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Demonstration of a novel technology for water disinfection at The Sustainable City – Dubai

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Final Report on

Demonstration of a novel technology for water disinfection at The Sustainable City – Dubai

By

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1. Background and rationale

The term greywater refers to relatively clean wastewater generated in residential communities or from commercial activities that is free of fecal contamination at source. Thus, for example, wastewater resulting from hand basins, baths and showers, kitchen sinks, and dishwashers is considered greywater as long as it is kept separate from the wastewater from toilets. Typical contaminants found in greywater include grease, food, household and laundry cleaning products, and personal care products. Greywater reclamation refers to the practice of treating the greywater to the extent that makes it safe for re-use in such applications as landscaping and irrigation. While greywater does not contain the high concentration levels of fecal contamination found in wastewater generated from toilets, it is not entirely free of such contaminants that enter the greywater stream from, for example, the washing of vegetables that have come in contact with animal manure. In countries such as Dubai where the ambient temperatures are high, the presence of even small concentrations of fecal contaminants can pose a significant health risk due to the rapid growth of microbial colonies that can severely reduce the opportunities for greywater re-use. It is there universally agreed that greywater intended for re-use for landscaping or irrigation purposes within the confines of a residential community must be treated to the extent that renders it free of pathogenic contamination.

The Master Plan for The Sustainable City – Dubai envisioned the collection and re-use of greywater as a central theme in the effort to establish an ecologically sustainable residential community in a region where available water supplies are somewhat limited. A physical plant for the treatment of greywater generated from the residential units was constructed and in use. It was designed to remove non-pathogenic contaminants using a variety of filters and membranes. Treatment of pathogenic contaminants was to be achieved by using chemicals such as Chlorine or Ozone. The use of these chemicals is not consistent with the ideals of sustainable development since these products are hazardous to produce, transport, store and use. They are also ineffective against certain pathogens such as viruses and, in the case of Chlorine, must be removed from the treated greywater before it can be used in irrigation.

The use of ultra-violet (UV) light to disinfect water is now wide-spread in water and wastewater treatment plants, and on a smaller-scale in municipal pools and water parks. The popularity of this method of treatment stems from it being chemical free, safe to operate, and is effective against almost all pathogens of concern to public health. Existing UV systems suffer from a number of common drawbacks inherent in their design, the most serious of which is the fact that the lamps used to produce the UV light are immersed in the water being treated and hence become covered with various organic and non-organic material which reduce their efficiency and demand excessive maintenance and down-times.

At the time when the SRTP call for proposals was announced, research was in progress at UC Davis aimed at developing a novel system for water disinfection with UV light that was free of many of the drawbacks of the existing commercial systems. Preliminary test results were available and these showed that the new system outperformed the conventional systems in terms of disinfection efficiency and power consumption. The central theme of the proposal was therefore to look into ways to improve the performance of the new system and then construct one to transport and install at The Sustainable City – Dubai. Once there, the performance of this system would be monitored and its suitability for deployment at the greywater treatment plant assessed.

2. Overview of Work Performed

2.1 System development

The new system operates as follows (refer to Fig. 1). Untreated water enters the system into a pressure vessel located at its base. A number of nozzles are installed at top of this vessel and are arranged radially and at angle with respect to the centerline in order to induce a strong swirling motion (vortex). Water exiting from these nozzles then flows vertically upwards inside a quartz tube – a material chosen as it allows for the transmission of UV light in the requisite wave length. A vent located at the center of the pressure vessel allows ambient air to flow into the low-pressure core of the vortex thereby creating an air column that reduces the depth of water flow. The presence of the vortex and air core has the dual benefit of circulating the water in such a way as to thoroughly mix it and to reduce its depth to ensure that the UV light penetrates it to ensure that all pathogens receive the minimum UV dose needed for their inactivation. The UV lamps are arranged around the outside of the quartz cylinder such that they irradiate the rising water without coming into contact with it. The treated water flows into a collection tray at the top via a weir which causes significant amounts of air to be entrained. This has the added benefit of enhancing the concentration of dissolved oxygen in the water.

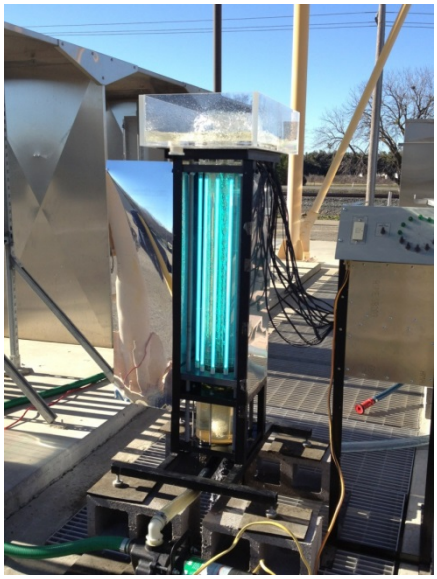

Figure 1: UV vortex system in operation.

Our efforts at improving the basic design centered on experimentations to determine the optimal design of the nozzles to maximize the rate at which water flows through them while at the same time minimize the hydraulic losses associated with the flow and with that, the energy consumption needed to pump the flow into the pressure vessel. Experiments were carried out on 6 different nozzle designs in which the ratio of inlet to outlet radii was the primary variable. Another aspect of the design that was the subject of optimization was determination of the relationship between the produced UV intensity (defined as the lamp power output per unit area) and the rate at which water flows through the system. In order to inactivate a pathogen of concern, it is important to ensure that it is exposed to a UV dose of a magnitude greater than a specific value appropriate to that pathogen. The UV dose is simply the product of the UV intensity and the exposure time – the latter being determined by the flow rate. As a result of these tests, we developed guidelines that relate the number of UV lamps needed to deliver a given UV dose to the power output per lamp, to the number of lamps, and to the desired flow rate.

To further optimize the system performance from both hydraulics and UV dose delivery standpoints, we performed computer simulations of the patterns of flow inside the quartz cylinder and correlated that with the depth of UV penetration into the rising water column. These simulations were performed using the FLUENT simulations software and representative results are shown in Fig. 2. The computer software, once adapted to represent the system geometry and the flow conditions, was then used to explore alternative design options via a systematic parametric study in which the influence of such parameters as the height and diameter of the quartz cylinder, the flow rate, the number and power of the UV lamps on the delivered UV dose and hence on the overall efficiency of the system was explored.

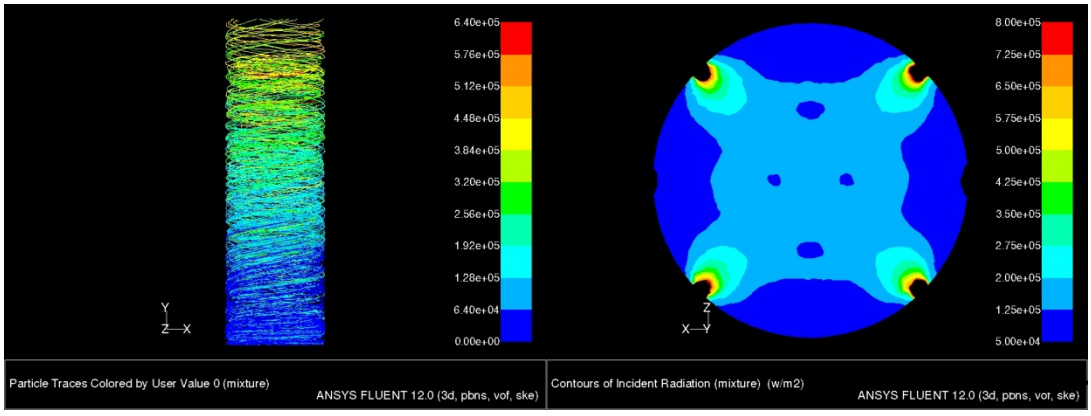

Figure 2: Computer simulations of the patterns of flow within the quartz cylinder (left) and of the UV intensity produced within the water column due to 4 UV lamps (right).

2.2 System testing

The system was extensively tested at a number of locations. These included:

- Greywater testing at the Environmental Engineering Laboratory at UC Davis: https://www.youtube.com/watch?v=FTJBtNqJvOs&t=199s

- The UC Davis Waste Water Treatment Plant

- The City of Davis Waste Water Treatment Plant

- The City of Winters - CA Waste Water Treatment Plant: https://www.youtube.com/watch?v=50cy1qveUAU

- The National Ornamental Research Station at San Rafael – CA (results published in the *European Journal of Plant Pathology*, Younis et al., 2019): https://www.youtube.com/watch?v=9opNrpAncuk

- The Campbell tomato processing plant in Dixon – CA (Results published in *Water Practice and Technology*, Mahoney et al., 2018)

- The Environmental Engineering Laboratory at UC Davis – Greywater experiment: https://www.youtube.com/watch?v=FTJBtNqJvOs&t=213s

- Experimental greenhouse at UC Davis for the hydroponic production of leafy vegetables (Fig. 3):

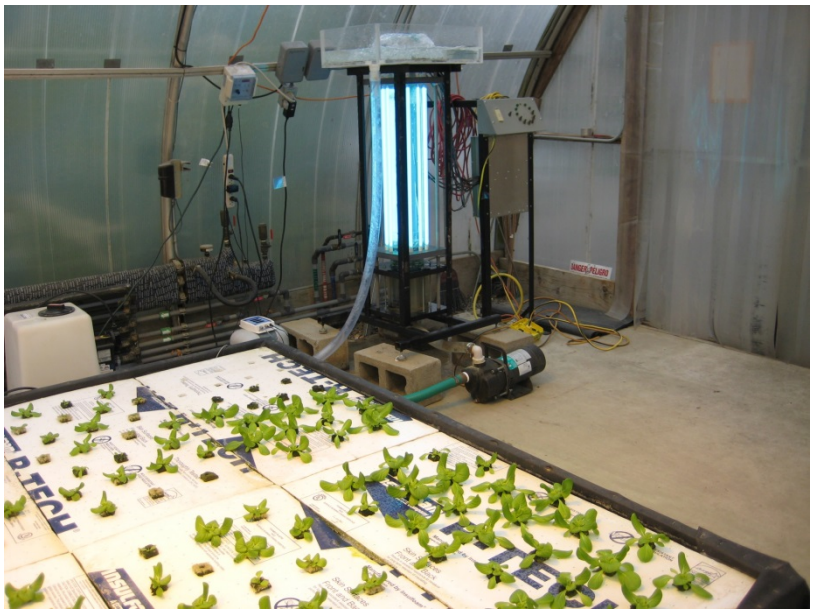

Figure 3: The UV vortex reactor in operation at the UCD experimental greenhouse.

2.3 System installation at The Sustainable City – Dubai

A system incorporating all the developments listed above was shipped in October 2016 to The Sustainable City – Dubai. The system was installed at the site where the gray-water treatment plant (GWTP) was located where it was connected to the electric supply and was operated using water from the pre-treatment stage. Videos showing this stage of testing can be viewed here:

https://www.youtube.com/watch?v=9qEDzwiEAY4
https://www.youtube.com/watch?v=LDDmVA3lFUQ

Water samples from the system outlet were obtained, both with and without the UV lamps being switched on. These samples were then tested using an IDEXX kit. The results showed that the untreated water contained high concentrations of total and fecal coliforms. The source of this contamination is most probably due to the contamination of the water either at source (e.g. washing of contaminated vegetables), or from residual contamination in the pipeline network that supplied the water to the GWTP. After treatment in the UV reactor, the concentrations of these contaminants dropped to below the no-detect level.

The system was then installed it in the #1 bio- dome where it was connected to the large fish tank in operation there:

https://www.youtube.com/watch?v=nfwvtvfQORk&t=1s.

Water samples that were taken before treatment showed the presence of significant levels of both bacterial (E. coli) and viral (most likely Viral Hemorrhagic Septicemia Virus VHSV) pathogens. After treatment, the waste was found to be entirely free of bacterial contamination. Testing for inactivation of viral contaminants can only be done by experimentation on healthy fish for which a UC Davis biological testing license would have been required.

