Water Research X 25 (2024) 100271

Contents lists available at ScienceDirect

Water Research X

journal homepage: www.sciencedirect.com/journal/water-research-x

A critical review of ultra-violet light emitting diodes as a one water disinfection technology

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ARTICLE INFO

Keywords:
UV LED
Disinfection
Water-energy nexus
Sustainable water treatment

ABSTRACT

UV light emitting diode (LED) disinfection technologies have advanced over the last decade and expanded the design space for applications in point of use, industrial, and now full-scale water treatment. This literature review examines the progression of UV LED technologies from 2007 to 2023 using key features such as total optical power, price, and wall-plug efficiency. The review found that optical power is increasing while the price per Watt is decreasing; however, the wall plug energy (WPE) is slowly improving over the last decade. These factors govern the feasibility of many UV LEDs applications and establish the current state of the art for these technologies. An analysis of inactivation rate constants for low-pressure, medium-pressure, and UV LED sources was undertaken and provides a comprehensive view of how current UV LED technologies compare to traditional technologies. This comparison found that UV LEDs perform comparably vs conventional UV technologies when disinfecting bacteria and viruses. Furthermore, comparison of reported reduction equivalent fluences for UV LED flow-through reactors at the bench-, pilot-, and full-scale were explored in this review, and it was found that LED treatment is becoming more effective at handling increased flowrates and has been proven to work at full-scale. UV LEDs do however require additional research into the impacts of water matrices at different wavelengths and the impact that each available LED wavelength has on disinfection. Overall, this work provides a broad assessment of UV disinfection technologies and serves as a state-of-the-art reference document for those who are interested in understanding this rapidly developing technology.

Introduction

Ultraviolet (UV) light has been used as a disinfectant in water and wastewater treatment facilities as earliest as 1910 and 1978 respectively as it is relatively easy to operate and can effectively reduce microbial contamination in drinking water and wastewater(Bolton and Cotton, 2008). Although conventional UV disinfection systems have been used at full-scale for decades, low-pressure (LP) UV lamp wall-plug efficiencies (WPE) have remained around 30–35 % (Bolton and Cotton, 2008). Additional issues arise from localized elevated temperatures near the surface of the lamps which can cause substantial organic and inorganic fouling on the protective quartz sleeves of UV lamps (Bolton and Cotton, 2008; Wait and Blatchley, 2005). This can be caused by both organic and inorganic factors which include high amounts of organics which can cause bioaccumulation on the light sources. As well high amounts of trace metals can cause scaling on the quartz sleeve hindering the disinfection (Montazeri and Taghipour, 2023). This fouling blocks the emitted light from the lamps, reduces treatment efficacy, and increases maintenance costs for the utilities operating the systems. Furthermore, traditional UV lamps contain mercury in fragile glass vacuum tubes which produce UV light when excited. These factors make handling and disposal an environmental burden that must be addressed. Additionally, mercury mining will be completely phased out by 2032 and poses a market risk for accessing raw materials after this point in time (Selin and Selin, 2022; Sodeno, 2023). The UV industry runs a serious risk if alternative sources of UV light are not developed before impacts of a mercury ban take full effect.

UV light emitting diodes (UV LED) offer a potential alternative to

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https://doi.org/10.1016/j.wroa.2024.100271
Received 24 July 2024; Received in revised form 24 October 2024; Accepted 27 October 2024
Available online 30 October 2024

traditional design as they contain no mercury and offer tremendous design flexibility. The output wavelength of the system is dependent on the composition of the p and n layers in the LED as this determines the band gap energy. Typical layers consist of aluminium nitride, gallium aluminium nitride, or gallium nitride with lower emission wavelengths achieved by increasing the aluminum content (Shur and Gaska, 2010). Power outputs and energy efficiencies are currently dependent on wavelength and typically decrease as the emission wavelength of the UV LED decreases (Allerman et al., 2004; Khan, 2006; Shur and Gaska, 2010; Zollner et al., 2021). While improvements in output and efficiency have been slow, it is expected that the power efficiencies and outputs of lower wavelengths will increase as semiconductor material science surrounding UV LEDs improves and becomes more commercially available (Hunter et al., 2020; Ibrahim et al., 2014; Zollner et al., 2021). Being mercury-free offers a potentially more environmentally sustainable option for UV treatment and enables UV disinfection in jurisdictions which prohibit the use of mercury entirely. Moreover, UV LEDs offer secondary benefits: increased germicidal treatments from the wider range of available wavelengths and physical design flexibility from the small robust point source formfactor.

While projections for improvements in efficiencies and output have been perpetuated for over a decade, the reality is that UV LEDs have WPEs that remain up to 6 % as of 2024 for various wavelengths (Chen et al., 2017; MacIsaac et al., 2023). The benefits gained from access to increased wavelengths could offset the current limitations regarding energy efficiency, however the efficiencies tend to decrease as wavelengths decrease. Traditional mercury-based UV systems emit light monochromatically at 254 nm which has high germicidal and electrical efficiency, but the maximum germicidal efficiency for pathogens of interest is not typically exactly at 254 nm (Beck et al., 2017; Sun et al., 2024). As such, there is a balance to be found using tailored wavelengths to target specific microorganisms to offset a portion of current poor performance in energy efficiencies of UV LEDs. UV LEDs are also often mistakenly referred to as monochromatic sources and while their emission bandwidth is narrow, they should not be treated as a single emission source. Figure S1 shows the relative intensity for LP, medium pressure (MP), 265 nm UV LEDs, and 280 nm UV LEDs which highlights the differences in emittance between each of the lamp types. UV LEDs have a well-defined, single peak but also have a distribution of emitted UV light at wavelengths above and below the peak. LP lamps emit over 90 % of their emitted light at 254 nm and are always treated as a monochromatic source when calculating fluence and intensity.

While UV LEDs have not reached maturity yet, consensus in the research community surrounding the mechanism of disinfection and feasibility of scaled application points toward UV LEDs being a powerful and sustainable treatment option for disinfection in both the water and wastewater sectors (MacIsaac et al., 2024; Sun et al., 2024). Furthermore, researchers are seeing the full potential of the increased design flexibility allowing for innovative implementation of applications previously thought infeasible in water treatment systems (Linden et al., 2019; MacIsaac et al., 2024). A lack of understanding of the current state of the technology has left many in industry with outdated views on UV LEDs which is limiting the implementation of the technology outside of niche markets. The growth of the technology over the past 5 years has been substantial and implementation of UV LED technologies is no longer years away, but imminent. This literature review will benchmark the current research on UV LED technologies. Topics covered will include a timeline of UV LED development, state of the art for UV LED technologies, a critical analysis of UV LED vs conventional UV for various challenge organisms, and a review of challenge organism dosimetry for flow-through UV LED reactors from bench- to full-scale.

Timeline of UV LED development

LEDs first gained popularity in the lighting industry during the early 2000s, and are now used beyond the visible spectrum for disinfection in the water and wastewater treatment industries (Rose, 2014). LEDs are composed of layers of various solid-state semiconductors which converts direct current into photons with a specific emission profile (Chen et al., 2017; Rose, 2014; Song et al., 2016). At the p-n junction boundary, a depletion region is created which inhibits charge carriers, and with a forward bias it allows for the reduction of the depletion zone width. This then allows charge carriers to move across the junction leading to a flow of current. There is a recombination at the junction on the n-side of electrons with the holes either emitting radiatively (light emission) or non-radiatively (heat generation). When the radiative recombination occurs a photon is emitted with a wavelength which corresponds to the bandgap width of the semiconductor. The bandgap and semiconductor materials are key components into the progression of LED technology especially for the development of UV LEDs.

The development of the blue LED in the 1980s, using a gallium nitride crystal for the semiconducting material, made LEDs a viable technology (Rose, 2014). By using the gallium nitride semiconductor, the blue LED emitted at wavelengths of 400 to 450 nm which coincidently brings the LEDs away from the visible range and onto the edge of the ultraviolet range. This LED changed the lighting industry drastically since they were combined with red and green LEDs to create a white LED which is the basis of many LEDs sold commercially (Muramoto et al., 2014; Rose, 2014; Song et al., 2016).

The alterations of the semiconducting material made for the blue LED is the forefront to the development of the UV LEDs. The alterations allowed a wider bandgap for the LED which makes a shorter wavelength. The most frequent semiconducting material used for UV LEDs are variations of III-Nitride semiconductors, which include gallium nitride (GaN), aluminium gallium nitride (AlGaN), and aluminium nitride (AlN). The composition of the materials can alter the emission wavelength depending on the ratio and material used. For example, an AlN UV LED was reported to emit a UV radiation of 210 nm whereas the AlGaN UV LED was reported to emit radiations between 210 and 365 nm depending on the ratio of AlN and GaN (Sholtes et al., 2016; Song et al., 2016). Furthermore, UV LEDs can be classified depending on their wavelength emission following the International Union of Pure and Applied Chemistry (IUPAC) UV sub-band classifications: UVA, UVB, and UVC. UVA wavelength ranges from 315 to 400 nm and can be called near ultraviolet light emitting diodes; whereas UVB and UVC are known as deep ultraviolet emitting diodes which range from 280 to 315 nm and 200 to 280 nm, respectively.

