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Thinking outside the treatment plant: UV for water distribution system disinfection

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CONSPECTUS

This work critically evaluates the current paradigm of water distribution system management and juxtaposes that with the potential benefits of employing UV irradiation, which we hope will catalyze a critical re-evaluation of the current practices in water distribution system management and spur critical research and a new way of thinking about secondary disinfection across the extent of distribution systems.

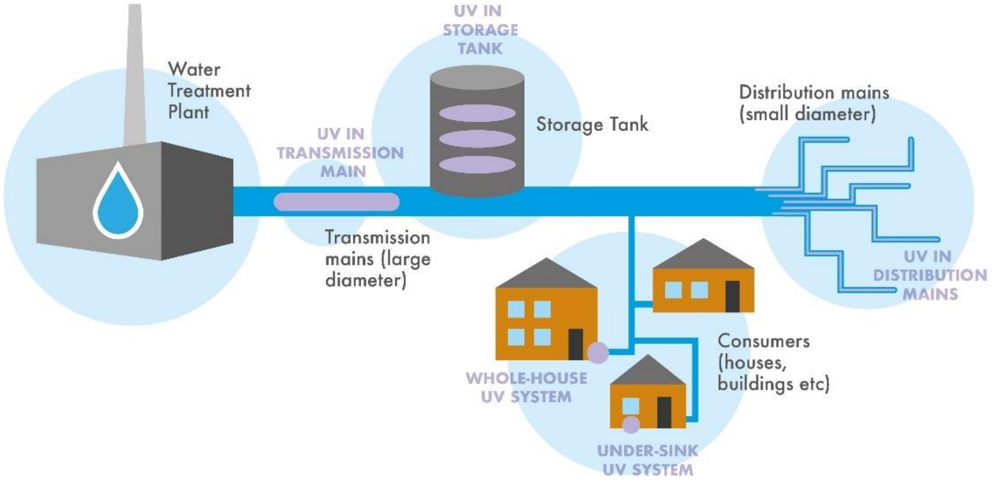
Given the recent advances in UV technology and the efficacy of UV disinfection against all pathogen classes, we now see UV applications for disinfection in many aspects of consumers lives: in water coolers, dishwashers, coffee makers, and disinfection of personal items like gym bags, water bottles, and toothbrushes. Public and regulatory concern over water quality and pathogens, especially the recent interest in building plumbing, calls out for new approaches to disinfection and distribution system management.

We envision a new model for secondary disinfection in water distribution systems utilizing emerging germicidal UV LED-based disinfection. UV irradiation in water treatment can achieve high levels of disinfection of all pathogens and minimize or eliminate the formation of regulated disinfection by-products. So why is UV not considered as a secondary disinfectant for distribution systems? In this paper, we lay out the logic as to the benefits and practicality of adding distributed UV treatment to assist in protection of distribution systems and protect water quality for human exposure.

The possible locations of UV irradiation in distribution systems are envisioned, potentially including UV booster stations along the distribution network, UV in storage tanks or their inlet/outlets, LEDs distributed along pipe walls, small point of use/entry treatment systems for buildings/homes/taps, or submersible swimming or rolling UV LED drones to reach problem pipes and provide a ‘shock’ treatment or provide sterilization after main breaks or repairs. The benefits of UV applications in water also include high effectiveness against chlorine resistant protozoa, no added disinfection byproducts, and compatibility of adding of UV to existing secondary disinfection strategies for enhanced protection.

Potential challenges and research needs are described such as use of UV-compatible pipe materials, implementation of sensors to monitor distributed LEDs, management of waste heat from the rear surface of the LED, and understanding the potential for regrowth of opportunistic microorganisms. Another notable challenge is the relatively stagnant regulatory environment in some countries to develop frameworks for evaluation and acceptance of UV technology in distribution systems that require a chemical secondary disinfectant.

Rapid advances in UV LED research has propelled the growth of this field, but needs still remain including understanding behavior of biofilms in pipes under UV irradiation including any beneficial effects that may be lost, the potential for fouling of LED emission surfaces and monitoring points, and provision of a distributed power network to run the LEDs. Regulators may want specific monitoring approaches, and advances in real-time monitoring of microbial viability, and engineers may need to develop new approaches to overall management.