At the end of the installation phase, the system was left operating at the bio-dome and the person in charge of fish welfare there was briefed on various issues related to the maintenance and safe operation of the system.

Subsequent to the system installation, water samples were taken from the fish tank and sent for analysis at the Al Hoty - Stanger Environmental Laboratories - Dubai. The report produced by this lab is attached in the Appendix. The results show a very low concentration of Biological Oxygen Demand (under the detection limit of 2.0 mg/L) and a high concentration of Dissolved Oxygen (6.6 mg/L which is approximately 80% of the maximum concentration achievable at that temperature). Both of which suggest that the UV system is performing very satisfactorily in improving the quality of the fish habitat.

The system was again inspected in December 2017, one year since it was first installed. It was found to be working satisfactorily. It was reported by the person in charge of the large fish tank in Bio-Dome 1 that the use of the UV system has effectively eliminated the growth of algae in the tank, a problem that had previously required frequent cleaning of the inside of the tank. Figure 3 shows the clear water environment obtained with the system in operation.

Figure 3: The fish tank in Bio-Dome 1 at The Sustainable City – Dubai showing the quality of the water with the UV system in operation (Photo kindly provided by Yazan Shaalan on February 2, 2017).

2.4 Further developments

In the process of performing the tasks specified in the original proposal, and in the nature of conducting research in an academic environment, a radically different system for water disinfection with UV light was developed and extensively tested. The new system is considerably smaller than the original system described above. It is also cheaper to produce, easier to install and operate, and is much more compact and robust. It is intended for use at the point where drinking water is consumed e.g. at drinking-water fountains and at kitchen sinks. However, the system can also be used for non-potable water such as in private swimming pools and in fish aquaria. A schematic drawing of the system is presented in Fig. 4.

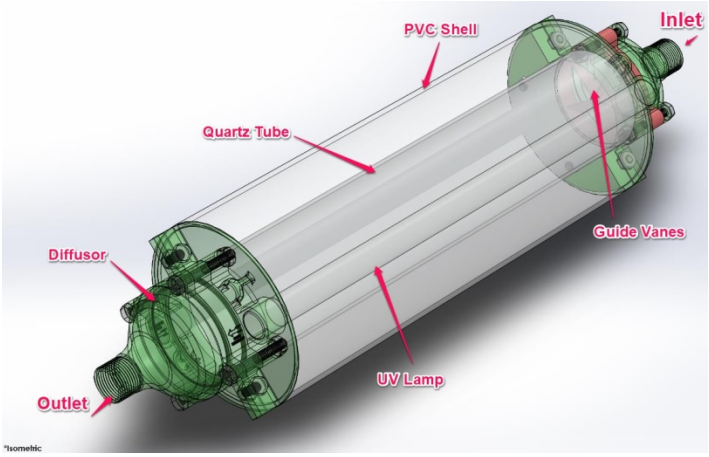

Figure 4: Schematic drawing showing the main components of the developed point-of-use UV system.

As with the vortex reactor, computer simulations we performed to optimize the design via a systematic parametric study aimed at minimizing the hydraulic losses while maximizing the UV dose delivered. Representative results of these computer simulations are presented in Figure 5. Shown these are the paths of massless particles representing pathogens that enter the system and then follow a helical trajectory induced by the swirl generator incorporated at the inlet.

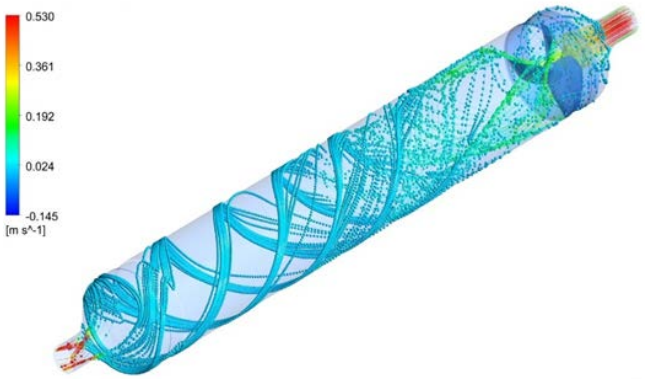

Figure 5: Computer simulations showing the helical trajectories of massless particles that enter the system to be exposed to UV light.

In designing and manufacturing the new system, advanced computer software for three dimensional solid modeling was used to ensure that the tolerances in the gaps between various components were minimized to ensure ease of assembly and prevention of water leaks. The key components manufactured using 3D printing. Details of this new system were published in a paper in the journal *Water*. This paper, which is available on open access basis (https://www.mdpi.com/2073-4441/10/9/1275/htm), contains all the electronic files necessary to 3D print the key components of the system. At the time of writing this report (3 May 2019), this paper was downloaded 787 times.

The system was installed at the UC Davis Arboretum during the summer of 2017 in order to test its efficiency in inhibiting the growth of algae. For this purpose, a floating platform was constructed in order to position the system in the part of the water body where the algae bloom was at its most dense. In order to power the UV lamp and the pump that was needed to lift the water from the pond into the system, a solar panel was installed on the floating platform, together with a battery to store the excess power generated during the daytime in order to keep the system running at night. The installation is shown in Fig. 6 and the results of this study and other, laboratory-based studies on the effects of UV light on algae growth are currently in review for publication in *Water and Environment Journal* (Younis et al., 2019).

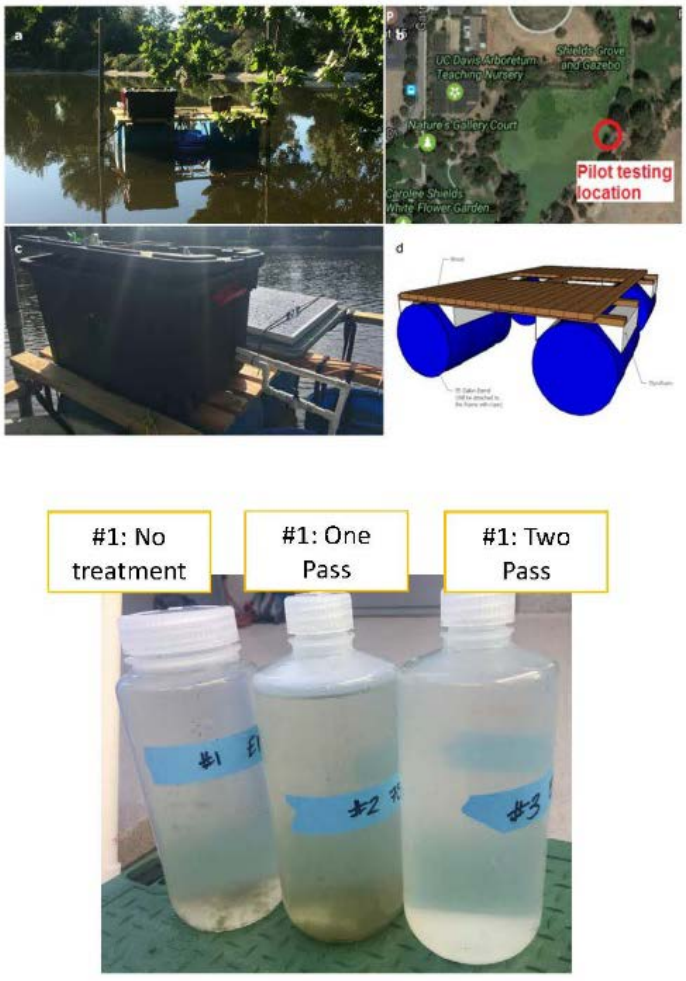

Figure 6: The point-of-use UV system installed on a floating platform at the UC Davis Arboretum to test its ability to inhibit the growth of algae in natural waters.

The system was installed at a Native American reservation in Covelo – CA where it is being used to disinfect the water used at their clinic. Details of this deployment were published in the journal *Water Environment Research* (Younis et al., 2019).

A formal request was put forward to modify the terms of the original proposal to allow for further development of this new system and to collaborate with researchers at the American University of Beirut in order to test the system in waters having the chemical composition and pathogenic load representative of what is found in under-served communities in Lebanon. Accordingly, a complete system was transferred and installed at the Environmental Engineering Laboratory of the American University of Beirut under the supervision of Professor Mutasem El Fadel. The electronic files for 3D printing were installed on their systems (https://www.youtube.com/watch?v=m90h8OD_qxU). A student pursuing a course of study and research towards the PhD degree was assigned to participate in this project. This research is still in progress and will be reported on once completed.

3. Outcome of Research

The generous support of Diamond Developers, The Sustainable City – Dubai via the SRTP initiative was acknowledged in all publications, seminar presentations and grant applications.

3.1 Peer-reviewed journal publications (all are attached as appendices)

1. Younis, B A, Mahoney, L, Schweigkofler, W and Suslow, K, 2019. Inactivation of plant pathogens in irrigation water runoff using a novel UV disinfection system. *European Journal of Plant Pathology*, vol. 153, pp. 907-914.
2. Mahoney, L, Younis, B A and Simmons, C W, 2018. A novel system for the treatment of wastewater from a tomato processing plant with UV light. *Water Practice & Technology*, vol. 13, pp. 662-672.
3. Younis, B A, Mahoney, L and Palomo, N, 2018. A novel system for water disinfection with UV radiation. *Water*, vol. 10, pp. 1-13.
4. Younis, B A, Mohaney, L and Yao, S, 2019. Field evaluation of a novel UV water disinfection system for use in under-served rural communities. *Water Environment Research*, vol. 91, pp. 75-82.
5. Younis, B A, Mahoney, L and Wilson, S, 2019. Control of algal bloom using a novel UV water disinfection system. *Water and Environment Journal* (in review).

3.2 Poster presentation

A solar-powered system for water disinfection with UV light for use in under-served communities. Poster presented at the UN Sustainable Development Goals Conference, Davis - CA, Jan 23, 2017 (https://unsdg.ucdavis.edu/).

3.3 Grants

1. Analysis of a 3D printed, point-of-use UV disinfection system for drinking water treatment. UC Davis Blum Center for Developing Economies Poverty Alleviation through Sustainable Solutions (PASS). Awarded 2016.
2. Center for Information Technology research in the Interest of Society (CITRIS). Computer modeling of flow in a UV reactor. Awarded 2017.
3. Design and installation of crop wash station. USDA & International Rescue Committee. Awarded 2018.
4. LEDs for UCD's UV System. Seed grant co-funding from UCD Global Affairs and College of Engineering to initiate collaboration with the El Najah University – Nablus, and Birzeit University – Ramallah. Awarded 2019.

4. Deliverables

1. Original research output published with full acknowledgement in peer-reviewed archive journals.
2. UV system installed and operating at Bio-Dome 1 at The Sustainable City – Dubai.
3. Development and successful testing of a compact, low-cost point-of-use UV system. Design details and 3D printing electronic files placed in the public domain.
4. Installation of system of item 3 at various under-served and refugee communities in the USA and in Lebanon.

Eur J Plant Pathol (2019) 153:907–914
https://doi.org/10.1007/s10658-018-01608-8

Inactivation of plant pathogens in irrigation water runoff using a novel UV disinfection system

Bassam A. Younis · Laura Mahoney · Wolfgang Schweigkofler · Karen Suslow

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Abstract Untreated recycled irrigation water has been shown to introduce and spread plant pathogens such as *Pythium* and *Phytophthora* in commercial nurseries. Nevertheless, few nurseries currently treat their recycled irrigation water. Instead, nurseries use prophylactic pesticides to control the spread of plant pathogens, which increases costs and promotes the growth of resistant pathogens. Of interest to California is the spread of *Phytopthora ramorum,* causal agent of Sudden Oak Death (SOD), responsible for the death of tens of thousands of trees in California and Oregon. This study investigated the use of a novel UV disinfection system to inactivate *P. ramorum* and other microbial contaminants at the National Ornamental Research Site at the Dominican University of California (NORS-DUC). In this system, the UV lamps do not come in contact with the water and hence remain free of the 'lamp fouling' problem. Tests on waters having the same characteristics as run-off from commercial nurseries showed a minimum of 3.7 log removal of bacterial species, 91.7% reduction of fungal counts, and 100% inactivation of the *P. ramorum* in the effluent. Treating the run-off from plant nurseries limits the spread of plant pathogens and enables the onsite re-use of the run-off.

