Comparison of ultraviolet light emitting diodes with traditional UV for greywater disinfection
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ABSTRACT
The current technological status of ultraviolet light emitting diodes (UV-LEDs) has reached a point where small-scale ultraviolet (UV) water disinfection applications, that is, for greywater reuse appear increasingly promising. This study compares the germicidal and economical aspects of UV-LEDs with traditional UV. Pure cultures and environmental greywater samples were exposed to different radiation doses from both UV sources with the germicidal effect comparative at equivalent doses. The impact of particle size on disinfection efficiency was investigated in two greywater fractions of varying mean particle size. Disinfection efficiency was found to be dependent on particle size with larger particles reducing microbial inactivation for both UV sources. Post-UV blending to detach particle-associated coliforms resulted in higher bacterial counts for both UV sources although to a lesser extent for UV-LEDs suggesting that it might be less affected by the presence of particles than traditional UV sources, possibly due to the UV radiation being emitted by multiple diodes at different angles compared to the traditional UV collimated beam setup. Nevertheless, removal of particles prior to UV disinfection is necessary to meet strict water reuse standards. Although UV-LEDs are currently prohibitively expensive, improvements in performance indicators might make this technology economically competitive within the next few years.

Key words | greywater, particle-associated coliforms, UV disinfection, UV-LED

ABBREVIATIONS AND NOTATION
BOD biological oxygen demand
CAPEX capital expenditure
CFU colony forming unit
COD chemical oxygen demand
CWRC California Wastewater Reclamation Criteria
DBPs disinfection by-products
LP low pressure
MPN most probable number
PACs particle associated coliforms
PBS phosphate-buffered saline
TSA Tryptone Soy Agar
TSB Tryptone Soy Broth
TOTEX total expenditure
TSS total suspended solids
UV ultraviolet
UV-LEDs ultraviolet light emitting diodes

INTRODUCTION
Greywater is becoming an increasingly important aspect of urban water reuse schemes, providing sustainable reductions in demand on fresh water sources (Casani et al. 2005; Liu et al. 2010), while minimising transport costs through constant on-site production (Jefferson et al. 1999). Liu et al. (2010) suggest that for many
non-potable applications, such as toilet flushing, low-grade, minimally treated water is sufficient. However, an important aspect of greywater recycling is the effective elimination of harmful microorganisms that pose potential risks to public health (Winward et al. 2008). Microbial water reuse standards vary worldwide depending on country, region and final reuse application (USEPA 2004), the most stringent of which is observed in conjunction with the California state title 22 standards of 2.2 total coliforms per 100 mL as an average over 7 days. The UK, devoid of its own legislation, falls under the EU Bathing Water Directive which accepts higher levels of risk for reuse of 10,000 total coliforms per 100 mL as a maximum (EU 2006). The British Standards Institution has recently produced some guidance for greywater reuse. The Greywater Systems Code of Practice BS 8525-1:2010 looks at four microbial water quality indicators: Escherichia coli, Enterococci, Legionella (for spray application only) and total coliforms, and the guidance levels depend on the greywater application (EA 2011). For non-spray applications, such as toilet flushing and garden watering, the guidance values are 250, 100, and 1,000 for the number of E. coli, Enterococci and total coliform per 100 mL, respectively. More stringent guidance values apply for washing machine application and spray-applications including car washing.

Among the numerous disinfection technologies available, ultraviolet (UV) light disinfection stands out due to its ability to provide successful inactivation of pathogens without producing disinfection by-products (DBPs) (Süß et al. 2003; Bowker et al. 2011), making it a healthier alternative to chemical disinfection (Chatterley & Linden 2010). UV inactivates microorganisms by conferring damage to their DNA (Jagger 1967) leading to either cell death or preventing proliferation (Süß et al. 2009). UVC (200–280 nm) is attributed most germicidal activity as it provides the UV spectrum absorbed by DNA (with peak absorbance of 260 nm (Kalisvaart 2004; Close et al. 2006). When exposing greywater samples to monochromatic UV (254 nm), Winward et al. (2008) reported for a dose of 5.8 mJ cm⁻² log inactivations of 3.0, 2.4 and 3.2 for total coliforms, E. coli and Enterococci, respectively. Complete inactivation was achieved at 277 mJ cm⁻² for E. coli and Enterococci while total coliforms were enumerated at 1.0 ± 0.2 log₁₀ culturable cells per 100 mL⁻¹. Friedler & Gilboa (2010) reported that a dose of 69 mJ cm⁻² in combination with biological treatment using a rotating biological contactor prior UV disinfection successfully inactivated Staphylococcus aureus present in greywater (10⁴ CFU mL⁻¹), used for toilet flushing.