INTRODUCTION

Water distribution systems represent the final infrastructure in multi-barrier public health protection, for delivering safe drinking water from the treatment plant to the places where people live, eat, and work. However, even when the most advanced treatment plant technologies are in use, water quality in the distribution system can be compromised due to aging and deterioration of buried pipe assets leading to increased vulnerability to contamination, and where chlorine is used as a residual, disinfectant decay and formation of disinfection by-products (DBPs) are of concern.

Surface water sources of drinking water typically have higher microbial contamination than groundwater sources and thus have been the focus for disinfection, with many groundwater systems distributing non-disinfected water directly to consumers. Primary disinfection, which will be considered in this paper as the disinfection that occurs in the treatment plant (whether in one of more stages of treatment), is often accomplished using chemical oxidants like chlorine and ozone, or using physical inactivation like ultraviolet (UV) disinfection. Secondary disinfection, which will be considered in this paper as the disinfection that takes place in the distribution system, is typically provided by chemical oxidants, with a persistent residual to provide protection as water travels from treatment plant to tap.

In the US, an estimated 93.7% of the population receive water with a secondary disinfectant[1], which is required for all surface water and vulnerable groundwater systems[2,3]. The trend in the US for the future will likely be to increase disinfection and/or disinfectant residuals. Under the Ground Water Rule, systems with microbial noncompliance will need to provide disinfection at the source as a minimum intervention[3]. Under the Revised Total Coliform Rule, corrective actions for microbial noncompliance include temporary chlorination and increases in disinfectant residuals[4]. However, many European countries distribute drinking water without a secondary disinfectant, either from groundwater or surface water sources rendered biostable via treatment, including the Netherlands, Germany, and Switzerland[5,6] so the precedent for secondary disinfectant-free water has already been set.

Goals for Distribution System Disinfection

The control of pathogens in water distribution is of primary concern in the delivery of safe drinking water. In some cases, treatment deficiencies have resulted in carryover of pathogens into the distribution system with widespread illness, such as the cryptosporidiosis outbreak in Milwaukee, Wisconsin, USA[7]. But increasingly waterborne disease outbreaks have been caused by distribution system failures including cross-connections with non-potable water systems, intrusion of pathogens through defects in distribution system facilities such as storage tanks, and main breaks and repairs[8–11]. Intrusion of pathogens through cracks or other pipe defects during low pressure events has the potential to be a source of contamination and is likely contributing to background rates of gastrointestinal illness, although the events are often of short duration and difficult to conclusively link to a specific incidence of illness[12,13]. As water infrastructure continues to age and deteriorate and undergo repair, the number of physical defects in pipes, storage tanks, and valves will continue to grow and correspondingly the risk of contamination events will increase.

Opportunistic pathogens (OPs), such as *Legionella*, are now the most frequently occurring etiology in waterborne disease outbreaks and have been shown to be associated with water distribution system occurrence and deficiencies in internal building plumbing in a large majority of cases[10]. Preventing and controlling contamination in internal building plumbing is increasingly a focus within the water industry, although significant challenges exist with regards to access, materials of construction, and accountability for water quality because the water utility responsibility, in general, ends at building connection location (often the water meter).

Beyond pathogens, a number of chemical water quality parameters, including metals and disinfection by-products (DBPs), are regulated within distribution systems because of their potential public health impacts. As research develops into the complex and inter-related constituents of distribution system water quality, it is becoming increasingly apparent that microbiological activity plays a role in many of these chemical reactions and thus drinking water quality must be considered more holistically.

The bulk of the microbial life present in water distribution systems is not directly harmful to human health and is present in the form of attached biofilm communities, rather than as planktonic organisms[14]. The biofilm and its associated extracellular polymeric substances (EPS) play a strong role in the accumulation and mobilization of metals and other inorganic contaminants like nitrate, often resulting in discoloration and water quality violations when the biofilm is detached by hydraulic events or changes in water chemistry[15]. Furthermore, metals of concern in drinking water distribution systems, including iron, manganese, lead, and copper, can all be influenced by microbial activity via microbially-induced corrosion and other metabolic activities within the biofilm, although the reactions are complex and poorly understood so it remains unclear whether the microbial activity accelerates or prevents corrosion[16]. Organic carbon in the water is consumed and transformed through chemical and microbiological reactions during travel through the distribution system.