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Keywords *Phytopthora ramorum* · UV disinfection · Vortex reactor · Irrigation run-off · Nursery plants

Introduction

Untreated irrigation water runoff and untreated recycled irrigation water have been shown to introduce and spread microbial pathogens, such as *Pythium* and *Phytophthora*, in commercial nurseries (Ali-Shtayeh and MacDonald 1991; Hong et al. 2003; Kong et al. 2003; Hong and Moorman 2005; Werres et al. 2007). Dispersal of these pathogens is also of concern in closed hydroponic systems. These pathogens belong to the Oomycota and are often referred to as water molds that are most active during wet and humid periods and produce flagellated spores, called zoospores that can spread through the water. *Phytophthora sp*. cause diseases in agriculture, arboriculture and natural ecosystems, and the estimated losses associated with these pathogens are in the billions of dollars (Erwin and Ribeiro 1996; Lamour 2013; Jung et al. 2016).

Of particular concern in California is the spread of *P. ramorum,* causal agent of Sudden Oak Death (SOD). Costs associated with SOD incorporate costs to property owners, ornamental nursery industry, and the state and federal government. There are hundreds of thousands of susceptible oak trees located on near developed communities. Infected trees in these areas will need to be removed, disposed of, and replaced at the cost of the landowner or local government. Kovacs et al. (2011) estimated that this would amount to a discounted cost of

$7.5 million and an associated $135 million in losses to property values for single family homes in California.

Sudden Oak Death was first noticed in the 1990s when California hikers along the central coast reported oaks suddenly dying (Grünwald et al. 2012). This die-off was frequently found along the interfaces between urban and natural areas. In 2000 the pathogen causing SOD, *P. ramorum*, was isolated and researchers soon noticed that it belonged to the same species as a newly described pathogen from diseased rhododendrons and viburnums in European nurseries in 1993 (Orlikowski et al. 2007). *P. ramorum* causes foliar and shoot blight on many plants, including important ornamental species, and bleeding cankers on the tree trunks leading to the death of the plant on relatively few hosts, like coast live oak (*Quercus agrifolia*) and tan oak (*Notholithocarpus densiflorus*). This disease is responsible for the death of tens of thousands of trees in California and Oregon and most strongly affects tanoak, coast live oak, California black oak, and Shreve's oak (Rizzo and Garbelotto 2003). *P. ramorum* also causes severe damage on plantations of the non-native Japanese larch (*Larix kaempferii*) in the United Kingdom and Ireland; the disease on this new host was named 'Sudden larch death' (Grünwald et al. 2012).

Abundant inoculum can be produced on foliar hosts (e.g. *Rhododendron sp., Camellia sp*.) and spread from there to both foliar and non-foliar hosts. Due to this mode of transportation, there are instances of the *Phytopthora* species moving from ornamental nurseries to the natural environment due to uncontrolled contamination (Ghimire et al. 2011). Nevertheless, few nurseries currently treat their irrigation water (Banihashemi et al. 2010). Instead, nurseries use fungicides to control the spread of fungal pathogens and oomycetes, which increases costs and promotes the growth of resistant plant pathogens. In addition, these plant pathogens may be suppressed when under the presence of fungicides and proliferate when the fungicide is discontinued (Hong et al. 2003). For these reasons, various techniques, including the use of chlorine, ozone and UV light, have been used to mitigate the spread of the pathogen, but each technique has its drawbacks.

Most methods for the treatment of irrigation water can be costly for small operations. The most common treatment method used is liquid chlorine injection. This technique requires consistent addition, monitoring of chlorine concentrations, assessment of the system water quality and on-site storage (Hong et al. 2003; Abu-Orf et al. 2014). The chlorine dose needed is dependent on water quality because the high nitrogen and organic content in the dissolved and suspended matter incorporated in irrigation run-off increases the chlorine demand on the system. Ozone has similar limitations to using a liquid chlorine injection, but it can be generated on demand. Nevertheless, generally ozone has higher capital costs compared to the use of liquid chlorine and ultra-violet (UV) light treatment (Abu-Orf et al. 2014).

Ultraviolet light works as a disinfectant by exciting the nucleic acids in DNA and RNA. This excitation results in the dimerization of adjacent nucleic acids and prevents the further transcription of the DNA or RNA and inhibits replication. Since UV disinfection is a physical treatment process, it avoids generating toxic by-products caused by the use of oxidizing chemical disinfectants, such as chlorine. Similarly, there is no additional smell or taste added to the water, no danger of overdosing the disinfectant, and no need to store hazardous materials on site. Another benefit of UV disinfection over chlorine and ozone is that it alone is effective against both bacterial and viral pathogens.

The ability of a UV system to disinfect agricultural water run-off is dependent on its ability to deliver a UV dose sufficient to inactivate the pathogens of concern. The UV dose depends on the intensity of the UV light emitted by the lamps, on the flow rate of the water through the system, and on the UV transmittance (UVT) of the water. Factors that determine the UVT include the level of suspended solids, the turbidity, color, and the concentration of soluble organic matter. The run-off from agricultural activities is often high in dissolved and suspended matter and the resulting turbidity can thus be sufficiently high as to lower the water's transmittance of UV radiation thereby increasing, sometimes by more than 4-fold, the UV dose that is required to inactivate *Pythium* and *Phytophthora* (Banihashemi et al. 2010). Thus it is important that the water quality parameters of the untreated influent be quantified to ensure that the UVT does not fall below a level that would reduce UV light penetration and thus inhibit its germicidal ability. It is also important that the UV system itself, through aspects of its design, remains capable of delivering sufficient UV dose even when the UVT is low. One way to increase the UV dose is to reduce the flow rate of the water through the system thereby increasing the time in which the pathogens are exposed to the UV light. In many commercial

applications, this is not an acceptable remedy due to the large quantities of runoff water generated in daily operations. Moreover, by decreasing the flow rate, the resulting flow can become laminar leading to significant reduction in mixing. When mixing is reduced, the disinfection efficiency in conditions of low UVT is also reduced since the pathogens that are not brought sufficiently close to the source of the UV light can leave the system without having received sufficient dose for inactivation.

Recently, a novel system for water disinfection with UV light was developed and tested with success in the treatment of effluent from a number of municipal waste water treatment plants (Younis 2014). This system, by virtue of a number of features unique to its design, has the potential of being particularly suitable for use in agricultural and horticultural operations where the water run-off is often low in UV transmittance. The new system also benefits from being free of the problem of 'lamp fouling' that is present in most commercially-available UV systems. In such systems, the UV-emitting lamps are immersed within the water being treated and hence, with time, become covered with bio-film and mineral deposits that reduce the intensity of the emitted light and necessitate frequent system shut downs for cleaning. The objective of this study was to introduce this system to the plant-pathology community by testing it, in situ, at a facility for the study of diseases of ornamental plants to assess its performance in inactivating *P. ramorum* in actual irrigation run-off water representative of that obtained in commercial nurseries.

Materials and methods

The UV system presented here is shown in Fig. 1. Untreated water enters the system into a pressure vessel located at the bottom of the column and exits this vessel through a series of nozzles arranged along the circumference of a circle. Affixed to the top of this vessel is a

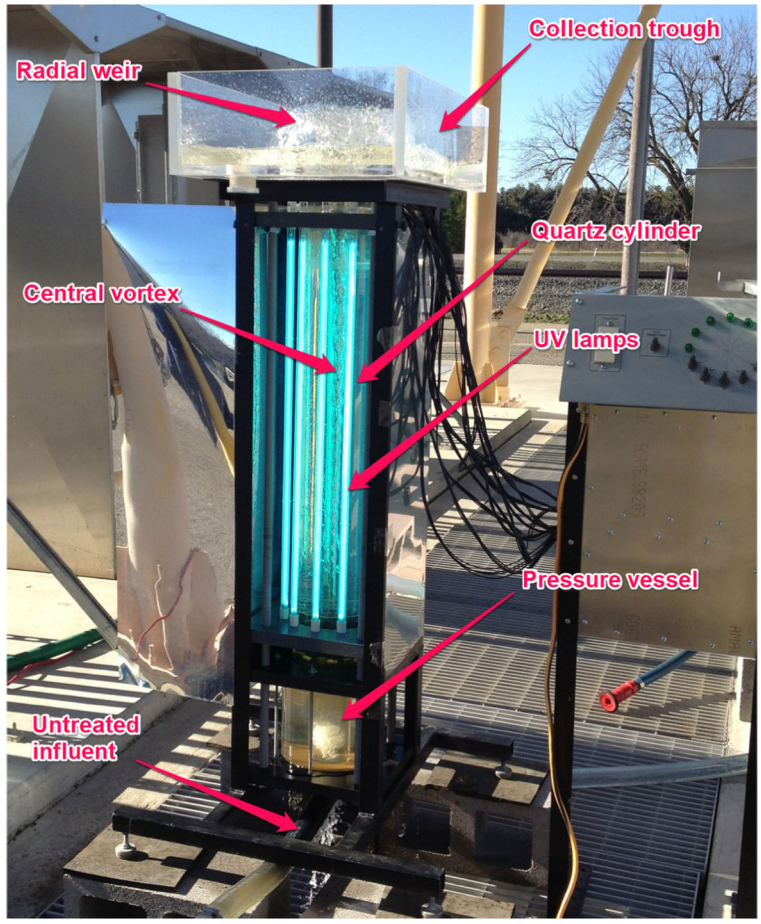

Fig. 1 Photograph of the UV system in operation

quartz cylinder; quartz being one of the few materials that allow UV-C radiation (with the 254 nm wavelength required for effective inactivation) to pass through. The manner in which the water enters this cylinder causes it to rotate as it rises to the top. The rotating motion, coupled with the presence of a drain port at the cylinder base, lead to the formation of a central air vortex in the shape of a cone with its broad base located at top of the cylinder. The UV lamps are arranged around the outside of the quartz cylinder and thus do not come in contact with the water being treated. In this way, the problem of lamp 'fouling' does not arise. The combined rotational and axial motions of the water rising induce high levels of shear stress on the inside walls of the quartz cylinder. These high levels of shear stress provide a self-cleansing mechanism in that they prevent material from adhering to the inside of the cylinder which thus remains free of 'fouling'. Due to the rotational motion of the water, the levels of turbulence kinetic energy are increased leading to vigorous mixing and hence to uniform exposure to UV radiation. Since the UV lamps are arranged circumferentially around the outside of the quartz cylinder, pathogens that may become imbedded into suspended solids experience increasing probability of receiving UV dose sufficient for their activation since the UV light is radiated from all direction. In a conventional commercial system, where the water flow is linear and parallel to the UV lamps, embedded pathogens are more likely to exit the system before receiving adequate dose. At top of the cylinder, the treated water overflows as though over a radial weir into a collection trough and from there into an outlet tube either to be re-used elsewhere. The passage of the treated water above the weir is associated with significant entrainment of air into the water thereby elevating the percentage of dissolved oxygen while simultaneously lowering the water temperature.

