODIS

The Solar Disinfection Method (SODIS) utilizes PET drinking bottles and six hours of strong direct sunlight to disinfect water at POU (SODIS, 2012). This method, while conceptually very attractive because the technology is minimal, suffers drawbacks because of its absolute requirement for intense sunlight year round. The action spectra for pathogens also strongly favour UV wavelengths but, due to atmospheric filtering, these are diminished when the sun is obscured by cloud or is at low elevation angles due to locality (latitude) and seasonality. Disinfection volumes are also limited to *ca* 1 L drinking bottles, and daylight hours.

By using a PV-powered system, it appears feasible to exploit the whole sunlight spectrum (including visible) to generate electricity which can be stored in a battery to provide disinfection on demand, with a guaranteed amount of UV dosage. By sizing the PV array accordingly, sufficient energy supply could be ensured, in essence concentrating the solar energy collected across a large area. With appropriate reactor design, it might also be used with larger drinking water containers to provide a complete disinfected household supply.

4. Conclusion

PV powered LED disinfection has the potential to provide a new market and application for PV power. Its requirements are similar to lighting and pumping, which has already been successfully widely deployed in developing countries. The integration of water disinfection could reduce the risk of waterbone diseases.

Successful disinfection within a six hour period was demonstrated with 270nm and 365nm radiation using the bench-scale prototype, making the concept feasible even with less germicidally efficient, low-cost, mature LED technologies. Power costs are small compared to the outlay in UV LEDs and are currently not the limiting factor though this could change is LEDs decrease in price.

UV-C LEDs demonstrated superior disinfection speed, with low power requirements. As UV-C and UV-B (280-315nm) LEDs continue to mature, their costs are expected to fall along

with an increase in power output, lifetime and efficiency, further improving their appeal. It was also demonstrated that commercially available LEDs vary in their spectral output quality and power output, and that disinfection units should take this into account.

The concept is able to address constraints with SODIS. In order to bring the concept to reality, research into integration and matching with PV power and optimal reactor design for POU water containers is necessary. This would allow for solar-powered water disinfection all year round outside of equatorial zones currently favored for SODIS.

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