Disinfection by-products are formed when chemical disinfectants, predominantly chlorine, react with organic and inorganic matter. When free chlorine is used as a secondary disinfectant, the production of DBPs continues beyond the treatment plant throughout the duration of water distribution. The occurrence and speciation of DBPs are strongly influenced by microbial activity within the distribution system as biofilms can contribute additional DBP precursor material[17] as well as degrade certain DBP species[18].

With the addition of ammonia to free chlorine to form chloramines, the formation of the currently-regulated chlorinated DBPs is controlled and thus chloramination has become a popular compliance strategy for DBP regulations, although chloramination is also associated with nitrite, nitrate and other by-products of concern[19]. However, the presence of ammonia through excess dosing or decomposition of the chloramines can serve as a nutrient source for microbial communities and in the extreme, microbially-mediated nitrification reactions can occur that produce toxic nitrite and nitrate. Control of nitrification is an important part of distribution system management for chloraminated systems and control of microbial growth forms an essential element of such programs.

Current State of Microbial Compliance

Compliance rates for microbial indicators in the Netherlands, which does not use a chemical secondary disinfectant, are generally 99.9%, meaning that on the order of 30 samples per year are positive for total coliform[5]. Data for England for 2015 lists 128 positive total coliform samples (Table 1). Scaled by population to compare to the Netherlands, English water utilities achieve a similar compliance rate using secondary disinfection. By contrast, for 2013 the USEPA reports 8,065 violations of the total coliform rule[20]. Scaled by population to compare to the Netherlands, the US compliance would equate to 429 violations per year for microbial standards. While the sampling frequency and other differences make it difficult to draw strong conclusions, this data does indicate that US distribution systems, although predominantly delivering water with a secondary disinfectant, have relatively poor microbial compliance[1].

Table 1. Summary of microbial compliance monitoring for selected countries

Country	Annual Coliform Monitoring Frequency	Secondary Disinfection?	Equivalent Annual Samples per 1000 m^3/day	Typical Non-Compliance (Number of Positive Total Coliform Samples per Year)	Compliance Rate Scaled to NL Population	Source
Netherlands (NL)	26 samples per year per 2000 m^3/day	N	13	30	30	[5]
England	12 per 5,000 population (@150 L/person/day)	Y	16	128	40	[21]
US	12 per 1,000 population (@ 400 L/person/day)	Y	30	8,065*	429	[20]

*Under USEPA regulations, a violation may include multiple positive total coliform samples but each violation was taken as a single positive sample for this analysis because individual sample results were not available.

Can We Do Better?

Maintenance of aging water distribution systems is becoming increasingly complex and difficult. For systems using a secondary disinfectant, the accumulation of oxidizable material at the pipe wall, including corrosion by-products as well as biofilm, will exert an increased demand on disinfectant residual. Disinfectant decay rates are significantly impacted by increases in temperature, resulting in locations at the extremities of the distribution system that experience longer periods with little or no disinfectant residual[22]. There are relatively few interventions available to address distribution system water quality problems, given the lack of direct accessibility to pipes and inability to quickly change water chemistry at the treatment plant, so utilities often employ localized tactics like spot flushing, shock chlorination, and boil water notices. But these local interventions typically cannot solve the core water quality problems, many of which are related to excessive microbial growth.

As consumers become increasingly aware of environmental sustainability issues, water use is changing through conservation practices like shorter showers and replacement of high water use appliances, through to redesign of buildings with greywater recycling for toilet flushing. Fully decentralized, off-grid buildings with their own treatment systems are particularly appealing in rural areas, where distances to connect users to a centralized system mean that pipe installation costs can be prohibitive. These changes have potential water quality implications for stand-alone systems such as increases in water stagnation and increases in likelihood of cross-connections between potable and non-potable systems, both of which may exacerbate problems associated with microbial growth within the pipes.