Inherent issues with composition of light extraction

Despite UV LEDs having gained popularity due to their environmental and design benefits they do have their own challenges. Specifically, UV LEDs have inherent challenges with their external quantum efficiencies (EQEs). To evaluate the performance of UV LEDs the EQE is used as a key indicator which is produced by a combination of the light extraction efficiency (LEE) and internal quantum efficiency (IQE) (Li et al., 2022). The IQE is defined as the number of photons emitted from the active region per electron injected into the LED. This can result in the following equation:

Eq. (1) ***Internal Quantum Efficiency Equation*** *(Li et al., 2022)*

$$\eta_{\mathrm{int}} = \frac{\mathrm{Photons\ (active\ region)/s}}{\mathrm{electrons/s}} = \frac{P_{int}/(h\nu)}{I/e} \quad (1)$$

Where P_{int} is described as the optical power emitted from the active region of the semiconductor, I is the injection current and e as the elementary charge of the electron. However, the LEE accounts for the loss of photons escaped from the LED due to loss through absorption, refraction, and reflection by the lamp components. The LEE is defined as follows:

Eq. (2) ***Light Extraction Efficiency Equation*** *(Li et al., 2022)*

$$\eta_{\text{extraction}} = \frac{\text{Photons (escaped from device)/s}}{\text{Photons (active region)/s}} = \frac{P_{out}/(h\nu)}{P_{int}/(h\nu)} \quad (2)$$

Where P_{out} is the optical power emitted from the device. Therefore, by combining the two equations the true efficiency of the LED in terms of the number of useable photons produced per electron input, EQE, can be defined as follows:

Eq. (3) ***External Quantum Efficiency Equation*** *(Li et al., 2022)*

$$\frac{\text{Photons (escaped from device)/s}}{\text{electrons/s}} = \frac{P_{out}/(h\nu)}{I/e} = \eta_{int}\eta_{extraction} \quad (3)$$

Through previous research UV LEDs have shown that the EQE decreases rapidly as the wavelength becomes shorter with a majority of the EQEs reported being below 10 % which is much lower than the mainstream blue LEDs (Kim et al., 2010; Li et al., 2022; Muramoto et al., 2014). The poor LEEs are typically attributed to the absorption of the emitted radiation in the p-type GaN films (Li et al., 2022; Muramoto et al., 2014). Other plausible causes of reduced LEEs at lower wavelengths arise from issues in crystal growth. A cladding layer is required for AlGaN UV LEDs with a larger band gap which results in a higher threading dislocation density; furthermore, the shorten wavelengths required for germicidal UV LEDs results in a decreased in composition which increases the negative effects of the threading dislocations (Muramoto et al., 2014).

Methods to improve LEE are dependent on the composition of the LED chip design. Normal chips are designed with semiconductors in a layer-by-layer fashion beginning with the n-type layer followed by the p-type layer which are on top of an optically transparent sapphire substrate (Chen et al., 2017). Whereas the flip chip design which flips the layered semiconductors and are connected to a sub mount with higher thermal conductivity so that the thermal heat is reduced. The flip chip as well shows an approximate two-fold increase in efficiency compared to the standard chip (Bergmann et al., 2023) due to removing the substrate bonded LEDs which reduces the number of interfaces and allows practicable texturing of the exposed AlGaN surface (Bergmann et al., 2023). However, the flip-chip are more costly for production compared to the standard LED chips.

The efficiency of key factors is continuously changing due to the rapidly advancing research in this field. Recent studies demonstrate that UV LEDs with AlN-sapphire substrates perform around 1 % EQE and 0.28–0.75 % when the substrate is composed of bulk AlN (Rass et al., 2023). Furthermore, this study shows that the EQE decreases below a 1 % EQE with wavelengths shorter than 250nm. Regarding current studies, many institutions have shown an increase of EQE when the composition of the LED is changed. Yi-Wei et al. (2023) showed that EQEs of 3.01 % to 5.49 % of 280 nm LEDs were achievable when the aluminum mole fractions were altered. Furthermore, IQEs as high as 80 % have been reported for InGaN LEDs, and researchers are currently exploring methods to increase the IQEs of AlGaN LEDs by using transparent p-AlGaN layers and highly reflective p-type layers neither of which are currently commercially viable (Xu et al., 2023).

Another important parameter discussed in the UV LED industry is WPE. This an energy conversion efficiency to identify the conversion of electrical power from the system into optical power and can be expressed as follows:

Eq. (4) ***Wall Plug Efficiency Equation***

$$WPE = \frac{P_{out}}{I \times V} = \eta_{int}\eta_{extractions}\frac{h\nu}{e \times V} \quad (4)$$

Where V is the voltage of operation. This shows that the WPE is directly proportional to the EQE of the device. The WPE is the key indicator for operational costs associated with UV LED reactors.

Progression of key factors for efficiency and feasibility of treatment

Historically, UV LEDs have had poor optical power outputs below 1 mW with an expected 20-fold increase for every decade of development (Crook et al., 2015). However, an exponential upward trend for total optical power output has been observed for UV LEDs (Fig. 1A). Optical power of LEDs from 2007 through 2023 were extracted from the papers cited (Beck et al., 2017; Betzalel et al., 2020; Chatterley and Linden, 2010; Hull et al., 2019; Montazeri and Taghipour, 2023; Nyangaresi et al., 2018; Oguma et al., 2013; Rattanakul and Oguma, 2018; Romero-Martínez et al., 2022; Sholtes et al., 2016; Würtele et al., 2011), product list from DigiKey and product information sheets from manufacturers (Bolb Inc., 2023; Boston Electonics, 2023; "DigiKey Home," 2024; Klaran, 2023; Thor Labs, 2023). The total optical power output of the LED in 2007 was 0.36 mW (Chatterley and Linden, 2010), this has increased substantially since, with the average reported total optical power from manufacturers now 119 mW with a range of 31–388 mW (Bolb Inc., 2023; Boston Electonics, 2023; Klaran, 2023; Montazeri and Taghipour, 2023; Thor Labs, 2023). This represents 331 times increase in output power of LEDs in the past 16 years; however, it is difficult to determine any trends as most of this increase has occurred in the last few years and the data from 2023 are highly variable.

Dollar per watt is a parameter key to the capital cost of UV LEDs. The values shown in Fig. 1B were extracted using similar methods as total optical power output. UV LEDs have been associated with a high capital cost; however, with new development in material science and manufacturing, these costs have decreased over the past 16 years. In 2007 it was reported that the price of a 265 nm LED was $644,000 USD-W^{-1}; whereas the average price of UV LEDs between 265 and 280 nm is $1466 USD-W^{-1} as of 2023 (Bolb Inc., 2023; Boston Electonics, 2023; Chatterley and Linden, 2010; Klaran, 2023; Thor Labs, 2023). This is 439 times decrease in cost; however, trends are difficult to determine for similar reasons to the optical power output. Currently, the most efficient LEDs are priced at 620 USD-W^{-1} for 265 nm and 450 USD-W^{-1} for 275 nm (the average price per watt for all LEDs examined after removing the substantially more expensive ThorLabs LEDs in 2023 is 454 USD-W^{-1}) indicating that the more moderately priced LEDs do not come at a compromise of UV output.

The WPE of UV LEDs has been steadily increasing from 2013 to 2023 according to data available in studies and from manufacturers (Fig. 2). The average WPE of LEDs in 2013 was reported as 0.69 % with a range of 0.36–0.9 %. A decade later The WPE of LEDs was on average 2.23 % with a range of 1.02–6.15 % These values represent 3.23 times increase in energy efficiencies over the last decade. The highest efficiencies reported were the 265 nm and 275 nm LEDs from Bolb Inc. with WPEs of 5.7 % and 6.2 % for standard 100 mW optical outputs, respectively (Bolb Inc., 2023). This rate of increase is far less compared to the advancements in optical power and decrease in cost of LEDs; however, research is continuing to overcome the challenges limiting efficiencies because commercial viability will not be realized without powerful and energy efficient LEDs.

