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Point-of-use water disinfection using ultraviolet and visible light-emitting diodes

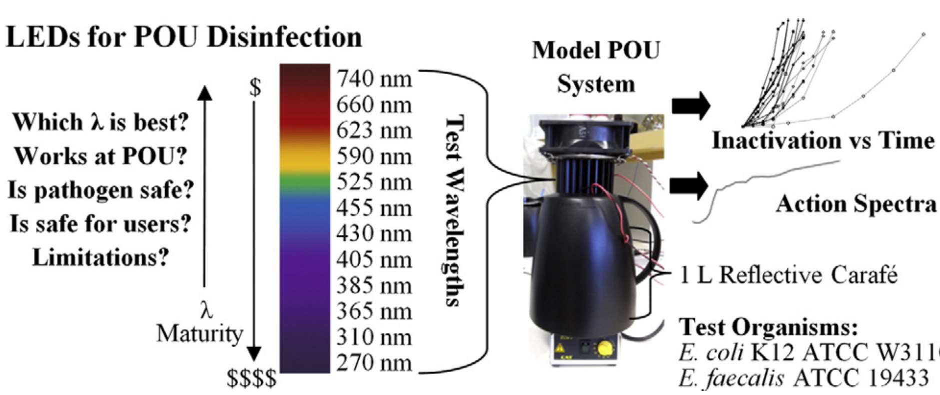
Gough Yumu Lui [a,b], David Roser [a,*], Richard Corkish [b], Nicholas J. Ashbolt [a,c], Richard Stuetz [a]

[a] UNSW Water Research Centre, School of Civil and Environmental Engineering, University of New South Wales, Sydney, NSW 2052, Australia
[b] School of Photovoltaics and Renewable Energy Engineering, University of New South Wales, Sydney, NSW 2052, Australia
[c] School of Public Health, South Academic Building, University of Alberta, Edmonton, Alberta T6G 2G7, Canada

HIGHLIGHTS

- Disinfection of *E. coli* and *E. faecalis* achieved with 270 and 365–455 nm LEDs
- No significant disinfection was found with 310 and >455 nm LEDs.
- UV-C LEDs offer speed and low-power; UV-A LEDs offer slower but safer operation.
- Significant photo-reactivation and lag phase was observed with UV-A disinfection.
- POU LED disinfection practical, subject to cost and engineering considerations

GRAPHICAL ABSTRACT



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ABSTRACT

Improvements in point-of-use (POU) drinking water disinfection technologies for remote and regional communities are urgently needed. Conceptually, UV-C light-emitting diodes (LEDs) overcome many drawbacks of low-pressure mercury tube based UV devices, and UV-A or visible light LEDs also show potential. To realistically evaluate the promise of LED disinfection, our study assessed the performance of a model 1.3 L reactor, similar in size to solar disinfection bottles. In all, 12 different commercial or semi-commercial LED arrays (270–740 nm) were compared for their ability to inactivate *Escherichia coli* K12 ATCC W3110 and *Enterococcus faecalis* ATCC 19433 over 6 h. Five $\log_{10}$ and greater reductions were consistently achieved using the 270, 365, 385 and 405 nm arrays. The output of the 310 nm array was insufficient for useful disinfection while 430 and 455 nm performance was marginal (≈4.2 and 2.3-$\log_{10}$s *E. coli* and *E. faecalis* over the 6 h). No significant disinfection was observed with the 525, 590, 623, 660 and 740 nm arrays. Delays in log-phase inactivation of *E. coli* were observed, particularly with UV-A wavelengths. The radiation doses required for >3-$\log_{10}$ reduction of *E. coli* and *E. faecalis* differed by 10 fold at 270 nm but only 1.5–2.5 fold at 365–455 nm. Action spectra, consistent with the literature, were observed with both indicators. The design process revealed cost and technical constraints pertaining to LED electrical efficiency, availability and lifetime. We concluded that POU LED disinfection using existing LED technology is already

Abbreviations: Deep-UV, LEDs emitting in the UV-B (290–320 nm) and UV-C (100–290 nm) region; DWL, dominant wavelength, the wavelength where peak emission occurs; FWHM, Full Width at Half Maximum, indicating spectral emission width at 50% intensity; LED, light-emitting diode, a semiconductor device which produces light from a DC current through electroluminescence.

* Corresponding author at: Water Research Centre, School of Civil and Environmental Engineering, University of New South Wales, Sydney, NSW 2052, Australia.
E-mail addresses: gough@student.unsw.edu.au (G.Y. Lui), djroser@unsw.edu.au (D. Roser), r.corkish@unsw.edu.au (R. Corkish), ashbolt@ualberta.ca (N.J. Ashbolt), r.stuetz@unsw.edu.au (R. Stuetz).

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technically possible. UV-C LEDs offer speed and energy demand advantages, while UV-A/violet units are safer. Both approaches still require further costing and engineering development. Our study provides data needed for such work.

1. Introduction

Existing point-of-use (POU) disinfection technologies, employing chemicals and filtration, often fall short of meeting the water disinfection needs of remote and regional communities. This is because they are constrained by logistics and efficacy issues such as supplying limited lifespan and high cost consumables, performance limitations, high energy demand, safety assurance and reliability (Lui et al., 2014). Irradiation by ultraviolet (UV) or shorter visible wavelength light, is an attractive alternative (Bolton and Cotton, 2008) because light can inactivate a broad range of microorganisms, uses no chemical consumables, generates few disinfection by-products, and leaves no residual odour or taste.