Given the potential benefits associated with managing microbial growth within water distribution systems and buildings, and the disadvantages associated with chemical secondary disinfectants, could there be a role for UV disinfection to play within the distribution system? If microbial growth and pathogens could be better managed within deteriorating infrastructure through relatively low-cost retrofit UV solutions, could the effective asset life be extended? This paper examines the benefits, pitfalls, and research needs to evaluate how UV disinfection could be applied at different scales and in different settings to improve drinking water safety for all consumers.

ENVISIONING DISTRIBUTION SYSTEM MANAGEMENT WITH NOVEL UV APPROACHES

Light emitting diodes (LEDs) are an emerging UV technology with several characteristics that could make them ideally suited for management of water distribution system microbiology. Advantages of UV LEDs, aside from lacking hazardous mercury contained in conventional UV lamps, include nearly instantaneous powering on, ability for unlimited cycling, long lifespans, and small size coupled with high power density which enable innovative design architecture[23]. These characteristics, and circuitry amenable to solar power[24], make UV LEDs a natural fit for disinfection at the point of use[25] and in small systems[26].

Another key advantage of UV LEDs is the ability to select their emission wavelength for optimized disinfection. A recent study demonstrated greater inactivation of OPs by 265 nm LEDs than conventional low pressure (LP) mercury lamps[27]. Another recent study combined UV LEDs with LP lamps or a KrCl excilamp (another novel UV source) to demonstrate electrical efficiency rivaling that of current mercury-based medium pressure (MP) polychromatic lamps while alleviating disadvantages of MP such as large electrical requirements, visible light production that increases fouling and photorepair, and wasteful non-germicidal photon emission[28]. Selection of emission wavelength can be based on action spectra of target pathogens[29,30], or based on spectral molecular mechanisms of disinfection, including direct photolysis and indirect photolysis (by production of reactive species[31]) of genetic material[32] and proteins[33]. While DNA damage tends to dominate bacterial inactivation with a peak efficacy around 265 nm corresponding to nucleic acid absorbance, protein damage is important for viruses where wavelengths around 280 nm and < 240 nm correspond to protein absorbance and increased disinfection efficacy. Importantly, protein damage by LEDs can also prevent enzymatic repair processes[34].

While LEDs with higher wavelengths (> 240 nm) are currently more feasible than lower wavelengths for disinfection due to their longer lifespans (up to 10,000 hours), lower cost, and higher external quantum efficiencies (EQE, the efficiency of converting electrons to photons that are emitted, up to 20 %), LEDs with wavelengths as low as 222 nm but with very low EQE and lifetimes have been manufactured[23]. As a result, higher wavelength LEDs have greater overall electrical efficiency and less waste heat production. Higher wavelength LEDs are also more powerful emitters, so UV doses can be achieved in shorter exposure times, enabling higher flowrates in reactor design[35]. If LED technology development continues to follow the trend of Haitz's Law, where output increases by 20X while price drops by 10X each decade, wavelength tailored LED disinfection will soon be feasible across the entire UV-C range.

The proven efficacy of LEDs against a variety of bacteria, viruses, and spores has been recently reviewed[36], and the literature has since grown rapidly[27,37–40]. The positive prospects for LED water disinfection, including considerations for design optimization, were also highlighted in a special publication issue[41].

What are the potential benefits?

Because of this bright outlook and rapid recent development, UV LEDs have strong potential to be used in a heterogenous secondary disinfection approach that could be a middle ground for innovation between homogenous management in disinfectant free systems (e.g., the Netherlands) and chlorine residual systems (e.g., the US). This approach could enable targeted treatment of areas prone to problems associated with microbial growth (nitrification, corrosion, overgrowth) or areas where populations are more vulnerable to infection. A heterogenous approach to distribution management is a significant paradigm shift toward more sustainable multibarrier protection that could help revolutionize water treatment in response to climate change impacts, impending infrastructure investments, increased population and urbanization, and increased water reuse practices. LEDs will be a key tool in decentralized, heterogenous secondary disinfection across a variety of scales and resource settings (e.g., dense megacities and skyscrapers requiring vertical management, sprawling metropolises and large buildings such as hospitals requiring horizontal management, off-grid, throughout homes, and throughout pipe networks).