One of the factors with a major impact on the efficiency of disinfection is the presence of particles. Particles interfere with UV transmittance by scattering (Qualls et al. 1985) and absorbing light (Templeton et al. 2007) as well as by shielding particle-associated organisms from exposure (Caron et al. 2007; Winward et al. 2008). Shielding is well documented for particle-associated coliforms (PACs) with particle size being an important parameter (Cantwell & Hofmann 2008). It has been suggested that viruses can be shielded by particles ≤2 μm (Templeton et al. 2005) whilst bacteria require particles of 7–10 μm and protozoa ≥5 μm (Amoah et al. 2005).

Despite its obvious advantages, the implementation of UV disinfection is currently hampered by the high energy demand and associated costs of traditional UV (Chatterley & Linden 2010). The prospect of greatly lowering these costs by economically efficient UV-light emitting diodes (UV-LEDs) has therefore received considerable attention (Würtele et al. 2011). Although UV-LED technology is in its infancy with efficiency below 1% (Beetles et al. 2007), it is expected to replicate visible LEDs with efficiencies of 75% for 100,000 hours of operation (McDermott et al. 2008). This is significantly higher than the efficiency of traditional UV systems at approximately 58% (USEPA 2006). Würtele et al. (2011) concluded that with improved power output, life-span and reduced costs through scale-up UV-LEDs are an attractive alternative to traditional UV sources for disinfection applications.

This study is aimed at providing a comparison of technical and cost parameters of traditional UV and UV-LEDs with a future forecast for UV-LEDs. One of the objectives was to directly compare the efficiency of both UV sources for disinfection of greywater. Apart from comparing overall germicidal performance, special emphasis was given to the presence of particles. Greywater typically has particle size distributions of 2–2,000 μm (Winward et al. 2008) making the evaluation of UV-LEDs in presence of particles highly relevant.
METHODS

Traditional UV and UV-LED sources

Two distinct devices were used as sources of traditional UV and UV-LEDs (Figure 1). Traditional UV radiation was generated by a collimated beam device (Wedeco AG, Germany) which consisted of four low pressure (LP) mercury lamps emitting UV radiation at 254 nm, controlled by a pneumatic shutter. UV-LED radiation was generated by 21 individual 255 nm LED photodiodes (UVTOP.TOS9/FW; Sensor Electronic Technology Inc, USA) which were positioned in three parallel circuits, each consisting of seven LEDs. The LEDs were soldered to a plate connected to a power source (Agilent Tech. E3612A, Direct Current) with a current setting of 60 mA, allowing each set of seven LEDs to receive 20 mA, as specified by the UV-LED manufacturer.

Normalisation of UV doses from different UV sources

For normalisation of UV doses, the emitted light intensity from each UV source was calculated using potassium ferrioxalate ($K_3[Fe(C_2O_4)_3]$) actinometry in deionised water following the procedure of Lam et al. (1973). UV intensities were found to be 2.44 and 0.099 mW cm$^{-2}$ for the collimated beam and UV-LEDs, respectively. The UV dose was normalised by varying the exposure time as suggested by Bolton & Linden (2003). Due to the distinct configurations of the two UV light sources, each required different sized Petri dishes. The traditional UV beam used a 20 cm diameter dish while the UV-LED unit used a 10 cm diameter dish. Volumes of 250 mL (traditional UV) and 50 mL (UV-LED) were chosen to provide a uniform 1 cm sample depth, which according to Lam et al. (1973), provides a UV absorbance of 99%.