UV LED maturation projection

Output power and cost are the two most predicted metrics when discussing the future of UV LEDs. For UV LEDs to be a realistic choice for both household and community water disinfection the power outputs needed to increase, and cost needs to decrease (Chatterley and Linden, 2010). In 2010 it was estimated that by 2013/2014 LEDs would increase from 0.36 to 100 mW for output power while decreasing in cost from 664,000 to 100 USD-W^{-1} (Chatterley and Linden, 2010). Furthermore, in 2014 it was estimated that by 2015 UV LEDs would reach optical powers of 64 mW power outputs with cost dropping to 42.7 USD-W^{-1} (Ibrahim et al., 2014). These values further improving by 2020 to optical powers of 675 mW and a cost of 0.06 USD-W^{-1}. While many predictions have been made, few have reflected on the past predictions with current

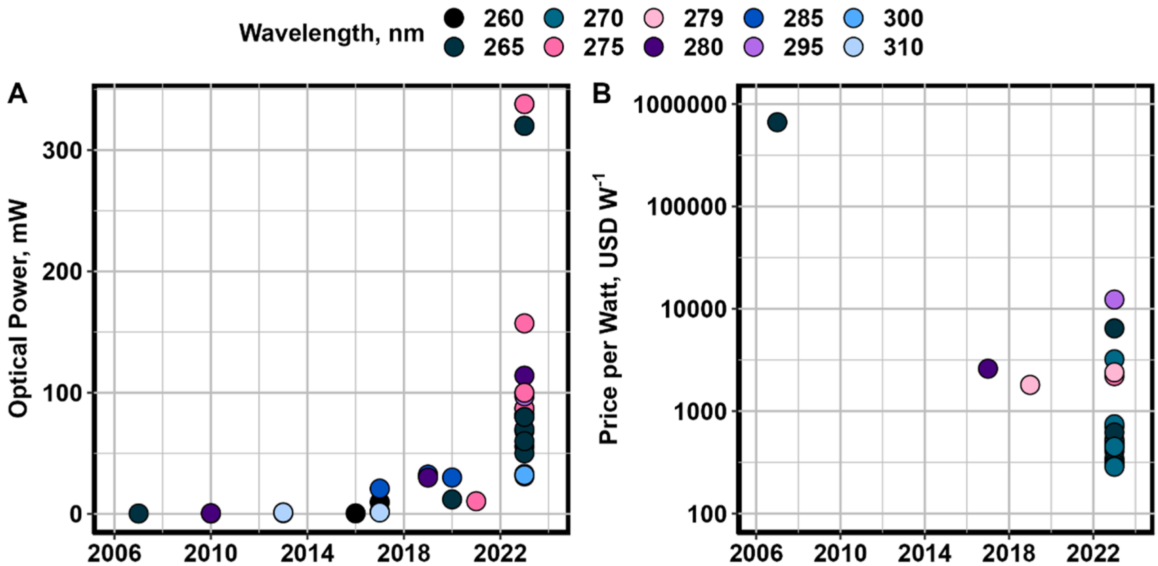

Fig. 1. Optical Power Output (A) and USD per Watt (B) for UV LEDs from 2007 to 2023 (Data Derived from Published Reports as Described in Table S1).

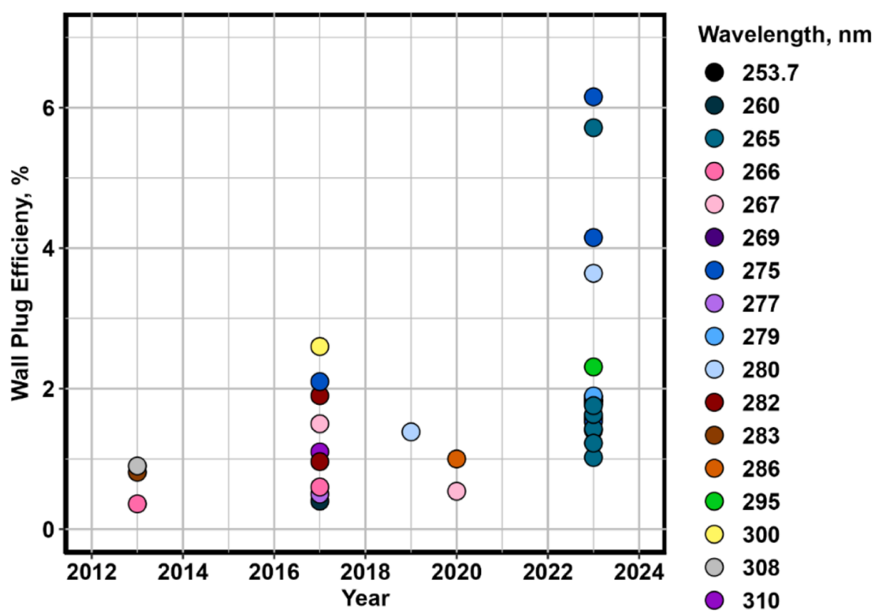

Fig. 2. Wall Plug Efficiencies of UV LEDs from 2013 to 2023.

figures. Comparing the estimations for optical power and cost to the averages found in this review (Table S1), these two predictions in the early 2010s were highly optimistic. The 2010 prediction for 2013/2014 is now close to the reality of LEDs in 2023, and the cost is still between 4.5–14.6 times higher compared to the predictions. Moreover, the predictions in 2014 greatly overestimated the rate of development of LEDs and the power and cost by 2020. Additionally, with current figures and trends explored in this review, it would be conceivable see power outputs approach 675 mW in the coming years; however, the cost is likely to still be much higher compared to the predicted 0.06 USD W^{-1}. There is no indication of UV LED development slowing and a benchmark of 100 mW output for 2–3 USD would amount to costs that are still an order of magnitude higher than a LP system but (Amano et al., 2020). Conventional low-pressure (LP) lamps have a WPE of approximately 33 % which marks a significant difference when compared to what current UV LEDs can achieve (Lawal et al., 2017). The trends presented in this review show an optimistic future for LEDs with improvements in power output coupled with decreased costs; however, the limits of adaptation of the technology will be dependent on breakthroughs to increase the energy efficiencies.

Current UV LED disinfection performance

The main inactivation pathway for UVC disinfection is through pyrimidine dimerization. This occurs when one of two adjacent pyrimidine bases (thymine in DNA and uracil in RNA) absorb a UV photon causing a chemical bond to form between the two. The main pyrimidine dimers responsible for inactivation are known as *cis-syn* cyclobutene pyrimidine dimers and 6–4 photoproducts; however, the latter are often produced in insignificant quantities compared to the cyclobutene photoproducts (Yokoyama and Mizutani, 2014). Oguma et al. (2002) showed that formation of 100 thymine dimers in a bacterial genome is sufficient to inactivate *E. coli* species. Nucleotide bases have a peak absorption band near 260 nm and below 230 nm proteins begin to absorb more UV radiation compared to the nucleotides. As such, typical disinfection mechanisms are related to the photochemical changes in the nucleic acid (DNA or RNA) structure using wavelengths between 230 and 280 nm with dimer formation at 289 nm dropping by 69.2 % compared to 253.7 nm (Eischeid and Linden, 2007). The peak absorption profile of microbe DNA depends on the exact composition of the adenine, guanine, thymine, and cytosine nucleotides (Bolton and Cotton, 2008). Consequently, organisms have been found to have wavelength dependent responses to UV treatment known as the action spectrum (Beck et al., 2015; Mamane-Gravetz et al., 2005; Rattanakul and Oguma, 2018).

Disinfection performance of indicator and challenge organisms across uvc/uvb wavelengths

Articles used in this review were selected based on a few inclusion criteria. Specifically, only studies that included fluence based kinetics (i.e., no time-based studies), and wavelengths between 253.7–300 nm using low-pressure mercury, medium pressure mercury, UV LED or other radiation sources were included. The k-value indicates the susceptibility of an organism to a given wavelength of UV radiation, as such, this was the main parameter collected to compare effectiveness of different UV sources. Engauge Digitizer was used to extract the data points in the log-linear region and k-values were calculated using the Chick-Watson model for articles that did not report inactivation kinetic rate constants (k-value) but had sufficient inactivation data. No bacteria, virus, or protozoa were excluded from the review, and species and strain were recorded when reported. Furthermore, nominal wavelength, treatment matrix, incident intensity and UVT% were recorded when reported. Based on the inclusion criteria, 30 articles were selected for review and a summary of the matrix, wavelengths, and species examined is in Table 1.

Fig. 3 shows the reported inactivation kinetics for various microorganisms for wavelengths between 253.4–300 nm. Species of organism, strain, and wavelength were shown to impact the UV sensitivity with the peak germicidal effect between 253.7–270 nm. Average inactivation rate constant for bacteria across all wavelengths and studies was 0.499 mJ^{-1} cm^2; whereas, the average for viral targets was 0.104 mJ^{-1} cm^2. *B. pumilus* spores were found to be the most resistant across wavelengths followed by Phi 6 bacteriophage then *B. subtills* spores. Qbeta, PhiX174, *E. coli* and L. *pneumophila* were found to be the most susceptible organisms across all studies (Table S3-S4). It is important to note that comparing different studies to each other is challenging as the methods and experimental setups can vary and the specific model of UV LED can govern the intensity of light that was used to deliver a fluence. Better continuity in methods for determining the action spectra of microbes is needed as more wavelengths of UV C emitting LEDs become available.