Specific applications of UV throughout distribution systems, as depicted in the Conspectus graphic, could include UV booster stations along the distribution network, UV in storage tanks or their inlet/outlets, LEDs distributed along pipe walls, small point of use/entry treatment systems for buildings/homes/taps, or submersible swimming or rolling UV LED drones to reach problem pipes and provide a ‘shock’ treatment or provide sterilization after main breaks or repairs. Small LED systems could be applied ubiquitously throughout the built environment to disinfect tap water sources that result in a variety of day-to-day ingestion, inhalation, and contact exposures, such as in cooling towers, evaporative coolers, decorative fountains, misters at the grocery store or amusement parks, aquatic facilities, in public water fountains, at fire hydrants, at emergency eyewash stations, etc. One study even demonstrated efficacy of UV at reducing dispersal of bioaerosols from toilet flushing[42].

On its own, UV easily disinfects protozoa and most bacteria including OPs, as shown in Figure 1. At a UV dose of 16 mJ/cm^2, which is required by NSF/ANSI 55 for Class B point of use (POU) devices (to disinfect nuisance organisms in otherwise safe water), 4 log inactivation is achieved for most bacteria, including the more UV-resistant *Mycobacteria*. Using a dose of 40 mJ/cm^2, which is required for Class A POU devices (to disinfect pathogens), would offer even more bacterial protection and provide additional protection against enteric and respiratory viruses. Employing LEDs to deliver these doses for secondary disinfection would increase protection from disease outbreaks and minimize microbially induced water quality issues, while reducing potential for chlorinated DBPs. This heterogenous approach would be even more effective when coupled with primary treatment to produce biostable water.

While we believe that UV alone has great potential for chemical-free primary and secondary disinfection process, UV could be integrated into existing systems to mitigate problems discussed above, as illustrated in Figure 2. Providing virus disinfection with low-level free chlorine and protozoa control with low dose UV at the treatment plant, followed by OP control by distributed UV LEDs in the pipe network, would allow simultaneous pathogen control and DBP minimization. Another hybrid strategy would combine advanced oxidation of microbes and contaminants induced by interaction of UV with chlorine residuals, which a recent study found to control OPs more efficiently than chlorine alone[43]. UV LEDs could provide multibarrier protection to various oxidants by adding UV as primary, intermittent booster, or distributed disinfectant. Primary disinfection to achieve biostability of the water would enable more hybrid treatments, e.g., ozone and biofiltration for primary disinfection followed by distributed or booster UV LEDs for secondary disinfection would provide comprehensive advanced treatment and aesthetically pleasing water.

What are the potential pitfalls?

Although the possibilities for application of LEDs throughout distribution systems seem limitless, there are several practical and fundamental hurdles to overcome. For example, UV may cause solarization of plastic pipe materials, and implementing LEDs will increase power requirements of water treatment and distribution unless they can be offset by solar or micro-hydro power. Additionally, UV LEDs are still too costly for immediate widespread implementation by a public water utility. A retrofit option that would allow UV LED installation in existing pipes to ensure water quality despite asset deterioration could potentially bring the largest financial returns by extending the useful service life of pipe assets but would require engineering design to address challenges of replacement and maintenance in buried pipes.

Unlike conventional lamp technology, the face of the LED does not generate heat at the emission surface, and therefore would not experience similar precipitative fouling. However, water chemistry, resuspended sediments, and biofilm sloughing can increase turbidity and background water absorbance that can cause mineral or biological fouling. These factors attenuate penetration of UV to target organisms and can negatively impact UV sensors that may be necessary for monitoring. A simple telemetric on/off indicator would verify that UV LEDs are delivering disinfecting light. Hydraulic conditioning, which is used in the UK to maintain system performance by periodic flushing to strip biofilms and accumulated material[15], or chlorine shock treatments could be used to help combat fouling.