UV inactivation experiments

Pure culture exposure

E. coli (ATCC 25922) was grown for 16 hours at 37 °C in Tryptone Soy Broth (TSB; Oxoid, UK) on a rotary shaker at 120 rpm. The culture was diluted with TSB to an optical density at 600 nm (OD$_{600}$) of 1.0. Cell suspensions of 25 mL (traditional UV) and 5 mL (UV-LED) were harvested and diluted 10-fold in phosphate-buffered saline (PBS, pH 7.4) to give suspensions of 250 mL and 50 mL, respectively, which were transferred into Petri dishes. Prior to exposure suspensions were stirred for 10 s using a magnetic stir-bar (40 × 8 mm for the collimated beam and 15 × 4.5 mm for the UV-LEDs), with continuous stirring during the exposure. After reaching the desired radiation dose, aliquots of 0.5 mL were taken and stored on ice until further processing. After UV exposure, aliquots of cell suspensions were transferred into the top row of sterile 96-well plates (Fischer Scientific Ltd, UK). Dilutions were made by stepwise mixing of 10 μL of cell suspension with 90 μL of sterile PBS, pre-distributed into the lower rows using a multichannel pipette. For each undiluted or diluted suspension, a 3 μL volume was subsequently spotted on a plate containing TSA and incubated at room temperature for 24 hours. Colonies on plates were visualised using a G-Box imaging system (Syngene, UK).

Greywater inactivation

Greywater samples were collected from 18 specially plumbed residential properties located at Fedden House on the Cranfield University Campus. Greywater was collected using a dip-sample from a circular holding tank fed
by kitchen and bathroom sinks, as well as baths and showers. The samples were collected in sterile autoclaved polypropylene containers and used within 2 hours for UV exposure experiments. For water quality analysis, samples were stored at 4 ± 1 °C for a maximum of 2 hours. Table 1 shows a summary of the main parameters measured during this study. In this case turbidity was not measured but previous studies using the same source of greywater reported turbidity levels in the region of 35 ± 16 NTU (Pidou et al. 2008). Environmental greywater samples were exposed to UV doses of 0 to 120 mJ cm⁻² for both UV sources. IDEXX Colisure and Quanti-Tray 2000 (Maine, USA) were used for enumeration of total coliforms and E. coli. IDEXX Enterolert and Quanti-Tray 2000 (Maine, USA) were used for enumeration of Enterococci.

**Particles and UV inactivation**

Greywater was settled in a 5 L settling column, 2 m in height, with taps at 1 L intervals to create varying fractions of mean particle size. Settlement was carried out for 2 hours, creating a gradient of smaller particles at the top of the column, while larger particles, which settled at a faster rate, were at the base of the column. Following settlement, the top 2 L were withdrawn to provide a greywater fraction without large particles. In addition, an unfractionated sample of raw greywater was also used to assess the impact of larger particles being present. Particle size distribution analysis was carried out for the unsettled greywater as well as the settled fraction, in addition to water quality measurements. Both the settled and unsettled fractions were exposed to 41 mJ cm⁻² from each UV source, based on the inactivation curves produced from the greywater exposure. Subsequently half of the exposed greywater samples were blended to disperse PACs, demonstrating the impact of particles on coliform survival following UV exposure. Blending was carried out using a heat-sterilised blender (KitchenAid, model No. 5KSB52BBU4) and blended for 60 s at low speed. Between fractions the blender was rinsed three times with deionised water and heat-sterilised with boiling water to prevent cross contamination. Total coliforms were enumerated using IDEXX Colisure and Quanti-Tray 2000 (Maine, USA).

**Water quality analysis**

Water quality measurements for biological and chemical oxygen demand (BOD/COD) and total suspended solids (TSS) were carried out using Standard Methods (APHA 2005). Measurements of particle size distributions were performed using a Mastersizer 2000 (Malvern, UK), which according to the manufacturer has minimum and maximum detection limits of 0.2 μm and 2,000 μm, respectively. Samples were analysed five times, using a measurement time of 25 s at a refractive index of 1.52, and subsequently averaged for particle size distributions. Data were provided as volume weighted means (D[3/4]) as well as D10, D50 and D90 values with each referring to the diameter below which lies the indicated percentage of total particles present in the sample.

**Cost analysis**

An approach described previously by Ibrahim et al. (2014) was applied here to predict the economic cost of UV-LED in comparison to the traditional UV. TOTEX (total expenditure) was used to assess the future economic viability of UV-LED systems in comparison to the traditional UV for two different scenarios: single house disinfection for greywater recycling that included non-spray applications such as toilet flushing and garden irrigation and a greywater recycling system in a medium-sized hotel (March 2004). In both cases, the TOTEX was calculated over a 15 year period taking into consideration the
capital investment in the lamps, the lamp replacement cost over the operation period and the total energy cost using fixed rates per kWh of £0.13 for domestic applications and £0.09 for commercial applications (Ibrahim et al. 2014).