Many studies have compared UV LED performance against LP systems as they are the standard used in most disinfection applications and found varying results on which was more effective. Bowker et al. compared 255 and 275 nm UV LEDs to LP system on bacterial and viral targets and found that the 255 LED performed worse compared to the low-pressure system. The author's hypothesis was that the LEDs were less intense (6x dimmer) causing lower log reductions for similar fluences (Bowker et al., 2011). They also showed that 275 nm was outperform all other wavelengths tested on the T7 bacteriophage and that all LEDs performed worse compared to the LP system when MS2 was tested; however, both systems were within the acceptable range of the Ultraviolet Disinfection Guidance Manual developed by the United States Environmental Protection Agency (USEPA). Sholtes et al. (2016) compared 260 nm LEDs to LP systems and found significant difference in performance for *E. coli* species; however, the LEDs outperformed the LP system when *B. subtilis* spores and MS2 were tested. Chatterley & Linden (2010). also found no statistically significant difference between 265 nm LED and LP system for treatment of *E. coli*. Beck et al. (2017) showed that 260 and 280 LEDs performed as well as LP lamps, but had larger energy requirements for similar log reductions. Woo et al. (2019) showed that 260 and 280 nm LEDs outperformed the LP results reported by Ryu et al. (2018) against various Human Enteroviruses.Overall, it was reported across the literature that LEDs have comparable efficacy to LP systems for most species and strains; however, the optimal wavelength varies between species and strain.

The germicidal increases from alternative wavelengths compared to 254 nm can help offset current limited energy efficiencies of UV LEDs. For *E. coli,* it was observed that 260, 265 and 280 nm showed improved kinetics rates upwards of 117 % (Figure S2). For L. *pneumophila*, there was a 300 % increase with 255 nm LED, and a 195 % increase with a 275 nm LED compared to a LP system. MS2 also saw substantial increases in performance at 275 and 285 nm (67 % and 54 %, respectively) compared to 254 nm. These data highlight how important choosing the proper wavelength will be, as the wrong wavelength can decrease performance upwards of 50 % even in the germicidal range of 254–280 nm for specific organisms which may be important to consider for regulatory discharge limits. Additionally, the variation in k-values at the essentially same wavelength (255 nm UV LEDs vs LP) further highlights the need to have details on the operational conditions for UV LED studies. A 300 % difference in k-value at the same wavelength and fluence range should not be possible and is not fully discussed in the referenced work. An issue with measuring the fluence with the LEDs in this study could be the cause of this difference, but repetition of this work should be conducted to provide better context for this result.

Matrix effect

Inorganic, organic and particulate contaminates in real water matrices can have substantial impacts on disinfection performance. Würtele et al. (2011) explored 269 and 282 nm UV LEDs for disinfection of *B. subtills* in various water matrices. They found that treatment in surface water, tap water, and secondary effluent all produced similar log reduction values. They also observed that the 269 and 282 nm UV LEDs produced similar log-linear kinetics, however the 282 nm experienced a tailing phase which limited the upper level of disinfection achieved compared to the 269. Crook et al. (2015) tested LP and 255 nm UV LED for disinfection of environmental *E. coli* and *Enterococci* sp. in greywater systems collected from 18 residential properties. The authors found that the two UV systems performed comparably, and that sufficient inactivation of the microorganisms was achievable at a fluence of 41 mJ^{-1} cm^2.

Chevremont et al. (2012) examined the treatment effects of UVA and UVB/UVC combined systems on effluent collected from an activated sludge process. These authors used time-based kinetics instead of fluence, while outside the inclusion criteria an exception was made for this article as it was the first example of potential use of UV LEDs in municipal wastewater treatment in 2012. MacIsaac et al. (2023) compared treatment efficacy of environmental *E. coli* species using 280 nm LEDs and LP system at the bench-scale. The authors found that the 280 nm outperformed the LP system with greater log-linear kinetics and a higher upper level of treatment. The authors hypothesize this increased performance of the 280 nm LEDs was due to the energy of the LED emitted photons being absorbed more by particle-associated bacteria compared to the 254 nm treatment (MacIsaac et al., 2023). While the number of articles related to LED treatment of real water matrices remain low, the evidence indicates that UV LEDs can treat to the same level or better compared to LP systems.

Strain effect

Through the literature explored, it was evident that the strain of a given species has an impact on UV disinfection susceptibility. For example, Buse et al. (2022). examined the impacts of 3 wavelengths of UV LED on 4 different strains of L. *pneumophila*. They found that 255 nm LED was the most effective at treatment followed by the 265 and then 280 nm. The kinetics between wavelength remained the same across species, however the susceptibility to treatment overall was influenced by the strain. This was further evident for *E. coli* where species strain was shown to impact both the general UV susceptibility and action spectra.

Table 1
Summary of UV based inactivation studies.

Test Matrix	Scale	Wavelengths nm	Organism	Reference
Synthetic	CB	253.7 (LP) 265 275 285 300	*E. coli* CGMCC 1.3373 *P. aeruginosa* ATCC 27,853 *M. fortunitum* ATCC 35,855 *S. aureus* CGMCC 1.2456 *B. subtilis* ATCC 6633 Phi6	(Sun et al., 2023)
Synthetic	CB	255 280	MS2 QBeta PhiX174	(Aoyagi et al., 2011)
Synthetic	TL	253.7 (LP) 260 270 280 290	MS2	(Beck et al., 2016)
Synthetic	CB	253.7 (LP) 255 275	*E. coli ATCC* 11,229 MS2 ATCC 15,597 B1 T7	(Bowker et al., 2011)
Synthetic	CB	253.7 (LP) 265	*E. coli* ATCC 29,425	(Chatterley and Linden, 2010)
Synthetic	CB	253.7 (LP) MP 260 280	*E. coli* ATCC 29,425 MS2 ATCC 15,597 B1 *B. pumilus* ATCC 27,142	(Beck et al., 2017)
Synthetic	CB	253.7 (LP) 265 280 300	*E. coli* IFO 3301 *B. subtilis* ATCC 6633 QBeta ATCC 23,631 B1 L. *pneumophila* ATCC 33,152 *P. aeruginosa* ATCC 10,145	(Rattanakul and Oguma, 2018)
Synthetic	CB	265 280 300	L. *pneumophila* ATCC 33,152 *P. aeruginosa* ATCC 10,145 *V. parahaemolyticus* NBRC 12,711 *E. coli* IFO 3301 *B. subtilis* ATCC 6633 *F. calicivirus* ATCC VR-782 QBeta ATCC 23,631 B1 MS2 ATCC 15,597 B1	(Oguma et al., 2019)
Synthetic	CB	265	*E. coli* ATCC 11,229	(Song et al., 2019a)
Synthetic	CB	253.7 (LP) 265 280	*E. coli* CGMCC 1.3373	(Li et al., 2017)
Synthetic	CB	265 275 310	*E. coli* CGMCC 1.3373	(Nyangaresi et al., 2018)
Synthetic	CB	265 280	*E. coli* IFO 3301	(Oguma et al., 2013)
Wastewater	CB	285	MS2 ATCC 15,597 B1	(Nguyen et al., 2019)
Wastewater	CB	253.7 (LP) 280	*E. coli* Environmental	(MacIsaac et al., 2023)
Wastewater	CB	253.7 (LP)	*E. coli* Environmental	(Rauch et al., 2022)
Synthetic	CB	253.7 (LP) 260	*E. coli* ATCC 13,033 MS2 *B. atrophaeus* spores	(Sholtes et al., 2016)
Synthetic **Wastewater** **Drinking Water** **Surface Water**	CB	253.7 (LP) 270 280	*B. subtilis* ATCC 6633	(Würtele et al., 2011)
Synthetic	CB	253.7 (LP)	Coxsackievirus A10 ATCC VR168 Echovirus 30 ATCC VR-322 Poliovirus 1 Mahoney Enterovirus 70 ATCC VR-836	(Ryu et al., 2018)
Synthetic	CB	260 280	Coxsackievirus A10 ATCC VR168 Echovirus 30 ATCC VR-322 Poliovirus 1 Mahoney Enterovirus 70 ATCC VR-836	(Woo et al., 2019)
Drinking	CB	255 265 280	L. *pneumophila* ATCC 33,152 L. *pneumophila* ATCC 33,156 L. *pneumophila* ATCC 33,215 L. *pneumophila* sg1 dw	(Buse et al., 2022)
Synthetic	CB	280	L. *pneumophila* ATCC 33,152	(Lara De Larrea et al., 2023)
Drinking Water	CB	275	MS2 ATCC 15,597 B1	(Jarvis et al., 2019)
Synthetic	CB	265 285	*E. coli* MG 1655 MS2 ATCC 15,597 B1	(Betzalel et al., 2020)
Synthetic	CB	253.7 (LP) 265	*E. coli* IFO 3301	(Hosoi et al., 2017)

(*continued on next page*)

Table 1 (*continued*)

Test Matrix	Scale	Wavelengths nm	Organism	Reference
		280 300		
Synthetic	CB	253.7 (LP) MP 289(MP Filtered)	*E. coli* C3000	(Eischeid and Linden, 2007)
Greywater	CB	253.7 (LP)	*E. coli* Environmental	(Crook et al., 2015)
Synthetic	CB	255 265 280 285 295	*E. coli* MG1655	(Pousty et al., 2021)
Synthetic	CB	253.7 (LP)	*E. coli* ATCC 11,229 *S. aureus* ATCC 25,923 *B. subtilis* ATCC 6633 Poliovirus 1 LSc2ab	(Chang et al., 1985)
Synthetic	CB	275	*E. coli* ATCC 8739 *B. subtilis* ATCC 6633	(Romero-Martínez et al., 2022)
Synthetic	CB	253.7 (LP) 260 275	*E. coli* ATCC 11,229 QBeta	(Jenny et al., 2015)

CB = Collimated Beam.
TL = Tunable Laser.