Testing of the UV reactor performance was carried out at the National Ornamental Research Site at the Dominican University of California (NORS-DUC). At this site, quarantine plant pathogens are studied in a mock nursery under field conditions that mimic those found in commercial nurseries (Johnson-Brousseau et al. 2011). For the experiment, irrigation water from the research site was collected and stored for 7 days prior to the experiment to have enough volume to run the reactor at a flow of 2.2 l/s and to provide the endogenous population of bacteria, oomycetes and fungi for the test. Tests were conducted on two separate occasions; in June 2013 and in October 2013. On the day of testing, this water was also spiked with *P. ramorum* zoospores to ensure its presence in the test water. *P. ramorum* zoospores were produced as described by Widmer (2009). *P. ramorum* strain 1,418,886 was grown on CV8-agar at 20 °C for approximately three weeks. Sporangia production was induced by adding 15 ml of soil extract water. Release of zoospores was induced by cold shock, and then zoospores were harvested and counted using a hemacytometer. A total of 5 l of zoospore suspension (concentration: 5×10^4 spores/ml) was added to a water tank of volume 1893 l for a final concentration of 1.3×10^2 spores/ml.

The UV reactor was placed in line with the effluent from the collection basin and was tested at a constant flow rate of 2.2 l/s. The tests were conducted under three separate conditions in which 4, 8 and 12 lamps were used. One liter of sample was collected from the influent of the disinfection system and one liter from each lamp condition to test samples for bacterial and fungal counts. The transmittance of the water was 76.4% UVT.

Bacterial counts were made from cultures growing on Reasoner's 2A, Acidified Dextrose Potato Agar (ADPA), and PARPH-V8. One milliliter of each sample was plated in triplicate on each media type and cultured using standard methods. R2A is the preferred media for culturing bacteria found in treated or potable water sources, water sources with low concentrations of endogenous bacterial populations (Reasoner and Geldreich 1985) and long incubation times (Van der Linde et al. 1999). ADPA is a media commonly used to culture fungal populations, but will also cultivate some bacterial populations. Acidification helps to reduce the amount of bacteria that will grow on the media (Mislivec and Bruce 1976). PARPH-V8 media contains pimaricin, ampicillin, rifamycin, pentachloronitrobenzene (PCNB), and hymexazol and is a selective media designed to isolate *Phytophthora sp.* (Ferguson and Jeffers 1999).

The UV dose supplied by the system was determined by quantifying its ability to remove the MS2 virus (*Escherichia coli* bacteriophage MS2 ATCC® 15597-B1™). MS2 is a male-specific (F+) RNA virus that infects bacteria. It has a similar structure to the polio virus and is widely used in water treatment research to assess the efficacy of a particular treatment method for virus removal (Bolton and Linden 2003; NWRI 2012). In the present application, water inoculated with MS2 to a given concentration was introduced into the UV

system where it was exposed to UV light produced from UV lamps that varied in number from 2 to 12. Samples of the treated water were collected and delivered on the same day to Biovir Laboratories Inc. (Benicia, CA) in accordance with the National Water Reuse Institute (NWRI) sampling guidelines (NWRI 2012). There, collimated beam testing was carried out according to standard methods (APHA 2005) to generate a dose response curve from which the actual UV dose delivered to the water was deduced. Results were obtained for water samples having UVT of 70 and 95%. The UVT was adjusted using instant coffee, an approved NWRI method (NWRI 2012). Each trial of the experiment used 1 l of MS2 with a titer of 10^{14} plaque forming units per milliliter (PFU/ml) for a final influent concentration of 10^8 PFU/ml. One liter of sample was collected for the collimated beam testing. The flow rate was kept constant at 2.2 l/s for all the tests.

Results

Analysis of bacterial inactivation

In water-treatment applications, reduction in bacterial counts achieved by a particular treatment method is measured in "log reduction" - the number of viable bacterial cells removed expressed on a logarithmic scale. For example, a 4-log reduction is a 10,000-fold decrease in the number of microorganisms present in the sample. A summary of the log reduction of the bacterial counts present in the irrigation water is presented in Table 1. Shown there are the results obtained from each of the bacterial culturing methods, and for three different lamp conditions corresponding to 4, 8 and 12 lamps. The results from the R2A and the PARPH culturing methods indicate that a minimum of 3.7 log reduction is achieved by the UV system. Low bacterial counts were seen on the APDA, because the acidification of the media suppresses bacterial growth.

Inactivation of fungi and *P. ramorum*

Microbial counts were evaluated using APDA to assess the fungal concentration and PARPH-V8 was used to determine the concentration of *P. ramorum*. Whereas true fungi (Eumycota) were present in the used nursery water as natural contaminants, *P. ramorum* was added as described above. One milliliter of each sample was plated in triplicate on each media type and cultured using standard methods. Fungal counts from the APDA media and PARPH media at each UV treatment are listed in Table 2. It can be seen there that the UV system removed about 75%, 91.7%, and 91.7% of fungal counts using 4, 8, and 12 UV lamps, respectively. It was also found that all lamp combinations of the UV system were able to inactivate 100% of the *P. ramorum* in the effluent.

Estimating the UV dose

California's water re-use policy Title 22 requires a demonstration of 5-log removal of MS-2, and the use of at least two reactors in series for redundancy to ensure a minimum level of safety in the system (NWRI 2012). Since only one reactor was tested, it must achieve at least 2.5 log removal of MS2 or a UV dose of 50 mJ/cm^2. A dose of 50 mJ/cm^2 is an approximate UV dose for 2.5 log removal. Figure 2a and b show the average log inactivation of MS2 and the average UV dose in the reactor with respect to change in lamp condition for the testing at UC Davis. From these figures, the reactor must operate with at least six lamps at a UVT of 95% and at least eight lamps at a UVT of 70% to achieve a

Table 1 Summary of bacterial reduction in irrigation water effluent

	R2A		PARPH-V8		APDA	
	Concentration, CFU/ml	Log Reduction	Concentration, CFU/ml	Log Reduction	Concentration, CFU/ml	Log Reduction
Influent	279,000 ± 19,000		48,330 ± 11,930		2330 ± 1530	
4 lamps	62 ± 3.5	3.7	4 ± 2.5	4.1	18 ± 11.9	2.1
8 Lamps	28 ± 2.8	4.0	10 ± 0.0	3.7	9 ± 0.0	2.4
12 Lamps	9 ± 2.1	4.5	1 ± 0.58	4.6	3 ± 1.7	2.9

Table 2 Summary of reduction of fungal and *P. ramorum* growth in irrigation water effluent

	APDA		PARPH-V8	
	Concentration, CFU/ml	Log Reduction	Concentration, CFU/ml	Log Reduction
Influent	4 ± 5.29		4.5	
4 lamps	1 ± 1.0	0.602	0	>0.65
8 Lamps	0.33 ± 0.58	1.08	0	>0.65
12 Lamps	0.33 ± 0.58	1.08	0	>0.65

minimum of 2.5 log removal of MS2. If only the 50 mJ/cm^2 UV dose condition is considered, then the UV reactor must operate with at least four lamps at a UVT of 95% and at least six lamps at a UVT of 70%.

Figure 2c is a plot that shows the electric energy needed by the reactor to achieve one log of MS 2 inactivation for every 3785 l of irrigation water treated. As the UVT decreases from 95 to 70%, the energy required to inactivate a log of MS2 increases as more lamps would be required to deliver the necessary UV dose. Also, for the 95% UVT case, the energy required for a log removal changes very little when more than six lamps are used. Hence this would be the ideal number of lamps that would be needed for use in these conditions.

Using the UVT of the water from NORS-DUC (76.4%), the results of testing at the Davis were used to determine the UV dose supplied to the irrigation water. Using linear interpolation with the data from Fig. 2b, the UV dose supplied to the NORS-DUC irrigation water was 51, 61, 82, 100 mJ/cm^2 for 4, 6, 8, and 12 lamps, respectively. Thus, to achieve a 5-log removal of MS2, two reactors each with four lamps would be needed to deliver the required UV dose. However, from a practical standpoint, since the percent of dissolved organics in the water can cause fluctuations in the UVT, it would be prudent to use six lamps. Achieving a 5-log removal in the irrigation water ensures that plant pathogens are not spread to the natural wildlife and renders the water suitable for reuse within the nursery.

Additional low-cost safety measures can also be used in conjunction with UV treatment to help facilitate reuse within the plant nursery, such as filtration and settling. Since UV treatment is a physical process, pathogens embedded in soil particles may be shielded from treatment (Abu-Orf et al. 2014). In fact, Title 22 requires that the turbidity of the treated water be less than 5 NTU to account for this problem (NWRI 2012). Minimizing this risk and meeting Title 22 requirements can be achieved by first allowing heavy particles to settle out of the waste stream and then screening out suspended particles with a filter before treatment, typically with a nominal diameter of 1–10 μm.

Conclusion

Treatment using ultraviolet light offers distinct advantages over chlorine and ozone because of the ease of maintenance and installation of UV systems. However, the poor transmittance and turbidity of the run-off from dissolved and suspended matter in irrigation runoff also increases the required UV dose to inactivate *Pythium* and *Phytophthora* by 2 to 4 times. The UV dose can be increased by decreasing the flow rate through the reactor, but a low flow can result in laminar flow which limits the success of the disinfection. Once flow becomes laminar, the UV dose is not equally distributed over each volume element in the reactor and active pathogens can leave the reactor (Crittenden et al. 2003). The novel UV design discussed in this paper was designed to overcome this problem and effectively treat irrigation water for harmful plant pathogens, such as *Pythium* and *Phytophthora*. In addition, this study focused on the removal of *P. ramorum* due to its particularly harmful impact on the ecosystems in many parts of the world. This study determined that the novel UV system supplies a UV dose of 51, 61, 82, 100 mJ/cm^2 when using 4, 6, 8, 12 lamps, respectively. A minimum

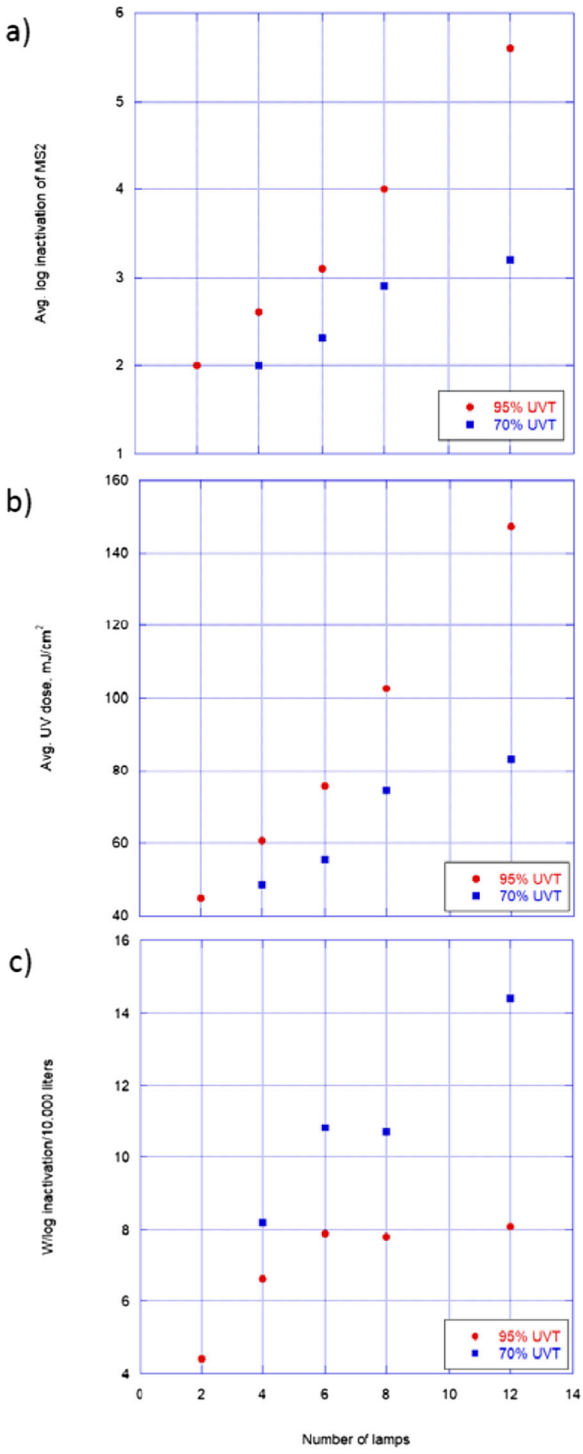

Fig. 2 Plots of the **a** average log inactivation of MS2, **b** average UV dose, and **c** energy use per log inactivation

log removal of 3.7 was obtained in the system for all lamp conditions for the removal of bacterial species. In addition, this level of treatment removed about 75%, 91.7%, and 91.7% of fungal counts using 4, 8, and 12 UV lamps, respectively. Most notably, the UV system was successful in inactivating 100% the *P. ramorum* in the influent even when only four lamps were in use.