RESULTS AND DISCUSSION

Pure culture exposure

In an initial experiment, cell suspensions of E. coli were exposed to UV doses ranging from 0 to 300 mJ cm\(^{-2}\) using traditional UV-LP lamps at 254 nm and UV-LEDs at 255 nm. Following exposure, samples were diluted and spotted on agar plates. Results demonstrate a clear dose-response with complete loss of culturability at 100 and 125 mJ cm\(^{-2}\) for traditional UV and UV-LEDs, respectively (Figure 2; data not shown for higher UV doses). Inactivation of E. coli by traditional UV tended to be more gradual with increasing UV dose, whereas equivalent doses from UV-LEDs tended to show a different kinetics: a more rapid initial decline after exposure to 25 mJ cm\(^{-2}\) was followed by a plateau effect until complete loss of culturability was achieved at 125 mJ cm\(^{-2}\). The effect might be attributed to the different setup of experimental conditions (one collimated beam comprising four LP lamps compared to 21 individual LED bulbs exposing different volumes of bacterial suspensions).

For UV-LEDs, at 75 mJ cm\(^{-2}\) there seems to be marginally more growth than at 50 mJ cm\(^{-2}\) (at 0 and 10 dilution factor) but the observed overall trend was clear with culturability reduced with increasing UV dose. The remaining residual presence of culturable cells at higher UV doses for UV-LEDs may be a result of the substantially longer exposure time required to achieve an equivalent UV dose compared to traditional LP lamps. Due to lower light intensities emitted by current UV-LEDs, an exposure time of 16.85 min was required to achieve a dose of 100 mJ cm\(^{-2}\), compared to 17 s long exposure for traditional UV. Oliver & Cosgrove (1975) suggested that as long as UV dose is equivalent, microbial inactivation will be comparative independent of the exposure time. Benabbou et al. (2007), on the other hand, reported an ‘induction period’ for inactivation of E. coli at lower light intensities using UVA-LEDs. It was suggested that bacterial DNA repair mechanisms may be more efficient at low light intensities, but might eventually be lost at higher doses due to an accumulation effect.

In contrast to the data presented for UVC-LEDs at 255 nm, no loss of culturability was observed for UVA- and UVB-LEDs emitting at 365 and 310 nm, respectively, for UV doses up to 300 mJ cm\(^{-2}\) (data not shown). Hamamoto et al. (2007) reported a 5-log inactivation of E. coli using UVA-LEDs at 365 nm, and Benabbou et al. (2007) achieved complete inactivation (6-log) of E. coli using UVB-LEDs at 290 nm. However, respective doses required to achieve these levels of inactivation were 315 and 14.4 J cm\(^{-2}\), significantly higher than the UV dose range applied in the present study.

![Figure 2](https://iwaponline.com/jwrd/article-pdf/5/1/17/378222/jwrd0050017.pdf)
UV inactivation of greywater

To further compare the disinfection efficiency of the two UV sources, environmental greywater was exposed to UV radiation ranging from 0 to 120 mJ cm$^{-2}$ from both traditional UV and UV-LEDs followed by enumeration of indicator organisms (Figure 3). Concentrations of indicator organisms (per 100 mL) prior to UV exposure were $1.7 \times 10^6$, $1 \times 10^4$ and $7 \times 10^2$ CFU for total coliforms, *E. coli* and *Enterococci*, respectively. UV disinfection efficiencies appeared comparable for both UV sources. Total coliforms showed >5-log inactivation for doses of 120 mJ cm$^{-2}$ independent of the UV source, while *E. coli* and *Enterococci* were completely inactivated after applying a dose of 41 mJ cm$^{-2}$. For total coliforms, the inactivation curves shown in Figure 3 demonstrate typical characteristics of UV disinfection (Brahmi et al. 2010) with a rapid initial decline in bacterial numbers of 3-log units at relatively low UV doses (2.4–12.2 mJ cm$^{-2}$, independent of the UV sources) followed by slower inactivation rates at higher UV doses. Doses between 12.2 and 41.5 mJ cm$^{-2}$ resulted in an additional 1.2-log inactivation for traditional UV and 0.8-log for UV LEDs. The kinetics of UV inactivation was categorized in three distinct stages by Brahmi et al. (2010). The first stage has the highest density of susceptible microorganisms and therefore low doses have a greater germicidal effect. The second stage suggests that microorganisms are less accessible to radiation, possibly due to photons being absorbed by particles which shield microorganisms. This protective effect would explain a slower inactivation rate. The tailing effect, or third stage, suggests that organisms are largely inaccessible to UV radiation as they are associated with particulate matter. The presence of PACs can thus lead to a null inactivation kinetic where a maximum inactivation rate is reached. The hypothesis is in agreement with a study by Winward et al. (2008) on the extent of particle association in greywater, reporting the presence of live total coliforms even at doses as high as 1107 mJ cm$^{-2}$, suggesting that UV could not fully penetrate particles and therefore microorganisms remained protected. Another potential reason for incomplete inactivation might be seen in the microbial heterogeneity of total coliforms with some species being more resistant to UV than others (Guo et al. 2009). The described characteristics of total coliforms make them appear good indicators of UV disinfection performance (Winward et al. 2008).