Fig. 4 examines the impact the strain had on reported *E. coli* k-values. Examining the k-values between 254 and 280 nm shows a wide range across all strains. ATCC 11,229, IFO 3301, and MG 1655 were found to be the most susceptible through the germicidal range k-values between 0.4–1.2 mJ^{-1}-cm^{2}; and the environmental and ATCC 29,425 were the least susceptible with k-values all below 0.4 mJ^{-1}-cm^{2}. The most effective wavelengths were found at 254 (IFO 3301 & C3000), 265 nm (ATCC 11,229, CGMCC 1.3373, MG 1655) and 280 nm (Environmental). Interestingly, for ATCC 29,425 the LP, MP, 260, 265 and 280 nm all show virtually the same k-value. Furthermore, for all strains examined in this review where there is an LED and LP comparison there is at least one wavelength of LED that performs comparably or better. This indicates that LED disinfection for E. coli can be tailored to optimized disinfection.

Radiation intensity effect

Deviation from the time-dose reciprocity has been shown to occur in biological photo-processes such as inactivation. Well not true for all strains of a species (Fig. 4), the MG 1555 strain was found by Pousty et al. (2021) to be impacted by radiation intensity, where orders of magnitude lower produced higher levels of inactivation. This phenomenon was noted to be wavelength dependant, not occurring at 265 nm, but at wavelengths of 275, 285, and 295 nm. The effect was shown to be more pronounced as the wavelength increased. The authors examined different stress response of the *E. coli* in the study and found that the longer wavelengths produced a larger stress response related to reactive oxygen species (ROS), vs the lower wavelengths which were found to be more related to direct DNA damage. This was an interesting finding as typically it has been shown that higher intensities produce higher levels of inactivation in bacterial cells (Sommer et al., 1998, 1996), as repair mechanisms could not compete with the rate of dimer formation. However, yeast cells have been shown to be more susceptible to low intensity treatment (Sommer et al., 1998). Pousty et al. (2021) suggest that radical damage is the main inactivation mechanism at the lower intensities, and the authors also note that in a real water matrix the radical species would likely be scavenged if produced extracellularly.

UVA and dual wavelength treatment mechanism

Exposure to UVA radiation can cause sublethal effects in microorganisms such as reduced growth rates, reduced nutrient uptake, membrane damage, protein oxidation, decreased ATP production and cellular mutation (Bosshard et al., 2010). Hydroperoxidase enzymes are key to controlling the generation of ROS as they scavenge any H_2O_2 produced by cellular metabolism (Hoerter et al., 2005). If this defense system is hindered or rendered non-functional then an imbalance of ROS and antioxidants in the cell leads to a state know as oxidative stress (Bosshard et al., 2010; Hoerter et al., 2005; Song et al., 2019b). UVA irradiation of *E. coli* pure cultures lead to a disruption in the respiration processes for fluences above 30 *J* cm^{-2} where UVA radiation disrupted the respiration cycle in *E. coli* by forming ROS intracellularly causing damage to the enzymes responsible for ATP production (Bosshard et al., 2010). The effects of UVA irradiation on *E. coli* response was irradiance dependant (Hoerter et al., 2005). Applying a continuous irradiance of 0.74 mW cm^{-2} during growth lead to growth delays and increased resistance to UVA applied at lethal irradiance in subsequent generations of *E. coli*. The researchers showed that a fluence of 12.5 *J* cm $^{-2}$ applied with an irradiance of 5.0 mW cm^{-2} led to extensive oxidation of cellular proteins inhibiting key enzymatic functions which ultimately lead to cell death. Initial lethal effects (approximately 2 log reduction of CFU mL^{-1}) with UVA radiation were found at fluences above 95 *J* cm^{-2} leading to between 4 and 5 log reductions in colony forming units after 24–48 hour of dark incubation following irradiation (Bosshard et al., 2010).

Disinfection synergies have also been evaluated for combination of UV LED wavelengths. A study by Chevremont et al. (2012) showed synergistic effects using combinations of UVC (254 nm) or UVB (280 nm) and UVA (365/405) nm LEDs in effluents collected from a waste activated sludge plant, and their findings show that the 280/365 nm was the most effective system. They suggest that UVA radiation indirectly effects bacteria by increasing the concentration of ROS in the cells; however, their work could not confirm this. Recently, Song, Taghipour, et al., 2019 observed that pre-treating a pure culture of *E. coli* with 52 *J* cm^{-2} of 365 nm UV LED radiation followed by irradiation with a 265 nm LED produced a synergistic effect 2 times greater than the sum of the treatments They were able to show in a subsequent paper that this synergistic inactivation was due to UVA radiation photosensitizing intracellular components to produce hydroxyl radicals ($^{\bullet}OH$) that then damaged critical cellular components such as the enzymes responsible for managing ROS concentrations and photo-repair (Song et al., 2019a). These findings support earlier work describing the sublethal and lethal effects of UVA radiation on *E. coli* cells (Bosshard et al., 2010). Combinations of 280 and 260 nm LEDs have also been explored for synergistic effects as proteins responsible for reactivation or repair mechanisms would absorb more radiation at 280 nm; however, it has largely been found that there are no synergistic effects when these two wavelengths are combined (Beck et al., 2017; Woo et al., 2019).

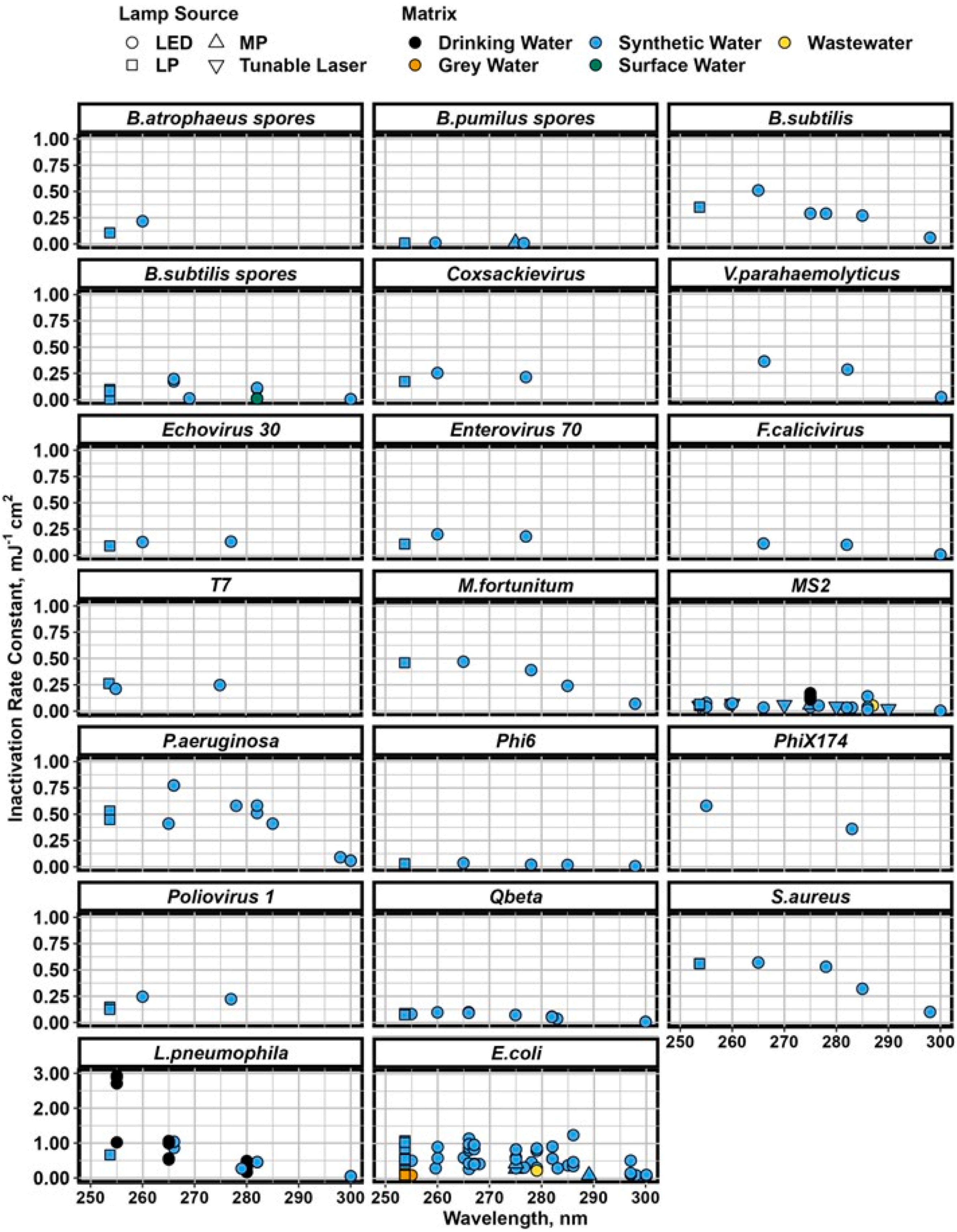

Fig. 3. Reported Inactivation Rate Constants for Various Microorganisms. The Fill Colours Represent the Water Matrix Tested, And the Shapes Represent the Different Lamp Sources: LEDs (Circle), Low-Pressure Mercury Vapour (Square), Medium-Pressure Mercury Vapour (Triangle), and Tunable Laser (Inverted Triangle).