However, an important technical challenge of UV LEDs is management of waste-heat generation off the back-end of the LED, which can lead to reductions in output and decreased efficiency in LED reactors if not managed[35]. Operating reactors in pulsed rather than continuous mode has also shown promise for better management of waste heat[44] although pulsing effect on extending LED lifetime needs to be examined. Because no synergy or detriment has been noted for simultaneous irradiation of viruses or bacteria with different wavelengths of UV-C LEDs[37,39] and synergy has been observed for sequential exposures[28], LED reactors in series may be biologically and electrically more efficient.

As with any UV disinfection technology, there are concerns around regrowth, reactivation and repair of microorganisms after irradiation. Mofidi and Linden[45] illustrated that regrowth of heterotrophic plate count bacteria following UV treatment was completely controlled by low dose chloramination. In a recent study, OPs inhabiting biofilms, corrosion products, and loose deposits seemed to be tolerant to UV/Cl_2 and Cl_2[43]. Another study raised concern over cyclical exposures that increased UV resistance in only one out of several tested strains of *Staphylococcus*[46]. Although the dose required for 4-log reduction of the strain ~doubled to 22 mJ/cm^2, this dose is still much lower than required for Class A POU systems (40 mJ/cm^2). Biofilm organisms might also be more UV resistant than their planktonic counterparts[47]. Finally, some OPs such as *Legionella* and *Mycobacteria* can reside in amoebae, which may shield them from UV. More studies are needed to determine and quantify these impacts in model and field systems, and to better understand specific impacts of UV disinfection on the water microbiome.

Thinking about UV applications in distribution systems also allows a fresh look at potentials for real-time microbial monitoring and remote operation, which currently rely primarily on surrogate measures like turbidity. Flow cytometry has been shown to be an effective monitoring tool, but cell counts alone are insufficient for monitoring UV disinfection[48]. ATP monitoring has been shown to be useful for monitoring UV disinfection with assay modifications that include a culture step to account for repair[49]. ELISA-based methods[50] and qPCR[51] may also prove useful for monitoring, although molecular methods may require additional refinement to distinguish infective cells from inactivated ones. These data demonstrate the need for tools that accurately quantitate UV disinfection efficacy so that systems can be designed without overdosing that cripples the sustainability of UV disinfection, while also conservatively accounting for repair and regrowth that could negatively impact public and environmental health.

Finally, there is a big unknown regarding regulatory and financial responsibility for monitoring and maintenance of distribution system water quality nearing and reaching the point of use. One strategy for success will be to employ a network of sensors to alleviate household and building owner responsibilities, offering the appropriate telemetry to remotely monitor and respond to problems. Another strategy would be to have water utility employees be responsible for maintenance or to respond to sensor malfunction. However, these strategies require changes to current approaches to water jurisdiction and regulation.

RESEARCH NEEDS

While a long-term hurdle slowing implementation of a safe, secure UV LED-chemical-free distribution system is likely the glacial pace of regulatory reform in countries that require a chemical-residual secondary disinfectant, there are clear public health, practical management and aesthetic drivers that provoke a new and radical re-thinking of distribution system pathogen management. While the authors believe that the scientific and engineering research community has already illustrated that such an approach is currently feasible and desirable, a number of research needs remain to provide further confidence to regulators, consulting engineers, and utility managers.

1. For regulators, a critical review of distribution management approaches and causes/frequency of noncompliance is needed to clarify approaches that are currently in use and their efficacy. This information will provide evidence for opportunities of heterogenous distribution management by UV to protect public

health. To enable this approach, the ability to monitor both microbial water quality and UV status/efficacy is clearly needed. Difficulties of monitoring microbial viability are compounded by the fact that the mechanism of UV inactivation is not only by compromising cellular integrity (like most oxidants), but is by damaging nucleic acids and proteins. Although sensors for current UV LED wavelengths are well established, more information is needed to inform monitoring of intensity vs on/off and best management strategies to process these signals.

2. Controlling biofilms and biofilm inhabitants in UV-based secondary disinfection systems is poorly understood, especially across different pipe materials. Similarly, UV disinfection of flocculated or otherwise protected OPs, such as *Legionella* engulfed in amoeba, has not yet been well proven. Understanding any further benefits from sequencing or simultaneous application of differing UV wavelengths, especially in relation to biofilm control and OPs is needed. Ultimately a new mindset of understanding and managing the water microbiome, and its associated chemical implications, needs to be developed, including research to identify any protective effects that the microbiome may be currently providing, targeting and supporting specific organisms and communities that are providing beneficial services (analogous to prebiotics and probiotics) and managing excessive growth of undesirable organisms (analogous to personalized medicine).