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Compliance with ethical standards

Ethical approval The authors declare that this manuscript reports on original research that has not been published elsewhere. All the authors have read and approved this manuscript. All authors also declare that the data have not been manipulated. This manuscript does not contain any experiments with human participants or with animals.

Conflict of interest The authors declare that they have no actual or potential conflict of interest.

References

Abu-Orf, M., Tchobanoglous, G., Stensel, H. D., Tsuchihashi, R., Burton, F., Bolton, G. (2014). Wastewater engineering: Treatment and resource recovery. McGraw Hill Education, New York.

Ali-Shtayeh, M., & MacDonald, J. (1991). Occurrence of *Phytophthora* species in irrigation water in the Nablus area (West Bank of Jordan). *Phytopathologia Mediterranea, 30*, 143–150.

APHA (2005). Standard methods for the examination of water and wastewater. In (21st ed.). American Public Health Association/American Water Works Association/Water Environment Federation Washington, DC.

Banihashemi, Z., MacDonald, J. D., & Lagunas-Solar, M. C. (2010). Effect of high-power monochromatic (pulsed UV laser) and low-power broadband UV radiation on *Phytophthora spp*. in irrigation water. *European Journal of Plant Pathology, 127*(2), 229–238.

Bolton, J. R., & Linden, K. G. (2003). Standardization of methods for fluence (UV dose) determination in bench-scale UV experiments. *ASCE Journal of Environmental Engineering, 129*, 209–216.

Crittenden, J. C., Trussel, R. R., Hand, D. W., Howe, K. J., & Tchobanoglous, G. (2003). *Water treatment: Principles and design* (2nd ed.). Hoboken: Wiley.

Erwin, D. C., & Ribeiro, O. K. (1996). *Phytophthora diseases worldwide*. St. Paul: APS Press.

Ferguson, A. J., & Jeffers, S. N. (1999). Detecting multiple species of *Phytophthora* in container mixes from ornamental crop nurseries. *Plant Disease, 83*(12), 1129–1136.

Ghimire, S. R., Richardson, P. A., Kong, P., Hu, J., Lea-Cox, J. D., Ross, D. S., Moorman, G. W., & Hong, C. (2011). Distribution and diversity of *Phytophthora* species in nursery irrigation reservoir adopting water recycling system during winter months. *Journal of Phytopathology, 159*(11–12), 713–719.

Grünwald, N. J., Garbelotto, M., Goss, E. M., Heungens, K., & Prospero, S. (2012). Emergence of the sudden oak death pathogen Phytophthora ramorum. *Trends in Microbiology, 20*(3), 131–138.

Hong, C. X., & Moorman, G. W. (2005). Plant pathogens in irrigation water: Challenges and opportunities. *Critical Reviews in Plant Sciences, 24*(3), 189–208.

Hong, C., Richardson, P., Kong, P., & Bush, E. (2003). Efficacy of chlorine on multiple species of *Phytophthora* in recycled nursery irrigation water. *Plant Disease, 87*(10), 1183–1189.

Johnson-Brousseau, S., Henkes, M., Kosta, K., Suslow, K., Posadas, A., & Ghosh, S. (2011). *Phytophthora ramorum* research at the National Ornamental Research Site at the Dominican University of California. *New Zealand Journal of Forestry Science, 41*, 101–113.

Jung, T., Orlikowski, L., Henricot, B., Abad-Campos, P., Aday, A. G., Aguín Casal, O., Bakonyi, J., Cacciola, S. O., Cech, T., & Chavarriaga, D. (2016). Widespread Phytophthora infestations in European nurseries put forest, semi-natural and horticultural ecosystems at high risk of Phytophthora diseases. *Forest Pathology, 46*, 134–163.

Kong, P., Hong, C., Jeffers, S. N., & Richardson, P. A. (2003). A species-specific polymerase chain reaction assay for rapid detection of *Phytophthora nicotianae* in irrigation water. *Phytopathology, 93*(7), 822–831.

Kovacs, K., Holmes, T. P., Englin, J. E. & Alexander, J. (2011). The dynamic response of housing values to a forest invasive disease: Evidence from a sudden oak death infestation. *Environmental and Resource Economics, 49 (3)*, 445–451.

Lamour K. (Ed.) (2013). *Phytophthora: A global perspective*. CABI Plant Protection Series; 2, Wallingford, UK.

Mislivec, P. B., & Bruce, V. R. (1976). Comparison of antibiotic-amended potato dextrose agar and acidified potato dextrose agar as growth substrates for fungi. *Journal of the Association of Official Analytical Chemists, 59*(3), 720–721.

NWRI. (2012). Ultraviolet disinfection guidelines for drinking water and water reuse. In G. M. Vartanian (Ed.). Fountain Valley: National Water Research Institute.

Orlikowski, L. B., Oszako, T., Trzewik, A., & Orlikowska, T. (2007). Occurrence of *Phytophthora ramorum* and other *Phytophthora* species in nurseries, trade stands, forests and water. *Journal of Plant Protection Research, 47*(4).

Reasoner, D. J., & Geldreich, E. E. (1985). A new medium for the enumeration and subculture of bacteria from potable water. *Applied and Environmental Microbiology, 49*(1), 1–7.

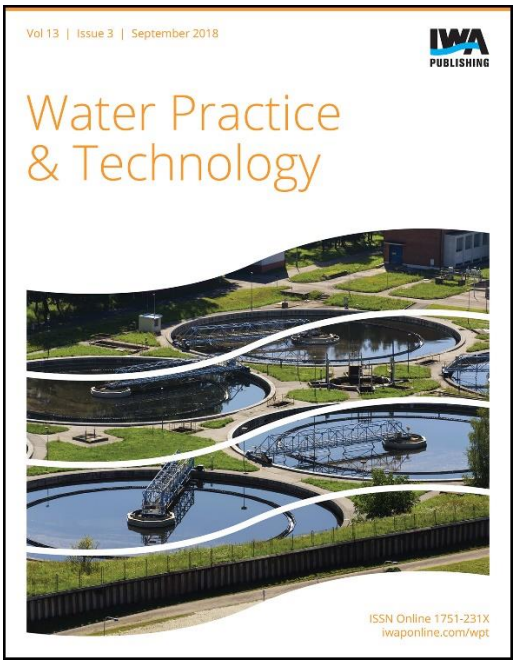
Rizzo, D. M., & Garbelotto, M. (2003). Sudden oak death: endengaring California and Oregon forest ecosystems. *Frontiers in Ecology and the Environment, 1*(4), 197–204.

Van der Linde, K., Lim, B. T., Rondeel, J. M. M., Antonissen, L. P. M. T., & de Jong, G. M. T. (1999). Improved bacteriological surveillance of haemodialysis fluids: A comparison between tryptic soy agar and Reasoner's 2A media. *Nephrology Dialysis Transplantation, 14*(10), 2433–2437.

Werres, S., Wagner, S., Brand, T., Kaminski, K., & Seipp, D. (2007). Survival of *Phytophthora ramorum* in recirculating irrigation water and subsequent infection of Rhododendron and viburnum. *Plant Disease, 91*(8), 1034–1044.

Widmer, T. L. (2009). Infective potential of sporangia and zoospores of *Phytophthora ramorum*. *Plant Disease, 93*(1), 30–35.

Younis, B. A. (2014). Demonstrating a vortex technology to disinfect wastewater with ultraviolet light. Report to California Energy Commission, CR 500-09-050 (also US patent publication number US 2016/0176727 A1, 2016).



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A novel system for the treatment of wastewater from a tomato processing plant with UV light

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Abstract

In tomato processing plants, the production of paste involves the use of heat to evaporate water to concentrate the tomato juice. The hot water isolated from the juice is then passed through cooling towers to cool it sufficiently before discharge. Recovery of excess and blowdown water from the cooling towers would decrease the net water demand of the plant and improve water efficiency. However, since this water has been exposed to the open air, it must be disinfected before reuse. This research investigated the use of a novel ultraviolet (UV) system to disinfect water from the cooling tower basins located at an industrial tomato processing facility. The objective was to assess, *in situ*, the disinfection system's performance with regards to its utility, and its ability and to treat wastewater generated in an operational, industrial-scale setting. Beyond typical wastewater microbial assays, 16S rRNA gene sequencing was employed to understand the bacterial communities present in the wastewater, and to screen for microorganisms that may pose a risk for water reuse in food processing facilities.

Key words: 16S rRNA sequencing, cooling tower, tomato processing plant, UV disinfection

INTRODUCTION

The urgent need for efficient methods for the treatment of industrially-generated wastewater to an acceptable standard to permit its reuse is best illustrated with reference to the conditions and prevailing practices in the State of California. In that state, 85% of the population depends on groundwater for some part of their drinking water supply while about 34 million-acre feet of water (42 billion cubic meters), much of which is groundwater, is extracted annually to irrigate approximately 9.6 million acres of land for agricultural use (Megdal *et al.* 2009; ACWA 2011). Unsurprisingly, groundwater reservoirs are regularly overdrafted to meet these demands. Areas of overdraft occur mainly in the Central Valley, along the coast, and in some parts of southern California (Lund & Harter 2013). In the Tulare Lake Basin, one of the most productive agricultural regions in the Central Valley with an estimated value of $17 billion per year, overdraft accounts for about 10% of total yearly water use (Croyle *et al.* 2014). In addition, from 2007 to 2013, groundwater levels in this region declined by almost 60 feet (18.2 m) while, from 2007 to 2011, the land subsided by 3.9 ft (1.2 m) (Borchers & Carpenter 2014; Croyle *et al.* 2014). One way to decrease water use and help meet overall water demand is to treat industrial wastewater onsite and reuse it in the facility.

Tomato paste production in California accounts for 90% of its production in the United States, equivalent to 35% of global production (Amon *et al.* 2013). Tomato processing relies heavily on the use of water (Barrios-Masias & Jackson 2014), with roughly 890 gallons (3.37 m^3) of water

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used per ton of raw material (Mannapperuma *et al.* 1993). Reduction of these flows improves water efficiency and reduces draws from surface and groundwater sources.

Although treatment and reuse of tomato processing wastewater may be an avenue to increase water efficiency, effective treatment of such wastewater is highly dependent on the quality of the wastewater generated from the various operations in the facility. When all effluent streams are consolidated, the wastewater from tomato paste production is high in suspended solids, chemical oxygen demand (COD), and color (Iaquinta *et al.* 2009). Much of this is due to carryover of dirt from the field that's removed during washing, and the presence of juice from damaged fruit. Often, a combination of biological treatment, nano-filtration, and some type of oxidative process is used to treat this type of waste stream (Sun *et al.* 2013; Alghooneh *et al.* 2015). However, these types of intensive treatments are not necessarily needed for all individual unit operation effluent streams within the facility. For example, the evaporation step to remove water from tomato juice, to concentrate the solids into paste, yields a condensate that is relatively low in dissolved solids and organic compounds. This condensate is then routed to cooling towers to reduce its temperature to a manageable level. Thus, isolating and treating cooling tower wastewater separately may avoid the need for rigorous treatment and yield water suitable for reuse in the facility, such as in the flumes that transport unloaded fruit into the facility.