Particle impact on UV disinfection efficiency

To assess the impact of particle size on disinfection efficiency, greywater was allowed to settle for 2 hours in a column to achieve stratification into fractions with different particle sizes. The top 2 L were removed and compared with the same greywater which had not undergone settling. Particle size distributions are shown in Figure 4 with mean particle sizes of 32 μm (settled) and 170 μm (unsettled).
The distinctness of the two fractions was reflected in the D10, D50 and D90 values shown in Table 1 with each D-value referring to the particle size below which lies a percentage of the total particles present in the sample. The D90 values suggested that 90% of particles were smaller than 35 μm (settled) and 475 μm (unsettled). In the unsettled greywater, the largest particle size detected exceeded 2,000 μm. Water quality analysis of the two fractions showed that water quality slightly decreased with increasing particle size. TSS increased from 51 to 60 mg L\(^{-1}\) and BOD from 53 to 58 mg L\(^{-1}\), while COD showed the strongest increase from 83 to 97 mg L\(^{-1}\).

Both greywater fractions (settled and unsettled) were subjected to a UV dose of 41 mJ cm\(^{-2}\) followed by enumeration of total coliforms without or with post-UV blending (Figure 5). Blending was performed to investigate the extent of protection of particle-associated bacteria with dispersed cells being able to be enumerated individually. For non-UV exposed samples, blending resulted in a slight increase in total coliform counts for both fractions suggesting particle associations of 30% (32 μm fraction) and 25% (170 μm fraction). UV exposure efficiently reduced coliform numbers for both UV sources. Reductions were, as expected, greater in the fraction with smaller particles. This result is in agreement with Templeton et al. (2005), demonstrating that the protective effect of particles is enhanced by larger particles which have higher shielding potential than smaller particles.

Comparing the efficiencies of the two UV sources, a discrepancy was found for the unblended and blended fractions. For the unblended fractions, total coliform counts were lower after exposure with traditional UV compared to UV-LED suggesting that traditional UV in our experimental setup was a more effective source for disinfection. Blending of samples after UV irradiation, on the other hand, modified this picture. Total coliform counts substantially increased for fractions exposed to traditional UV while undergoing only a very modest increase for fractions exposed to UV-LED. As a result, numbers of surviving coliforms were similar for the two UV sources for the greywater with a mean particle size of 32 μm, whereas for greywater with a mean particle size of 170 μm UV-LEDs produced lower counts than traditional UV. Results suggest that disinfection by traditional UV was more affected by the presence of large particles than disinfection by UV-LEDs. Although these results require

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**Figure 4** | Particle size distribution of environmental greywater. Greywater was settled for 2 hours to obtain particles of different sizes. Data are shown for the top fraction of settled greywater (solid line) and unsettled greywater (dashed line).

**Figure 5** | Surviving total coliforms from two particle size fractions following UV exposure at 41 mJ cm\(^{-2}\) for traditional UV (dark grey) and UV LED (light grey). Data shown for post-UV blended fractions and non-blended fractions. Blending was carried out at low speed to disperse PACs. Mean values from three measurements are shown with error bars reflecting standard deviations.
confirmation, the findings might indicate that bacterial inactivation in the presence of particles is not only dose-dependent, but might be influenced by irradiation time and the light source design. Independence of exposure time and pure dose dependence has previously been reported by Bowker et al. (2011); results were however obtained with planktonic cells. Longer exposure times as required for UV-LEDs might enhance penetration and provide an increased likelihood that PACs are exposed to irradiation compared to a scenario with traditional UV requiring substantially shorter times to deliver the same dose. The authors wish to emphasise that further investigations are required before decisive conclusions can be made.