3. Fouling must be further studied to understand impacts of mineral or microbial deposits on distributed UV disinfection systems (sensors, UV LED emission surface, quartz windows) under various water quality and secondary disinfection management strategies at LED-relevant wavelengths.

4. Powering and cooling many distributed UV LEDs throughout a distribution network is an engineering challenge. Opportunities for best utilizing on-site power in homes and buildings, and for locally-derived energy to power UV-based treatment (e.g., solar energy and harvesting energy from water flow) require further study and optimization. More pulsing studies are needed to fully understand impacts on energy conservation, thermal management, disinfection efficacy, fouling, and biofilms. Development of alternative thermal management strategies using pipe water or non-energy intensive cooling methods would also be advantageous.

5. The departure from chemical-based secondary disinfection will require new approaches to overall management of a distribution system. Hydraulics, pressure maintenance, flow rate, water use patterns, and water stagnation will need to be considered in light of the heterogeneity of UV system physical application. The need for spot flushing, shock chlorination, and other local interventions to maintain healthy water infrastructure under UV-based disinfection in aging pipes will need to be assessed. Finally, the pipe materials in use will have to be compatible with exposure to low intensity UV irradiation.

CONCLUSIONS AND OUTLOOK

While UV is a proven technology and has many advantages, there are some clear obstacles to wide-spread acceptance for distribution system disinfection. Regulations requiring a chemical disinfectant residual in some countries may be difficult to update in the near term. Better understanding of how long-term UV exposure can mitigate biofilm formation and the potential for colonization by OPs, as well as strategies for effective monitoring of UV efficacy are needed. The potential for fouling of the UV emission windows over long exposure periods and providing energy to power the LEDs and cool them will require some innovative system design. The next 10-20 years will see a significant investment in pipe replacement, so the opportunity is ripe to install new pipes with embedded UV LEDs and associated sensors, otherwise retrofit solutions will be required.

An immediate opportunity to apply UV LED technology to distribution systems is in buildings. Given the concerns over pathogens in building plumbing, UV can play an immediate role, alongside chlorine, in protecting the consumer from possible exposure to infectious pathogens. UV would also play an immediate beneficial role in systems that currently do not use chlorine and rely on biostable water to minimize occurrence of biofilms and pathogen proliferation. Considering the relative frequency of compliance issues, even distribution systems employing chlorine currently could benefit from targeted UV applications in distribution system disinfection. New housing developments and new piped water networks in low- and middle-income countries could also benefit from designing their systems from the start to consider UV applications. And in places where chlorine is suspect, or cultures shy away from the taste of chlorine or addition of residual chemicals to their water, UV can play a role in providing safe water and a protected distribution system.

Looking towards the future, it is incumbent on the scientific and industrial communities to lead the innovations that are required to achieve ultimate acceptance by regulators and the international community. This will include the applications of existing advances for monitoring and sensor approaches to system control. Emergence of the Internet Of Things (IOT) will make telemetric opportunities to monitor UV treatment accessible and ultimately provide water utilities and regulators with confidence in the performance and consistent operation of UV LEDs, without the use of a chemical secondary disinfectant, in providing safe drinking water to the public.