A physical treatment method, such as disinfection with ultraviolet (UV) light, is a promising method for treating water from cooling tower effluent, because it avoids generating toxic by-products caused from the use of oxidizing chemical disinfectants, such as chlorine. Similarly, there is no additional smell or taste added to the water, no danger of overdosing the disinfectant, and no need to store hazardous materials onsite (Crittenden *et al.* 2012). A physical treatment process is also desirable because of the seasonal nature of tomato paste production; no biological membrane has to be reestablished at the start of the season or maintained during the off-season. Ultraviolet light primarily works as a disinfectant by exciting the nucleic acids in DNA and RNA. This excitation results in the dimerization of adjacent nucleic acids and prevents the further transcription of the DNA or RNA and inhibits replication (Crittenden *et al.* 2012; Metcalfe & Eddy, 2014). Because organisms are inactivated and not removed, evaluation of disinfection efficiency depends on cultivation-based approaches. However, since the fraction of cultivable species in wastewater is typically 15% to 20% of counted cells, there is a significant cultivation bias when using these methods.

Conventional UV reactors involve flowing water through a bank of UV lights in a closed conduit or an open channel. Such systems often demand high capital and operating costs, inhibiting the wider adoption of the technology. This is due to the fact that the UV-emitting lamps (more specifically, their outer quartz tubes) come into direct contact with the untreated water and become fouled due to the accumulation of organic and inorganic material. To prevent this, mechanical cleaning systems are sometimes used, with periodic acid cleaning to further remove any residual fouling (Metcalfe & Eddy, 2014). These systems are costly to manufacture and operate, and can involve significant periods of downtime. Hence the availability of a UV system in which fouling does not occur would improve the prospects of adaptation of UV treatment in practice. Another unsatisfactory feature of the conventional design is that the channel through which water flows is lined with concrete which also easily fouls, causing frequent closures for cleaning. Thus, to maintain continuous operation while cleaning occurs, several redundant channels are employed at increased cost to the user (Metcalfe & Eddy, 2014).

The purpose of this paper is twofold. First, it is to establish the efficacy of using UV disinfection to treat cooling tower effluent from a tomato processing facility for water reuse. Secondly, it is to assess the performance of a novel UV system which is free from many of the drawbacks present in most commercially-available systems (Younis, 2016). The assessment is performed, *in situ*, at a large-scale processing facility, at the height of the tomato-paste production season.

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MATERIALS AND METHODS

The UV system

The UV system is described in Younis (2016). Figure 1(a) shows a three-dimensional rendering of the system with its major components labelled. Figure 1(b) is an engineering drawing showing relevant

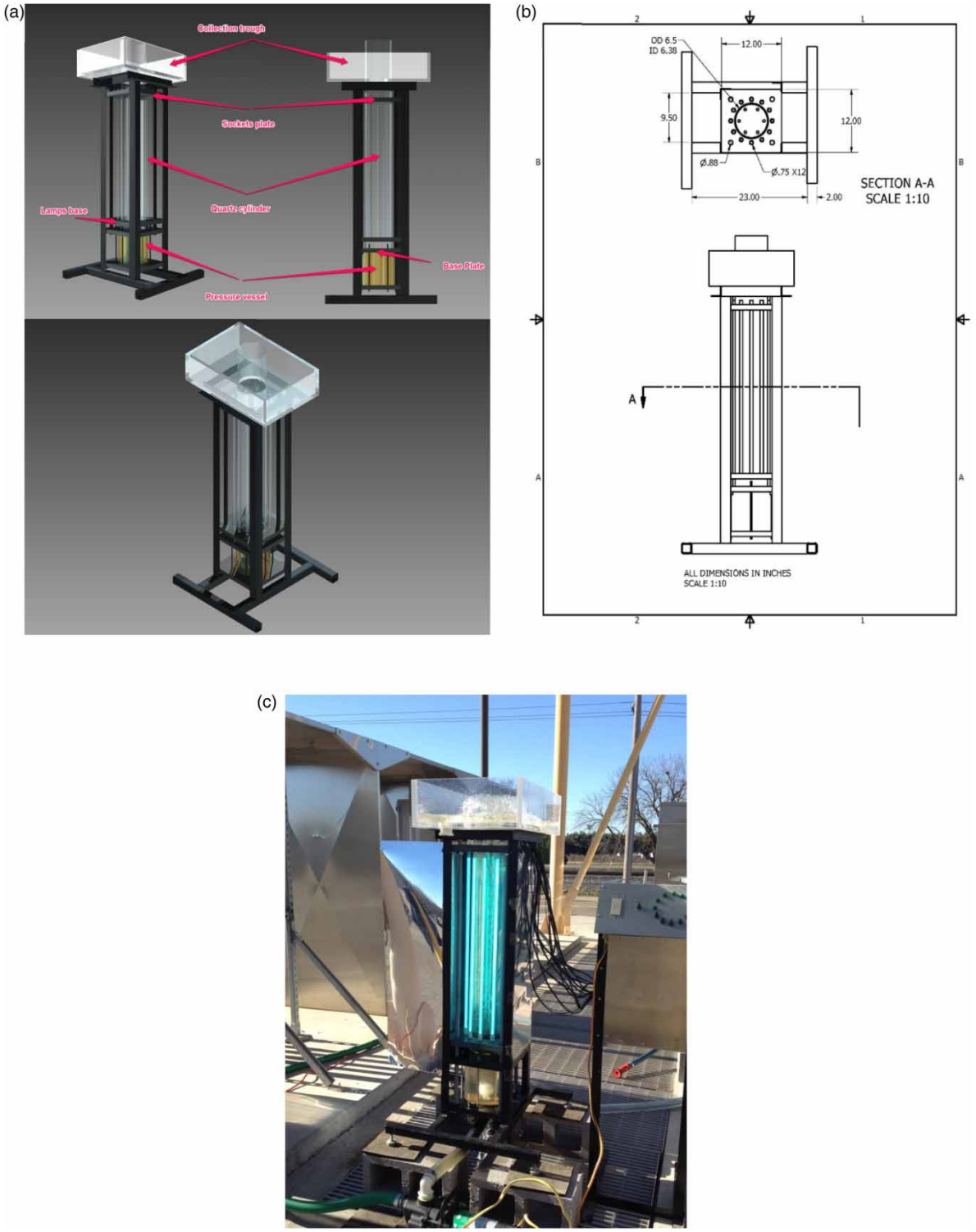

Figure 1 | (a) Three-dimensional rendering of the UV system, (b) schematic giving system dimensions, (c) photograph of system in operation.

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dimensions. Figure 1(c) is a photograph of the system in operation. Untreated water is introduced into a pressure vessel at the base of the system from which it flows through nozzles into a vertically-mounted quartz tube. The nozzles are arranged around the circumference of the quartz tube and hence the water rises within it in the form of a strong vortex. Through adaptation to the base of this tube, a central air core is formed in the shape of an elongated cone. This confines the water between the air column and the inner wall of the tube. Lamps emitting UV light are placed outside of the quartz tube and thus remain free of contact with the water. The number, length and power output of the lamps depends on the design flowrate and on the required fluence. In the design shown, 12 low-pressure Hg lamps, each 40 inches (101 cm) in length, were used. Since quartz allows for the transmission of UV light, the untreated water is exposed to light at the germicidal wave length without contacting the lamps. This altogether eliminates the lamp fouling problem. Further, the presence of the strong vortex leads to the generation of high levels of shear stress at the tube walls. These stresses form a mechanism for self-cleansing in that they prevent the accumulation on the surface of material that can eventually cause fouling on the inside of the tube. Finally, and since the lamps are located outside the quartz tube, they become easily accessible for the purpose of replacement, thereby eliminating the need for prolonged down-times for maintenance and for the infrastructure required to remove the banks of immersed UV tubes used in most commercial systems. After passing through the quartz tube, the treated water flows from the top into a collection trough from where it is conveyed away through tubes attached to the base of the trough. The top of the tube acts in the same way as a circular weir such that the water flowing over it becomes well aerated through the entrainment of ambient air (Figure 1(c)). Further details can be found in Younis (2016).

Site description

The Campbell Soup Company tomato processing plant in Dixon, CA is located in a rural area and obtains fresh water through onsite wells. The facility operates for about 90 days per year, typically July through September, depending on the tomato harvesting season. The site has five induced draft cooling towers that are used to cool the water from 160°F to 78°F (71°C to 25°C) at a loading rate of 31,111 gallons/hr (117 m^3/hr) (Amon *et al.* 2013).

Analysis of UV system at NSF

The tests at the National Sanitation Foundation (NSF) facility in Ann Arbor, MI were conducted to determine the system's ability to meet the requirements for the NSF/ANSI 50 and 55 standards for residential drinking water treatment and recreational water treatment, respectively. The system exceeded the requirements for 3 log reduction of *Pseudomonas aeruginosa* and *Enterococcus faecium*. A single pass test sample showed a log reduction of 6.4 of *Pseudomonas aeruginosa* and a 6.7 log reduction of *Enterococcus faecium*. When tested with the bacteriophage MS2, a single pass test sample showed a log reduction of 4.9. Comparison of the single pass log reduction to the results of a collimated beam test performed on the MS2 indicates that the test sample provided an equivalent UV dose (fluence) of greater than 60 mJ/cm^2 (assuming linearity of dose response curve, the UV dose would be 104 mJ/cm^2) for the observed test conditions.

UV treatment of cooling tower basin water

Onsite testing took place on 8/28/2015. The system was placed downstream of the cooling towers and drew from the water collecting in the cooling tower basins. The system was allowed to warm-up for 10 min before testing. The UV system was tested under two different flow rates: 10 gpm and 15 gpm (38 and 57 liters/min, respectively). For each experiment, the system used 6 low-pressure Hg lamps, each of 60 W power output.

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Microbial analyses

A standard water reuse system in California must follow California's water reuse policy, Title 22, which requires a demonstration of 5-log removal of the virus MS-2, an analog to the polio virus, to ensure a minimum level of safety to the public (NWRI 2012). However, these regulations were developed to ensure the safety of the public and not the safety of the manufactured product at the facility. Therefore, to promote the safety of the tomato product, both metagenomics and traditional cultivation techniques were also used to investigate disinfection efficacy and pathogenic risk.

Samples of basin water were analyzed for total and fecal coliform counts using Colilert Quanti-Tray^{TM} system (IDEXX Laboratories, Westbrook, ME). Samples were incubated at 37°C for 24 hours. Fungal counts were assessed using Potato Dextrose Agar (PDA) plates. Plates were incubated for 5 days at 25°C in the dark according to standard methods (APHA 2012).

UV radiation treats water by causing linkages in the DNA and RNA of microorganisms, thereby preventing further replication. Therefore, the organism remains viable, but can no longer replicate following treatment (Crittenden *et al.* 2012). Because of this, samples of the UV treatment system influent and effluent were enriched for viable microorganisms capable of replication using Luria Broth (LB). For the enrichment, 5 mL of sample was added to 45 mL of LB media and grown for 24 hrs at 35 $\pm$ 2°C at 300 rpm. This was performed in triplicate to identify statistically significant shifts in community composition in response to the UV treatment.

Genomic DNA was extracted from the samples using a Powersoil DNA Isolation Kit (Mo-Bio, Carlsbad, CA). This genomic DNA was used for obtaining count data for ITS and V4/V5 sequencing using the MiSeq platform. The samples were amplified for sequencing using a two-step process. The forward primer was constructed with the (5′-3′) Illumina i5 sequencing primer, a barcode (8–10 bp), a primer pad, and the 515 f primer (GTGCCAGCMGCCGCGGTAA) for bacteria and the ITS9 primer (GAACGCAGCRAAIIGYGA) for fungi. The reverse primer was constructed with the (5′-3′) Illumina i7 primer, a barcode (8–10 bp), a primer pad, and the 926r primer (CCGYCAATTYMTTTRAGTTT) for bacteria and the ITS4 primer (TCCTCCGCTTATTGATATGC) for fungi. The Qiagen HotStar Taq master mix was used to preform 25 µl reactions, with 1 µl of each 5 µM primer, and 1 µl of template (Qiagen Inc, Valencia, CA). ABI Veriti thermocyclers were used to perform the reactions using the following thermal profile: 95°C for 5 min, then 25 cycles for 94°C for 30 s, 54°C for 40 s, 72°C for 1 min, ending with one cycle of 72°C and a 4°C hold.