Traditional light radiation based methods, notably UV-C emission tube technology and SODIS, are also constrained by logistics, weather and geography. However, it is now possible, to efficiently and safely generate UV and visible light using light emitting diodes (LEDs). LEDs address disadvantages of current low-pressure (LP) mercury tube technology (Shur and Gaska, 2010) such as power-cycling penalties, warm-up time, high voltages, fragility, loss of lamp output (Heath et al., 2013), and mercury content. They have a lower power rating than most UV-C tubes and run on safe low-voltage direct-current (Brownell et al., 2008; Chatterley and Linden, 2009). Consequently, in combination with photovoltaic (PV) solar panels, they promise reliable cost effective low maintenance water disinfection for those communities which most need it e.g. in rural Africa, Asia and Latin America.

Despite this promise, developmental work is still needed. In our review of LED disinfection, we identified how commercial deep-UV LEDs continue to be expensive, exhibit suboptimal electrical efficiencies and have uncertain operational lifespans (Lui et al., 2014). Further, despite positive market growth projections and manufacturer statements indicating impending availability, low-cost high-powered deep-UV LEDs are yet to eventuate and advancement is also constrained by the limited number of manufacturers (Hirayama et al., 2015).

A separate question was which LED development road is preferable, one based on lower powered expensive UV-C based units or one based on more mature, UV-A (315–400 nm) and visible range (400–740 nm) LEDs which are also capable of substantial disinfection (Lui et al., 2014; Maclean et al., 2009; Mori et al., 2007) and are already commercially viable. Compared to UV-C and UV-B emitters, UV-A and visible light LEDs already have large markets (e.g. for lighting, signage), possess long lifetimes, and are relatively inexpensive, mass produced, and widely available. Their effectiveness should also be less impacted by absorption by waterborne organics (e.g. tannins), than UV-C (Cantwell and Hofmann, 2011).

From these considerations two central questions emerged for us. Firstly, what is the optimum mix of wavelength, disinfection power, LED cost, lifetime, and emission efficiency? Secondly, how well can engineering constraints and costs be harmonised with electrical power supply and the realities of regional community and household clean water needs? To answer these questions we perceived that we required detailed knowledge of i) LED inactivation variability, i.e. disinfection action spectra analogous to those for UV-C (Izadifard et al., 2013), and ii) experiment based insights into the engineering challenges e.g. ensuring eye safety, preventing overheating.

We concluded that to answer these questions we should undertake a series of pathogen inactivation experiments using a model (POU) reactor comparable to that which could be used in a regional or remote community. Thus we have quantified *Escherichia coli* K12 and *Enterococcus faecalis* inactivation by a range of wavelengths produced by commercially available LEDs spanning UV-C (270 nm) to deep red (740 nm). Inactivation rates, in turn, were used to estimate action spectra, and device construction experience was used to better understand reactor engineering needs.

2. Materials and methods

2.1. LED array power supply, configuration and characteristics

Commercially available LEDs, spanning UV-C to deep red, were surveyed for selection criteria such as suitable wavelength, affordable price, engineering convenience and stock availability. LEDs in mass-produced wavelength bins, preferably with a “star base” or hermetically sealed “through-hole” packages, were chosen for their availability, ease of array construction and robustness. In view of potential use with PV, low power demand and consumption was viewed as essential, and kept under 50 W to minimise risk of overheating and reactor size. Multi-emitter LED arrays were preferred and purchase costs were kept as low as practicable. The high costs of UV-B and UV-C LEDs reflects the absence of mass-production at present. The units finally selected are shown in Table 1.

To minimise heating and maximise output and lifetime, UV-A and visible wavelength arrays were mounted to a Fischer Elektronik SK 584/50 SA 1 K/W heatsink using thermally conductive paste. The 270 nm and 310 nm arrays were mounted on strip-board in a series configuration, with rear cooling of the TO-39 packages (Sensor Electronic Technology Inc, 2012). All arrays were cooled by a 120 mm computer fan.

Current driver units were selected to satisfy LED array power requirements. For 270 nm and 310 nm arrays, an On Semiconductor NSI45020AT1G 20 mA linear regulator was used. The power supply was set at 36 V to overcome the voltage drop of the LEDs and the regulator. For the 430 nm array, an XP Power LDU2430S1000 DC-DC 1000 mA LED Current Driver Module was used. The supply was set to provide 28 V, to ensure supplied power remained within the module operating specifications. For other wavelength arrays, an XP Power LDU2430S700 DC-DC 700 mA LED Current Driver Module was used. Power to the current driver units was supplied by a pair of Manson HCS-3102 switch-mode benchtop power supplies. Multiple current driver modules were run in parallel from each power supply with loading < 50% to ensure output stability. Current drivers (On Semiconductor, 2014; XP Power, 2014) were tested using a multimeter (Agilent Technologies U1241B) to confirm their current output specifications.

LED wavelength spectra, dominant wavelength (DWL) and full-width half maximum (FWHM) were measured at 21 °C for <1 s using an Ocean Optics S2000 fibre-optic spectrometer, UV-rated SMA-905 thick fibre-optic cable and OOIBase32 software.

Estimates of array power output were obtained in two ways, from manufacturer data sheets, and where possible by direct measurement. Firstly array light output power range and typical emission value, and electrical input power were obtained from test report data (270 and 310 nm arrays) or product datasheets, except for the 430 nm array, where no data were available and efficiency was assumed to be the same as 405 nm LEDs. Visible range LEDs' outputs which were reported in lumens were converted to mW using a photoptic to radiometric conversion chart (Labsphere, 2008). Electrical efficiency was calculated as estimated typical optical output power divided by electrical input power.