FIGURES

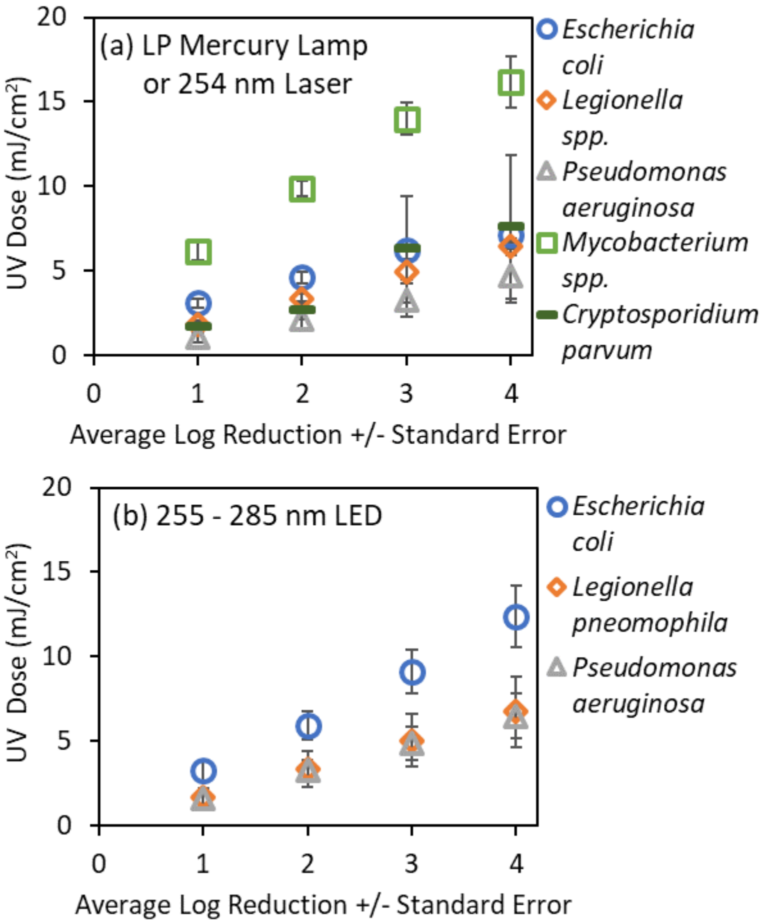


Figure 1: Literature summary of UV dose response to (a) conventional low pressure (LP) mercury vapor lamps or lasers emitting at 254 nm, and to (b) light emitting diodes (LEDs) emitting at 255 – 285 nm, for indicator bacteria (*E. coli),* OPs (*Legionella spp., Pseudomonas aeruginosa,* and *Mycobacterium spp.*), and protozoan pathogen *Cryptosporidium parvum*. Data from ref. # [27,36,37,52,53].

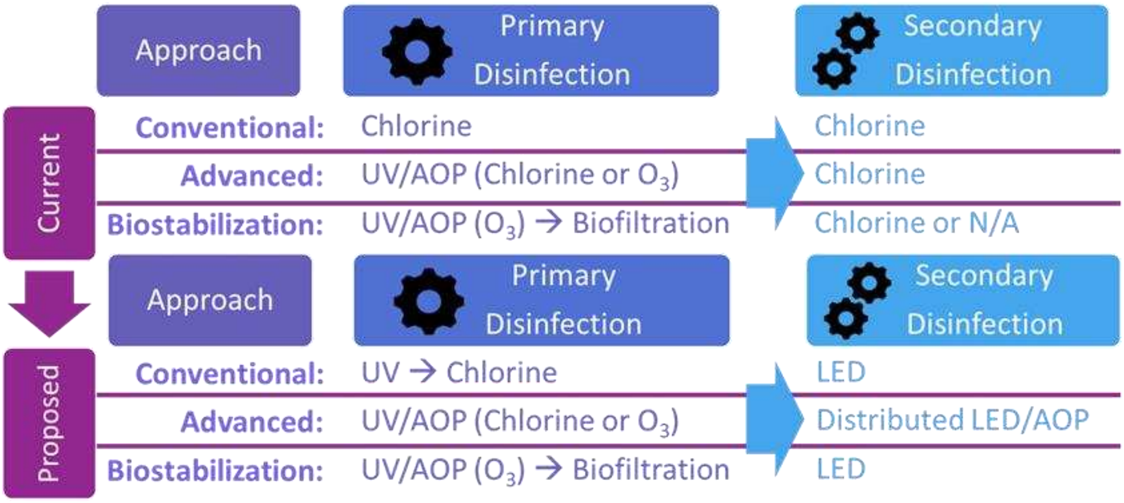


Figure 2: How UV and UV-based processes are currently integrated into water treatment and the proposed opportunities that are now evident for UV applications for drinking water.

BIOGRAPHICAL INFORMATION

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