Overall, our data suggest that inactivation efficiencies of indicator bacteria in environmental greywater samples are comparable for traditional UV and UV-LEDs. Both sources can provide sufficient microbial inactivation to achieve EU Bathing Water standards of 10,000 total coliforms per 100 mL with an applied UV dose of 12.2 mJ cm$^{-2}$. More stringent standards, such as the California state title 22 criteria of $<2.2$ total coliforms per 100 mL, however, appear to be beyond the disinfection capability of both UV sources at applied doses of 120 mJ cm$^{-2}$ used in the present study, most probably due to the presence of particles. To improve UV disinfection efficiency, allowing more stringent standards to be achieved, particle removal prior to disinfection seems necessary as proposed previously. Cantwell & Hofmann (2008), reported an increase in UV inactivation by $>1$ log when filtering surface water (11 μm pore size) compared to the unfiltered water. Darby et al. (1995) compared the effect of filtration on UV disinfection efficiency for secondary effluent following activated sludge and clarification. The study showed that filtered effluent was able to meet California Wastewater Reclamation Criteria (CWRC) of 23 total coliforms per 100 mL as a 7-day median (Darby et al. 1995) with 20% lower UV doses than unfiltered effluent. In order to meet the tighter $<2.2$ total coliforms per 100 mL criteria a dose of 97 mJ cm$^{-2}$ was required in filtered effluent, while unfiltered effluents were not able to consistently achieve these criteria. Furthermore, Oppenheimer et al. (1997) state that TSS concentrations $<4$ mg L$^{-1}$ allow successful inactivation of total coliforms (below detection limits) to be achieved by 120 mJ cm$^{-2}$, enabling tighter standards to be met.

**UV-LEDs versus traditional UV: cost analysis**

The experimental work has demonstrated that use of UV-LED is equally effective as traditional UV, such that consideration of its future uptake becomes one of economic and practical consideration. UV-LED technology has been limited by low power outputs and short bulb lifetimes (Würtele et al. 2011), which in conjunction with high unit costs currently prohibits its implementation. The available UV-LED bulbs’ output currently remains below 1 mW per bulb (Table 2) according to Sensor Electronic Technologies with the efficiency increasing marginally to 3–5% and only in certain applications (personal communication, SET 2014). Correspondingly, the continuous operating life of approximately 1,000 hours increased to 3,000 hours depending on application. The prices have remained constant in the past 3–4 years but a breakthrough is expected at the end of 2014 when a new product incorporating a number of bulbs (currently available for two wavelengths) will become available across the whole range of wavelengths and at very competitive prices (personal communication, SET 2014). Consequently, calculation of the TOTEX cost of a current disinfection unit is dominated by the capital cost of the innovative component (in this case the UV-LED bulb) consistent with examples of other innovative technologies in