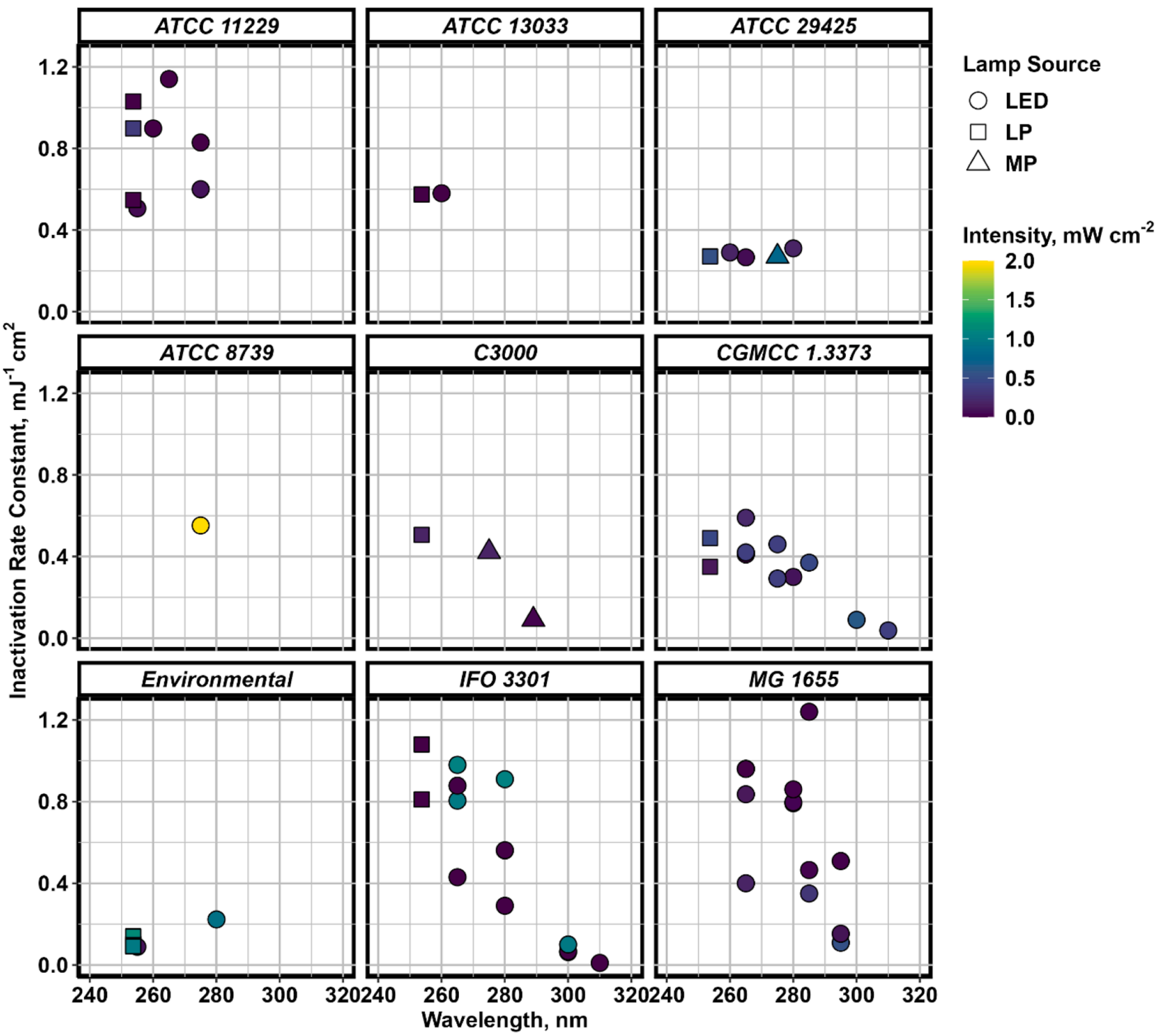

Fig. 4. Reported Inactivation Constants for E. coli Species. Shapes Represent Lamp Source and Colour Represent Measured Incident Intensity of the System. Note That Composition and Depth of the Matrix Will Dictate Delivered Dose.

Wavelength impacts on reactivation mechanisms

Reactivation mechanisms can be sub-categorized as photoreactivation and/or dark repair. In both cases photoproducts are either repaired or removed allowing for proper replication of the DNA to occur. In dark repair mechanism there can be a direct replacement of the photoproducts by first cutting out the damaged DNA section, resynthesizing the original structure, and finally reattaching this to where the damaged section was removed (Morita et al., 2010). Dark repair mechanisms have been shown to be used by most bacteria (Hijnen et al., 2006); however, it is less of a concern when considering coliform bacteria which are typically the target organism for regulatory discharge limits (Salcedo et al., 2007). Photoreactivation mechanisms use near-UV (310–480 nm or shortwave visible light) to activate an enzymatic process that cleaves the chemical bond formed between two thymine bases (Morita et al., 2010; Whitmore et al., 2001). Most strains of *E. coli* are known to have photoreactivation mechanisms (Oguma et al., 2002); however, this is not true of all microorganisms (Bolton and Cotton, 2008). Effects of photoreactivation have been shown to be reduced from MP UV by damaging the photolyase enzyme (Oguma et al., 2002). Similar effects on photoreactivation were observed from the application of UVA light using a 365 nm UV LED prior to UVC treatment; whereas, the application of UVA light simultaneously or following UVC irradiation reduced disinfection performance in *E. coli* pure cultures due to triggering photoreactivation mechanisms (Song et al., 2019a). The level of photoreactivation following disinfection treatment from various wavelengths of UV LEDs (peak wavelengths = 260, 280, and 300 nm) was examined but no significant difference in the level of reactivation for the three wavelengths was found (Hosoi et al., 2017).

Flow-Through system performance

Articles selected for this review relating to flow-through performance were based on specific inclusion criteria such as fluence-based kinetics, wavelengths between 253.7–300 nm, and LED, LP, or MP reactors being used. For articles reporting flow-through data that did not report REFs or log reduction value (LRV), Engauge Digitizer was used to extract the data and these values were determined. Species, strain, LED wavelengths, UVT%, flowrates, LRV, REF, total optical power, number of LEDs, and power per LED were collected where reported. Using these inclusion criteria, 11 articles were selected for review and spanned publication dates between 2010 and 2023 and included articles for pure culture, drinking water, and wastewater at bench-, pilot- and full-scale. A summary of wavelengths, organisms, and flowrates of the included studies is shown in Table 2. Recent work has demonstrated the feasibility of UV LEDs at scale for disinfecting wastewater and achieved a 3-

Table 2
Summary table for UV LED flow-through studies.

Test Matrix	Scale	Wavelength nm	Organism	Flowrates, mL-min^{-1}	Reference
Synthetic Drinking Water	FTR-B	265	*E. coli* ATCC 29,425	2.68–18.2	(Chatterley and Linden, 2010)
Synthetic	FTR-B	265 280	*E. coli* IFO 3301	385 (Recirculating)	(Oguma et al., 2013)
Wastewater	FTR-B	285	MS2 ATCC 15,597 B1	10–50	(Nguyen et al., 2019)
Synthetic	FTR-B	280	*B. subtilis* ATCC 6633	7.8–10.8	(Würtele et al., 2011)
Synthetic	FTR-B	275	*E. coli* ATCC 8739 *B. subtilis* ATCC 6633	1078–2549	(Romero-Martínez et al., 2022)
Synthetic	FTR-B	280	*E. coli* IFO 3301	40–100	(Wang et al., 2021)
Synthetic	FTR-B	265	MS2 ATCC 15,597 B1 Adenovirus ATCC VR5	750–2000	(Keshavarzfathy et al., 2021)
Synthetic	FTR-B	260 275	QBeta	109	(Jenny et al., 2015)
Drinking Water	FTR-P	280	L. *pneumophila* ATCC 33,152 L. *pneumophila* ATCC 33,156 L. *pneumophila* ATCC 33,215 L. *pneumophila* sg1 dw	10,410	(Buse et al., 2022)
Drinking Water	FTR-F	280	MS2 ATCC 15,597 B1	24.3–604	(Hull et al., 2019)
Synthetic Wastewater	FTR-F	275	MS2 ATCC 15,597 B1 *E. coli* ATCC 8739	20,000	(Montazeri and Taghipour, 2023)

FTR-*B* = Flow-Through Reactor Bench-Scale.
FTR-*P* = Flow-Through Reactor Pilot-Scale.
FTR-*F* = Flow-Through Reactor Full-Scale.

log reduction for wastewater at a flow rate of 817 m^3 day^{-1} (MacIsaac et al., 2024).