Products from the first stage of amplification were then added to a second PCR based on qualitatively determined concentrations. This second stage PCR used the following Nextera PCR primers: Forward – AATGATACGGCGACCACCGAGATCTACAC [i5index] TCGTCGGCAGCGTC and Reverse – CAAGCAGAAGACGGCATACGAGAT [i7index] GTCTCGTGGGCTCGG. The amplification had the same thermal profile as the first stage and was run for 10 cycles.

The amplification products were visualized using eGels (Life Technologies, Grand Island, NY). The products were then pooled equimolar and each pool was size selected in two rounds using Agencourt AMPure XP (Beckman Coulter, Indianapolis, IN) in a 0.7 ratio for both rounds. A fragment Analyzer (Advanced Analytical) and a Qubit 2.0 fluorometer (Life Technologies), was used to assess the size and quantify the selected pools, respectively. Then the pools were loaded on an Illumina MiSeq (Illumnia, Inc., San Diego, CA) 2 X 300 flow cell at 10 pM and sequenced according to the manufacturer's standard protocol.

The sequences were then assessed for quality to remove failed sequence reads, sequences with low tags, and sequences that were less than half the expected amplicon length. To account for paired sequences, PEAR Illumina paired-end read merger was used, these sequences were then processed using a trimming algorithm (Zhang *et al.* 2014). The USEARCH clustering algorithm was used to cluster the sequences into operational taxonomic units (OTUs) at a 4% divergence (Edgar 2010). Once the OTUs were selected using UPARSE OTU selection algorithm (Edgar 2013), UCHIME chimera

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detection software was used to locate chimeras (Edgar *et al.* 2011). Finally, to assess the final quality of the data, the OTU sequences were then compared to a database of high quality sequences derived from the NCBI database using a combination of the USEARCH global search algorithm and an internally developed python program that assigns taxonomic information to each sequence and then computes and writes the final analysis files.

Data processing

All statistically analyses were conducted in Microsoft Excel, R using the vegan package (Oksanen *et al.* 2007), and Past 3.x (HAMMER 2014). The R code is available in Appendix B.

RESULTS AND DISCUSSION

Water quality analysis

A summary of the water quality characteristics from the blowdown and overflow from the facility's cooling towers is given in Table 1. The high concentration of coliforms in this water makes it unsuitable for reuse under NSF and Title 22 standards. These standards would limit the allowed concentration of total coliform to 2.2 or 23 MPN/100 mL, depending on how the water is used. The turbidity of this water is also slightly too high for Title 22 standards. Title 22 requires a turbidity of less than 5 NTU to help prevent the spread of pathogens that are embedded in the particles in the water. This encasement can shield the pathogens from receiving the required disinfection dose by physically blocking the UV light or by contributing more organic matter in the water, necessitating of a higher UV dose (Crittenden *et al.* 2012).

Table 1 | Initial water quality of the cooling tower runoff at the Campbell tomato processing facility in Dixon, CA

Analysis	Cooling Tower Runoff
Turbidity, NTU	7.24 ± 1.2
Total coliform, MPN/100 ml	36,500 ± 7,354
Total fecal coliform, MPN/100 ml	0
Total fungal counts, CFU/ml	67.33 ± 11.02
UVT at 254 nm	95.9% ± 0.04%
Absorbance at 254 nm, 1/cm	0.0181 ± 0.0002
ORP, mV	214.7 ± 3.51
COD, mg/L	8.33 ± 2.52
Conductivity, μS	506.6 ± 3.50
TDS, ppm	351.9 ± 3.00
pH	7.42 ± 0.141

Nevertheless, these initial water quality characteristics have some qualities that are advantageous for the use of UV treatment. Namely, the UV transmittance (UVT) of this water is very high. This clarity means that UV light will easily be able to penetrate through the water column and inactivate any pathogens in the water.

Microbial analyses

Results from operation of the UV system at flow rates of 10 and 15 gallons/minute (2.27 and 3.41 m^3/hr) revealed complete disinfection of fungal species, but incomplete disinfection of total

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coliforms found in the water (Table 2). For total coliforms, there was a 2 and 3.8 log reduction at flow rates of 10 and 15 gallons/minute, respectively. However, this system previously achieved log reductions of 6.4 and 6.7 of *Pseudomonas aeruginosa* and *Enterococcus faecium* during NSF testing using synthetic wastewater. Thus, the lower level of treatment with cooling tower water at the processing facility is likely due to either the turbidity in the water or the species of bacteria present in the water. This inefficiency highlights the roles that water properties and the microbial community plays in determining disinfection performance and how performance against indicator species is not always a reliable parameter to measure disinfection performance.

Table 2 | Results for the biological testing under flow each condition of the UV system

Sample	Total fecal coliform, MPN/100 mL	Total coliform, MPN/100 mL	Total fungal counts, CFU/mL
Influent (cooling tower runoff)	0	36,500 ± 7,354	67.33 ± 11.02
UV treatment at 15 gpm	0	321.75 ± 32.60	0
UV treatment at 10 gpm	0	5.75 ± 0.78	0

Genomic analysis

The sequencing data was used to better understand the microbial community present in this water source and the respective sensitivity of the species within it.

Relative abundance

Rarefaction curves generated from OTUs showed a clear asymptote for both communities, this indicates that there was sufficient sampling to identify most OTUs within the microbial communities (Appendix A). This analysis revealed that microbial communities from the enriched samples lacked diversity; the culturing method favored *Pseudomonas*, *Clostridium*, and *Bacillus* species (Figure 2).

NMDS plots

As seen in Figure 3, the ordination results indicate a divergence in the culturable microbial communities after UV treatment. The 10 gpm (38 liters/min) samples are more dissimilar to the influent samples, since the lower flow rate allows for a greater UV contact time through the system and a greater level of disinfection. The cultured samples from the UV treatment at 15 gpm (57 liters/min) are more similar to the influent samples. However, the lack of overlap for the ellipses around the samples, indicating the 95% confidence interval, confirms that the samples are separate populations.

Species of interest

Table 3 presents a list of species isolated from spoiled canned tomatoes. Of these 12 species associated with spoilage, 8 of the species were found in the cooling tower runoff. Of these spoilage organisms identified, 6 were harmful bacteria and 2 were harmful fungi.

These microorganisms were not culturable on the PDA media used for plating and, as a result, viable counts could not be obtained for the treated samples. As shown in Table 3, a variety of media are necessary to culture all of the listed spoilage species. This highlights the diversity in microhabitats available in the cooling tower and the difficulty in assessing the treatment level for a range of pathogens.

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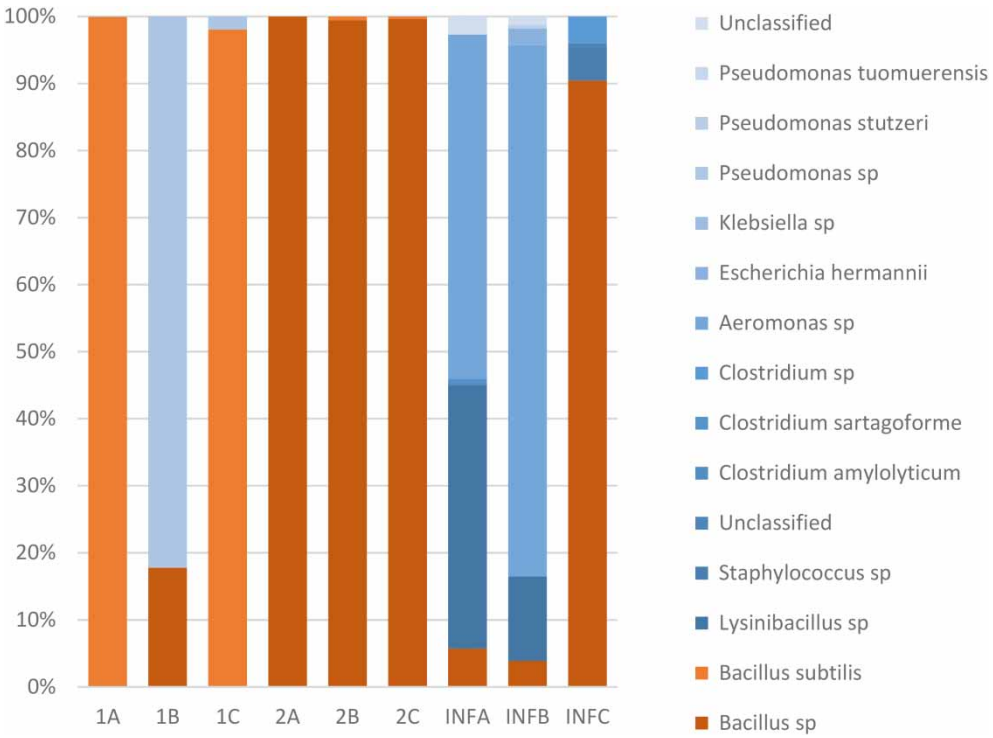

Figure 2 | Relative abundance of cultured bacterial species grouped by species, where 1A, 1B, 1C are the replicates for the effluent from the trial at 15 gpm, 2A, 2B, 2C are the replicates from the trial at 10 gpm, and INFA, INFB, and INFC are the replicates from the raw influent.

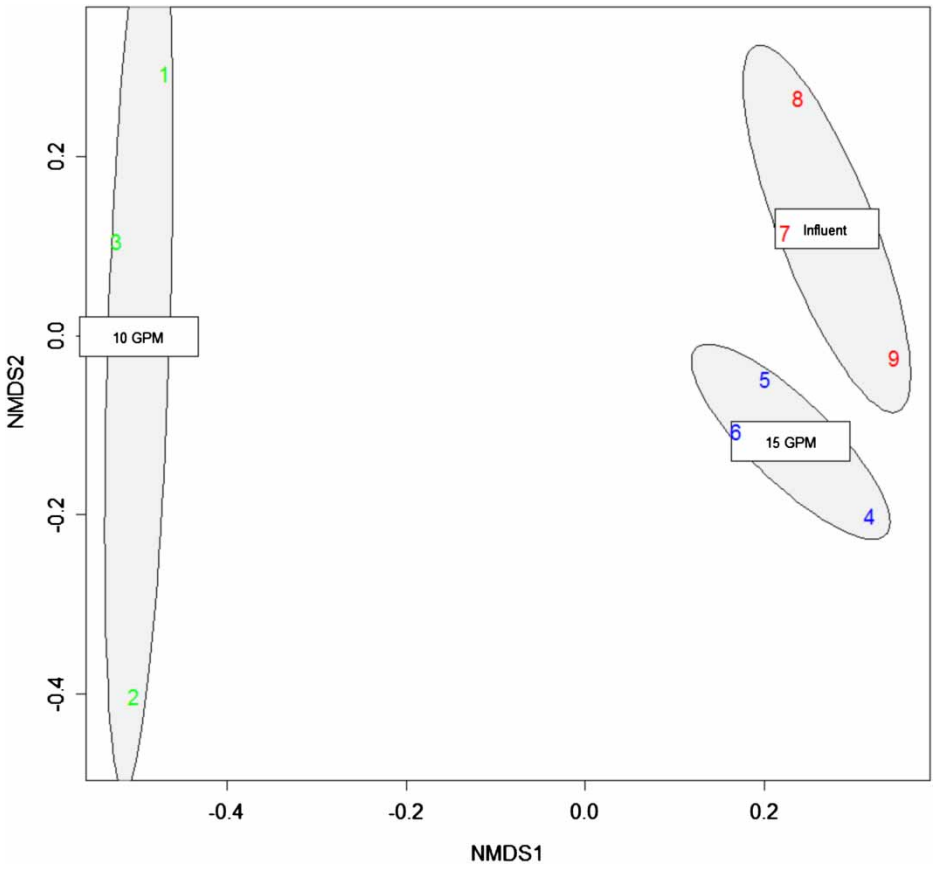

Figure 3 | Non-metric multidimensional scaling of the bacterial community data from the cultured influent and the effluent from UV treatment at 10 gpm and 15 gpm.