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<td>Power per bulb (mW.lamp$^{-1}$)</td>
<td>15,000</td>
<td>0.18$^e$</td>
<td>180$^d$</td>
<td>675$^f$</td>
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<td>Lifetime (hr)</td>
<td>9,000$^a$</td>
<td>1,000$^b$</td>
<td>3,000$^d$</td>
<td>100,000$^f$</td>
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<tr>
<td>Efficiency (%)</td>
<td>35–38$^b$</td>
<td>1$^d$</td>
<td>3–5$^d$</td>
<td>75$^f$</td>
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<td>Replacement requirement per year</td>
<td>1 $^a$</td>
<td>9$^d$</td>
<td>3 $^d$</td>
<td>0.3$^f$</td>
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<td>Cost per lamp (£)</td>
<td>30$^c$</td>
<td>24$^d$</td>
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<td>0.6$^f$</td>
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$^a$Chatterley & Linden (2010).
$^b$Brownell et al. (2008).
$^c$Data gathered directly from the manufacturer (Sensor Electronic Technology, Inc., USA).
$^d$Figure based on a 40% loss in power output experienced in the present study as well as a previous study by Würtele et al. (2011).
$^e$Ibrahim et al. (2014).
the past, such as membranes used in membrane bioreactors (Santos et al. 2011). Further, historical evidence from analogous innovations suggests rapid change in terms of the critical aspects of the technology that influence uptake. In the case of UV-LED bulbs, this relates to the power output of an individual bulb, the cost of each bulb and the operational lifetime. Comparison is most readily made to red light LEDs which were first invented in 1968 and are now widely used. Historical data show that for every decade of development the output per bulb has increased by a factor of 20 and the cost fallen by a factor of 10, a relationship known as Haltz’s law which is analogous to the equivalent profile in the microelectronics sectors as described by Moore’s law (Steele 2007). Development of more recent high brightness LEDs for lighting indicates an even more rapid development path with costs reducing by a factor of seven within 5 years although in part this is driven by the size of the potential market for domestic lighting. Both examples suggest that costs and operational lifetimes of UV-LED can be expected to change radically in the next few years. It is suggested that UV-LED will replicate the developments seen in visible light LEDs with the anticipated changes within 6 years leading to bulb output powers reaching up to 675 mW.lamp\(^{-1}\) at efficiencies of 75% with operational lifetimes of 100,000 hours (Ibrahim et al. 2014). However, in light of the rather stagnant development in the past 4 years the above forecasted numbers should be considered with caution as radical improvements will be required to achieve these targets. Only when the output power, lifetime and cost of the bulbs alter the balance of the TOTEX cost enabling a trade-off between increased capital cost and reduced operating cost, can UV-LEDs be considered for UV disinfection. Numerous examples now exist where this trade-off is effective in the case of visible light LEDs. For instance, in 2000, a factory in the USA switched to LED lighting incurring an increased capital cost of three times which was repaid within 2 years through the reduction in the annual electricity costs (Ibrahim et al. 2014). According to the forecast, in 2020 the highest proportion of the TOTEX for the UV-LED component of the disinfection system will be the operating cost resulting in minimal TOTEX values. The whole system will be easily operated by a low power source such as solar panels. The advantages of using LEDs for UV delivery extend beyond reduced operating costs as they are considered more environmentally friendly through not requiring toxic components such as mercury and are relatively instantaneous negating the disadvantage of traditional UV which require a warm-up period which was reported to be around 7 minutes in a recent trial (Chatterley & Linden 2010). While less important in large-scale disinfection where operation is relatively constant, the ability to turn up and down small-scale systems is very important in water recycling where systems can operate at anything from single house scale to large residential and office buildings (Pidou et al. 2007).

The significance of the points discussed above is illustrated with reference to the use of single tube UV systems as would be applied to a single house or an apartment block. The analysis is based on a comparison of capital and operating costs of traditional versus LED systems assuming a dose of approximately 20 mJ cm\(^{-2}\) is required to achieve the current guidance levels in BS 8525-1:2010 (EA 2011), as determined in the current study. Only the bulbs are taken into account as all other components are considered to be common enabling focus to be centred on the innovative component. The current CAPEX cost for one of the residential greywater recycling systems that uses bromide for disinfection is around £2,000 (Aquaco 2014).

Traditional UV systems utilising a single tube deliver the required drinking water disinfection dose of 40 mJ cm\(^{-2}\) (Linden et al. 2002) for flow rates of 2.7 m\(^{3}\) d\(^{-1}\) and beyond. For context, the case study of a 81 room hotel in Spain (referenced here) treats a continuous flow of 5.2 m\(^{3}\) d\(^{-1}\) (0.95 gpm) (March et al. 2004) with required treatment rates from single houses as low as 0.08 m\(^{3}\) d\(^{-1}\), such that the single tube systems can be seen as effective for a wide range of potential greywater applications. As mentioned previously, only 20 mJ cm\(^{-2}\) dose would be required based on this study to achieve the guidance values as recommended in the British greywater reuse standard (EA 2011). Our results suggest that for both a single house and a medium-sized hotel application, UV-LEDs will reach cost neutrality with a traditional UV in 2–3 years (Figure 6), and in 2020 the TOTEX (over 15 years lifetime) of the UV component in the disinfection system for a single house and a medium-sized hotel will be £17 and £72, respectively.
CONCLUSIONS

Results of this study suggest comparable germicidal efficiencies of traditional UV and UV-LEDs for greywater disinfection to achieve sufficient microbial inactivation within consent of EU Bathing water standards. In order to meet more stringent standards for greywater reuse it is suggested to minimally remove particles by filtration prior to UV disinfection. Given the current state of UV-LED technology, it is apparent that further investigation is required before definitive conclusions on disinfection efficiency can be made. The authors suggest that UV-LEDs show considerable promise for the future; however, currently, UV-LEDs are too expensive to qualify as an alternative to traditional UV sources. Economic viability for small-scale applications (as for greywater reuse for toilet flushing in hotels) might however be achieved within the next years given the technological advances in regard to power output, bulb efficiency and lifetime predicted by the manufacturers.

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