Achieved reduction equivalent fluences and flowrates

Fig. 5 examines the flowrates and REFs achieved by UV LED based reactors at various scales in publications between 2010 and 2023. Flowrates ranged from 2.7 to 20,000 mL min^{-1} and REFs ranged from 4.4 to 156.7 mJ cm^{-2}. Generally, the trend of increased REF and flowrate parallels the increase in total optical power of the systems. Examining the average of key parameters of LED reactors, (Table S2), the average optical power delivered in a single LED system of multiple LEDs reported in 2010 was 7.7 mW which increased to 1069 mW in 2023. This equates to 139 times increased in average power of treatment systems or 106 times decadal increase, translating into higher flowrates being treated. While there have been increases to achievable flowrates and optical power almost year-to-year, from 2022 to 2023 there was almost a 10-fold increase in flowrates and 3 times increase in optical power while reducing the number of LEDs in the system from 40 to 14. These increases of key parameters indicate the potential of full-scale performance as the magnitude of flowrates achieving substantial REFs continue to grow.

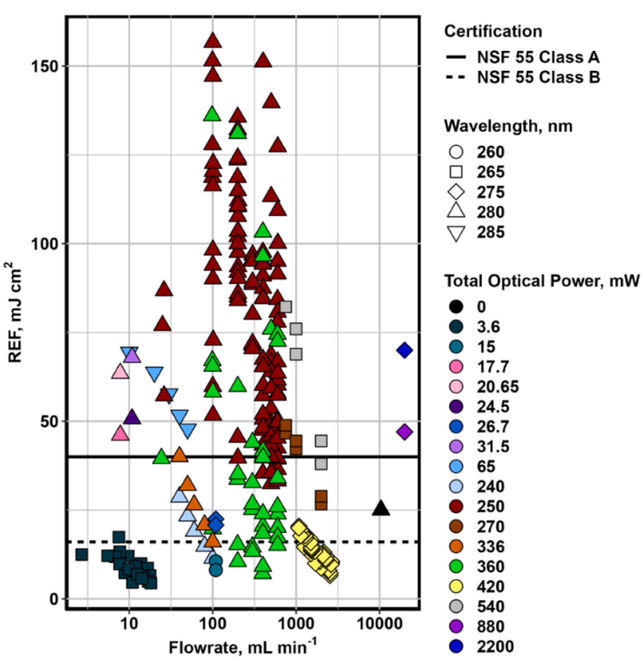

Fig. 5. Flowrate (Log-Scale) vs Reduction Equivalent Fluence (Linear-Scale) Extracted from UV LED Flow-Through Studies. Shapes Represent the Nominal Wavelength of The UV LED Used in The Study; the Colour Represent the Total Optical Power of the Units Used. The Solid Line Represents the Fluence Required for NSF 55 Class A Certification (40 mJ cm^{-2}, MS2) and the Dashed Line Represents the Fluence Required for Class B Certification (16mJ cm^{-2}, T1 or S. cerevisiae).

Synthetic matrix

Various biodosimeters have been used in studies to understand the REFs achieved by a flow-through reactors. Jenny et al. (2015) tested a custom reactor using 20 LEDs emitting at either 260 or 275 nm wavelengths (0.5 and 0.89 mW LED^{-1} respectively). The authors found that the reactors could achieve a maximum REF of approximately 9 mJ cm^{-2} for the 260 nm and 21 mJ cm^{-2} for the 275 nm set ups using Qbeta as the biodosimeter. The authors also varied the UVT% 254 nm of 92 % and 80 %. The lower UVT% samples had slightly lower REFs. Using the system arrangement, they achieved a 1.75 log reduction of *E. coli* ATCC 11,229 at flowrate of 109 ml min^{-1} and 92 UVT%. Romero-Martínez et al. (2022) used a custom UV LED reactor emitting at 275 nm with a total power output of 420 mW (40 LEDs) to treat various pathogens including *E. coli* and vegetative *B. subtilis*. The authors used the two species log-linear kinetics to calculate REFs and found sound agreement between fluence-based inactivation rate constants performed using collimated beam tests and the REFs determined at various flowrates. The system was tested at flowrates between 1 and 2.5 LPM and achieved REFs between 9.6–20.4 mJ cm^{-2}. These REFs are very similar to those reported by Jenny et al. (2015), but the flowrates were 9.9 times larger in the latter study. This is due to the vast improvements in power outputs of singular 275 nm LEDs since 2015 (0.89 mW in 2015 vs 10.5 mW in 2022).

Keshavarzfathy et al. (2021) designed and tested a serpentine style bench-scale reactor equipped with 18, 30 mW UV LEDs. The authors tested the reactor in 3 modes: Alpha, where the LEDs were placed on the sides of the entrance so that the light runs current with fluid on each pass; Beta, same as Alpha but with the LEDs placed so that the flow was concurrent to the light; and Gamma, where the LEDs were placed on both sides of each pass. The Gamma arrangement had a power output of 540 mW and achieved REFs for MS2 between 44 and 82 mJ cm^{-2} for flowrates between 2 and 0.75 LPM, respectively. The Alpha and Beta arrangements achieved lower REFs for MS2 between 26 and 48 mJ cm^{-2}. The authors tested the reactor again with Human Adenovirus in the Gamma setup and found that the reactor achieved REFs of 76 and 38 mJ cm^{-2} for flowrates of 1 and 2 LPM, respectively.

These papers highlight the importance of reactor design and how the placement of UV LEDs can be optimized to improve performance. UV LEDs allow for a much-expanded design space compared to conventional technologies which adds a layer of difficulty when comparing one reactor to another. Varying reactor geometry may lead to complicated fluence distribution profiles, but the use of REFs couples biodosimetry with flow-through data. The use of an actinometer when characterizing and designing LED reactors may provide further confidence in performance data. Traditional actinometers may such as p-chlorobenzoic acid (pCBA) do not absorb light in the regions of typical UV LEDs highlighting the importance of actinometer choice when characterizing a new device (Jung and Choi, 2006; Nichela et al., 2010; Rattanakul and Oguma, 2017; Wang et al., 2022). A recent paper outlined a method that is suitable for the tailored characteristics of UV LEDs (De Brito Anton et al., 2024; Pousty et al., 2023). Coupling actinometry data with biodosimetry data will provide a more complete picture of reactor performance and mechanics when assessing LEDs.

Drinking water

Hull et al. (2019) produced the first paper to evaluate UV LEDs for a small-scale drinking water system in Colorado, USA. The study looked at the impact of UVT% and flowrate on disinfection of native coliform for compliance and MS2 during challenge testing. The study found the small Pearl Aqua system from AquiSense to be robust enough to handle the range of water qualities experienced by the facility and found it to perform at the same level as the chlorine disinfection system installed at the plant without any maintenance at all throughout the year of the study (AquiSense Technologies, Erlanger, KY, USA). This paper was the first to illustrate the potential of UV LEDs for municipal drinking water treatment. The authors also note that the total annual cost to run the system at a REF of 40 mJ cm^{-2} and 0.5 LPM was 25 USD (95.12 $USDmL^{-1}$).

Jarvis et al. (2019) tested a full-scale 275 nm UV LED system in a drinking water system in Cranfield UK. This was the first full-scale drinking water UV LED reactor install and treated 6 MLD. The system had a total optical power of 100 W using 1000 LEDs, making it the most powerful drinking water LED unit reported in the literature. While REFs were not calculated and MS2 log reduction values not provided, the authors note that the LED system had equal or better performance compared to the LP full-scale system based on MS2 log inactivation and indicates that LEDs have a strong future for drinking water treatment applications.

Wastewater

While UV LEDs are growing in popularity for disinfection in drinking water treatment, there has been less interest in applying this technology to more challenging matrices such as domestic wastewaters due to limitations in energy efficiencies and power output of UV LEDs. However, these limitations are temporary and the fundamental interactions of UV light and contaminants in the wastewater are still being explored by some researchers. Currently only four papers have used flow-through reactors for treatment of domestic wastewaters. The first was from Nguyen et al. (2019) which showed that a readily available commercial system (PearlAqua 6d; AquiSense Technologies) effectively treated a primary treated wastewater at low flowrates. The reactor achieved a maximum REF of 69.4 mJ cm^{-2} at a flow of 10 $mLmin^{-1}$ and maintained a REF of 46 mJ cm^{-2} at a flowrate of 50 mL min^{-1}. While these flowrates are not practical for centralized treatments, the system only had an optical power of 65 mW, whereas the modern reactor designed by Montazeri & Taghipour (2023) with a total power output of 2200 mW could potentially allow for higher flows. The latter reactor was operated with municipal wastewater system as to rapidly foul the system. The authors operated the system at 20 LPM and achieved a REF of 70 mJ cm^{-2} using MS2 as a biodosimeter; however, they did not achieve consistent log inactivation of *E. coli* in the wastewater (0.2–1.2 logs). The authors note that the design of the reactor was optimized for high UVT% and not for the low UVT (55–64 %) of the test water. This shows that total optical power alone is not enough to effectively treat challenging matrices and optimized reactor design is also required for treatment of more challenging water matrices. Additionally, matrix and system limitations have been identified as the two governing factors for UV disinfection efficacy limits. Matrix limitations refer to characteristics of the NOM and particles that may limit the distribution of light with a water matrix whereas system limitations refer to physical treatment processes which can be optimized to remove particles and NOM which may negatively impact UV disinfection. Matrix and system limitations are highly specific to each wastewater matrix and should be investigated on a case-by-case basis (Rauch et al., 2022). UV LEDs have been examined for treatment of wastewater in reuse for agriculture and shown to slow biofilm formation (Randall et al., 2024). The final paper that examined full-scale disinfection of wastewater (UVT_{254} 54.6–66.2 %) using an UV LED reactor operated at flow rates of 517 and 845 m^2 day^{-1} using a 280 nm UV LED reactor (MacIsaac et al., 2024). The reactor used in this paper did not experience any fouling during the four-month runtime of the study or any quantifiable reduction in log reduction capacity at the conditions that were studied. Fouling of the internal wetter surfaces is expected during longer runtimes and should be monitored by inspecting these surfaces periodically. The reactor used in this study was equipped with two UVI sensors which provided real-time data during the study period.

Fouling

Both wastewater papers also are the only two studies that examine the mechanisms of LED system fouling. System fouling has been expected to be very different compared to LP systems due to the difference in location of heat generation between the LEDs and LP lamps and understanding these differences will be crucial for proper implementation, maintenance and reactor operation moving forward. Montazeri & Taghipour (2023) found that the LED system fouled to a 67 % reduction in REF in 22 days of continuous use; whereas, the conventional mercury system was found to foul to the same level in only 2 days of operation. Nguyen et al. (2019) noted a similar level of fouling to Montazeri & Taghipour in their system after 25 days of operation (63 % reduction in REF). This substantially slower fouling rate indicates that LED systems may require less frequent maintenance.

In terms of composition of fouling, Montazeri & Taghipour (2023) found that magnesium was not a substantial constituent of inorganically fouled regions, and that zinc oxides comprised 15 % of the inorganic fouling. Iron (44 %), calcium (19 %), and phosphorus (18 %) were also found to be major constituents of the inorganic fouling. The authors did not note what proportion of the fouling was organic and inorganic but did indicate that organic fouling was hindered and inorganic fouling was increased at places of high radiant flux. Nguyen et al. (2019). noted most of the fouling was organic, compared to the typical inorganic fouling of LP systems They found that 67 % of the fouling was volatile solids, 18.7 % was Calcium, and 4.8 % was manganese. Iron and phosphorus made up the remaining 0.47 % of the weight fraction For cleaning the systems, Montazeri & Taghipour (2023) found hydrogen chloride (0.5 M) had the greatest impact on cleaning, although it was found to be particularly ineffective on organically fouled regions. Nguyen et al. (2019) found that a 4 hour of a citric acid rinse completely removed all 25 days of organic and inorganic fouling, or as the authors suggest would be approximately 10 min of cleaning a day and in line with USEPA recommendations for LP lamps. However, it should be noted that the authors did not explore if 10 min of daily cleaning maintained the performance of the reactor. Both studies ultimately showed that fouling mechanisms are fundamentally different in UV LED reactors vs LP systems and that the fouling is easily mitigated with a cleaning regime.

Overall, fouling of UV LED systems is an important consideration that requires additional research to fully understand the implications of inorganic fouling in the absence of a heat source. Mechanical or chemical cleaning may be required depending on the influent water quality and the operational runtime for a reactor. UV LEDs decouple the direction of heat emission and UV light emission whereas conventional lamps emit heat and light in the same direction thus leading to the hypothesis that LEDs may foul at a slow rate when compared to the quartz sheaths of conventional lamps. This hypothesis must be tested as more large reactors come are installed for significant periods of time. The potential for reduced fouling for UV LED reactors could be a significant benefit for utilities when considering the operational and maintenance costs.

Lamp breakage

Lamp breakage is another hazard that should be factored in when considering the change from LP/MP lamps to LEDs. A single mercury lamp can contain anywhere between 20 and 400 mg of mercury which would immediately be released to the water environment during a breakage event (Aucott et al., 2003; Borchers et al., 2008). Breakage events are broken down into two categories 1) Offline lamp breaks and 2) Online lamp breaks. Offline breaks occur when a lamp is not in service and the ballast mercury is in the liquid phase and there is typically no flowing water around the lamp at the time of breakage (Borchers et al., 2008; United States Environmental Protection Agency, 2006). Online lamp breaks occur when the lamp is in service with water flowing around it. The ballast mercury is in the vapor state in this scenario and poses a greater risk to human health and the environment upon release (Borchers et al., 2008; United States Environmental Protection Agency, 2006). Utilities generally have abatement strategies when dealing with broken and spent UV lamps that include defined containers for handling end-of-life lamps that are kept in a well-ventilated area and is protected from outdoor elements (Environment and Climate Change Canada, 2017). LEDs avoid this issue entirely by not containing mercury and needing no special handling requirements in relation to human health and neurotoxin exposure. This secondary benefit will potentially save significant handling and hazardous material management costs by ensuring the disinfection process is inherently safer by eliminating the use of mercury.Future Considerations

The operational cost, reactor footprint, and sustainability of alternative technologies have been identified as key factors when comparing UV LEDs to conventional systems. Conducting a life cycle analysis considering these factors would be very beneficial in understanding how each technology compares especially give the unknown fate of the mercury lamp market as the Minamata Convention comes into effect. A better understanding of fouling rates and mechanisms has also been identified as a knowledge gap regarding UV LED reactors and their design. LEDs will need to continue on the path of improvement in order to have more widespread adoption along with regulatory approval for widespread use.

Conclusion

UV LED development has dramatically improved in the past 16 years and current state of the art LEDs have enabled a move from theoretically implementing LEDs at scale to doing so practically. The key factors for implementation of price, power output and efficiency will only continue to improve, making LED disinfection across the water and wastewater industry more accessible, affordable, and commercially viable. Full-scale use is underway and more will be learned about effective implementation of UV LED technology as these data become available from larger installs. Bottlenecks in the supply and access to highly efficient UV LEDs must be addressed as the market develops and more manufactures enter the UV LED market sector. As UV LED performance improves, it will allow for UV treatment to expand to applications where form factor and mercury issues currently limit implementation. As such, there is need to increase the understanding around how effective an installed UV LED system is operating, the impacts that wavelength selection has on required fluences and energy, and how alternative wavelengths of UV will interact with a diversity of water matrices. Better documentation of the specific LEDs that re used in studies would be beneficial when comparing works. UV LEDs can vary by orders of magnitude of brightness depending on the generation of LED and wavelength. Differences in manufacturing quality control and efficiencies may also be a source of some of the variability that is observed when comparing UV LED studies. The specific model number of LEDs that are used in studies is generally not reported, but as the technology changes so quickly, this information would be very important in providing context of UV LED kinetics. Ultimately, UV LEDs show a promising future for expanding the implementation of UV treatment across the water and wastewater sector.

CRediT authorship contribution statement

Kyle D. Rauch: Writing – review & editing, Writing – original draft, Visualization, Investigation, Formal analysis, Data curation, Conceptualization. **Sean A. MacIsaac:** Writing – review & editing, Writing – original draft, Visualization, Investigation. **Bailey Reid:** Writing – review & editing, Writing – original draft, Formal analysis, Data curation, Conceptualization. **Toni J. Mullin:** Writing – review & editing, Writing – original draft, Formal analysis, Data curation, Conceptualization. **Ariel J Atkinson:** Writing – review & editing, Data curation, Conceptualization. **Anthony L Pimentel:** Writing – review & editing. **Amina K. Stoddart:** Writing – review & editing, Project administration, Conceptualization. **Karl G. Linden:** Writing – review & editing, Conceptualization. **Graham A. Gagnon:** Writing – review & editing, Project administration, Conceptualization.

Declaration of competing interest

The author(s) declare no competing interests.

Acknowledgements

This study was funded through support from a Water Research Foundation [WRF Project #5173] and the authors would like to thank the Project Advisory Committee for their support and guidance.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.wroa.2024.100271.

Data availability

Data will be made available on request

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