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Table 3 | Spoilage-causing species, media needed for culturing, and sensitivity to UV disinfection

Spoilage organisms	Type	Present in cooling tower system	Cultivability[a]	UV Sensitivity (2 log removal) mJ/cm^2
Bacillus polymyxa	Bacterium	Yes	Beef Extract Agar	11.0[b]
Bacillus coagulans	Bacterium	Yes	Beef Extract Agar	11.0[b]
Staphylococcus aureus	Bacterium	Yes	Beef Extract Agar	6.6[c]
Streptococcus lactis	Bacterium	No	Brain Heart Infusion Agar	8.8[d]
Pseudomonas sp	Bacterium	Yes	Beef Extract Agar	10.5[e]
Clostridium sporogenes	Bacterium	Yes	TSA with defibrinated sheep blood	NA
Bacillus coagulans	Bacterium	Yes	Beef Extract Agar	11.0[b]
Saccharomyces sp	Yeast	Yes	Yeast and Mold Agar	13.2[f]
Candida sp	Fungus	No	Yeast and Mold Agar	NA
Mucor sp	Fungus	No	Potato dextrose Agar	35.2[g]
Penicillium sp	Fungus	No	Sabouraud's Agar	88.0[h]
Aspergillus niger	Fungus	Yes	Potato Dextrose Agar	330.0[c]

NA, Not Available.
[a]From ATCC database.
[b]*Bacillus subtilis* (AAW 2017).
[c](AAW 2017).
[d]*Streptococcus faecalis* ATCC29212 (Chang et al. 1985).
[e]*Pseudomonas aeruginosa* (AAW 2017).
[f]*Saccharomyces cerevisiae* (AAW 2017).
[g]*Mucor racemosus A* (AAW 2017).
[h]*Penicillium digitatum* (AAW 2017).

These harmful microorganisms must be inactivated if the cooling tower water is to be recycled in any applications that could come into contact with the tomato product. Most of these microorganisms require only a low dose of UV radiation to inactivate (Table 3). The only difficult species for the UV system to treat is *Aspergillus niger*, since it requires a UV dose of 330 mJ/cm^2 for 2 log reduction. However, *A. niger* colonies did not grow on the PDA media inoculated with cooling tower basin water, suggesting that they may be present in low quantities. Because of this, it may be possible to control *A. niger* via multiple passes through the UV system or filtration upstream of the UV system.

CONCLUSIONS

Substantial amounts of water are isolated from evaporators during the production of tomato paste on the industrial scale. This condensate is often routed to cooling towers ahead of discharge (Bartz & Showalter 1981). Because of its low turbidity and total dissolved solids (TDS), this water may potentially be reused within the processing facility. However, tomato processing water can harbor dangerous microorganisms that can either spoil the product or compromise the health of the consumer. For instance, *Listeria monocytogenes* can tolerate low temperatures and can thus multiply within the product before reaching the consumer. It is argued here that disinfection with UV light, being free of chemicals, provides the safest and most convenient method for use in food processing plants. However, since most analysis of UV treatment has been performed on drinking water and on domestic wastewater, its performance on the microbial flora in tomato processing is not well characterized. In this paper, a novel UV system was introduced and was evaluated *in situ* in water runoff from the cooling towers of an industrial tomato processing plant. The system offers several advantages

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over existing designs, primarily in not being prone to the problem of lamp fouling. Tests on the treated effluent indicated that the system was able to achieve a 6.7 and 6.4 log reduction of *Enterococcus faecium* and *Pseudomonas aeruginosa*, respectively. The applied UV dose was estimated to be greater than 60 mJ/cm^2. Genomic analysis of the cultured effluent samples showed a significant shift in bacterial populations after UV treatment and evaluation of species present in non-cultured samples indicated that several species associated with food spoilage were present in the cooling tower water run-off. Of the most concern on this list was *Aspergillus niger*, because it requires the relatively high UV dose of 330 mJ/cm^2 to achieve a 2 log reduction. This result indicates that effective disinfection would require multiple passes through the system, or a number of systems that are connected in series.

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REFERENCES

AAW 2017 *UV Irradiation Dosage Table*. [Online]. Available at: http://www.americanairandwater.com/uv-facts/uv-dosage.htm (Accessed 6 July 2017).

ACWA 2011 *Sustainability From the Ground Up – Groundwater Management in California – A Framework*. Association of California Water Agencies, Sacramento, CA.

Alghooneh, A., Razavi, S. M. & Mousavi, S. M. 2015 Nanofiltration treatment of tomato paste processing wastewater: process modeling and optimization using response surface methodology. *Desalination and Water Treatment* **57**, 9609–9621.

Amon, R., Maulhardt, M., Wong, T. & Kazama, D. 2013 *Industrial Water Energy Nexus Assessment: Campbell Soup California Tomato Processing Facility*. Prepared for: California Energy Commission.

APHA 2012 *Standard Methods for the Examination of Water and Wastewater*. American Public Health Association, Washington, DC, USA.

Barrios-Masias, F. H. & Jackson, L. E. 2014 California processing tomatoes: morphological, physiological and phenological traits associated with crop improvement during the last 80 years. *European Journal of Agronomy* **53**, 45–55.

Bartz, J. A. & Showalter, R. 1981 Infiltration of tomatoes by aqueous bacterial suspensions. *Phytopathology* **71**, 515–518.

Borchers, J. & Carpenter, M. 2014 *Land Subsidence From Groundwater Use in California*. Luhdorff and Scalmanini Consulting Engineers, California.

Chang, J. C., Ossoff, S. F., Lobe, D. C., Dorfman, M. H., Dumais, C. M., Qualls, R. G. & Johnson, J. D. 1985 UV inactivation of pathogenic and indicator microorganisms. *Applied and Environmental Microbiology* **49**(6), 1361–1365.

Crittenden, J. C., Trussell, R. R., Hand, D. W., Howe, K. J. & Tchobanoglous, G. 2012 *MWH's Water Treatment: Principles and Design*. John Wiley & Sons, Hoboken, NJ, USA.

Croyle, W., Alemi, M., Gutierrez, D., Mathis, D., Ericson, J. & Scruggs, M. 2014 *Public Update for Drought Response Groundwater Basins with Potential Water Shortages and Gaps in Goundwater Monitoring*. DWR, State of California, Sacramento, CA.

Edgar, R. C. 2010 Search and clustering orders of magnitude faster than BLAST. *Bioinformatics* **26**(19), 2460–2461.

Edgar, R. C. 2013 UPARSE: highly accurate OTU sequences from microbial amplicon reads. *Nature Methods* **10**, 996–998.

Edgar, R. C., Haas, B. J., Clemente, J. C., Quince, C. & Knight, R. 2011 UCHIME improves sensitivity and speed of chimera detection. *Bioinformatics* **27**(16), 2194–2200.

Hammer, O. 2014 Past 3. x–the Past of the Future. Universidad de Oslo. Consultado en internet en noviembre de.

Iaquinta, M., Stoller, M. & Merli, C. 2009 Optimization of a nanofiltration membrane process for tomato industry wastewater effluent treatment. *Desalination* **245**(1–3), 314–320.

Lund, J. R. & Harter, T. 2013 *California's Groundwater Problems and Prospects*. California WaterBlog [Online]. (Accessed November 11 2014).

Mannapperuma, J., Yates, E. & Singh, R. P. 1993 Survey of water use in the California food processing industry. *Food Industry Environmental Conference*.

Megdal, S., Hamann, R., Harter, T., Jawitz, J. & Jess, M. 2009 *Water, People, and the Future: Water Availability for Agriculture in the United States*. Council for Agricultural Science and Technology, Ames, IA, USA.

Metcalf & Eddy Inc., Tchobanoglous, G., Stensel, H. D., Tsuchihashi, R & Burton, F. 2014 *Wastewater Engineering: Treatment and Resource Recovery*. 5th ed. McGraw Hill, Boston, USA.

Water Practice & Technology Vol 13 No 3
doi: 10.2166/wpt.2018.064

NWRI 2012 *Ultraviolet Disinfection Guidelines for Drinking Water and Water Reuse*, 3rd ed (Vartanian, G. M., ed.). National Water Research Institute, Fountain Valley, California.

Oksanen, J., Kindt, R., Legendre, P., O'Hara, B., Stevens, M. H. H., Oksanen, M. J. & Suggests, M. 2007 The vegan package. *Community Ecology Package* **10**, 631–637.

Sun, S., Guo, Z., Yang, R., Sheng, Z. & Cao, P. 2013 Analysis of microbial diversity in tomato paste wastewater through PCR-DGGE. *Biotechnology and Bioprocess Engineering* **18**(1), 111–118.

Younis, B. A. 2016 Apparatus for UV disinfection of a liquid. US Patent Office ref. 20160176727A1.

Zhang, J., Kobert, K., Flouri, T. & Stamatakis, A. 2014 PEAR: a fast and accurate illumina paired-end reAd mergeR. *Bioinformatics* **30**(5), 614–620.

water

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A Novel System for Water Disinfection with UV Radiation

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Abstract: We present a novel system for water disinfection with ultra-violet (UV) radiation. In this system, the UV lamps do not come into contact with the water and hence remain free of fouling. The system incorporates a diffusor and a nozzle, with stationary guide vanes built into each. Their combined purpose is to reduce the hydraulic losses while imparting a strong swirl component to the flow. The swirl significantly enhances turbulent mixing processes and provides a self-cleansing mechanism that renders the system tolerant to high levels of turbidity and scaling. The hydrodynamic performance of the system was optimized using Computational Fluid Dynamics, while the manufacture of its key components was accomplished using advanced mechanical design software and three-dimensional (3D) printing. Biodosimetry testing with the bacteriophage MS2 indicated the delivery of a UV dose of 215.6 mJ/cm^2. This produced a 6.9 $\log_{10}$ reduction of *E. coli* and 7.12 $\log_{10}$ reduction of MS2. Assessment of the system with hard water containing high Ca, Mg, and Fe concentrations, and with water with turbidity of 18 NTU indicated that the $\log_{10}$ removal of *E. coli* remained above 5.

Keywords: UV treatment system; swirling flow; lamp fouling; 3D printing; CFD

1. Introduction

Most commercial systems for water disinfection using UV radiation in use derive their basic structure from a patent dating back to 1934 [1]. In the original system, as in the existing ones, the UV lamps are placed inside protective quartz tubes and inserted in the water that is to be treated. Water flows along the quartz tubes, carrying the pathogens of concern. The pathogens receive a UV dose commensurate with their time of exposure to UV radiation of a given intensity [2]. The received dose, if greater than a pathogen-specific threshold, disrupts the pathogen's DNA in such a way as to prevent their multiplication [3–5]. In applications where the water flow is pressurized, such as in a drinking-water supply and distribution network, the water flows in the gap between the quartz cylinders and an outer casing that serves to maintain the interior pressure at above atmospheric, and to prevent damage to the users. This method of irradiating water with UV radiation suffers from a number of drawbacks, of which three are relevant here. The first is that, with time, the quartz tubes become covered with mineral deposits and bio-film—the "lamp fouling" problem. Methods for keeping the tubes clear range from installing electrically-driven wipers that continually traverse the length of the quartz tube to scrape off the deposits that accumulate on it, to the more drastic action of taking the system out of service to scrub the quartz tubes clean, sometimes using acid solutions to loosen the deposits [6]. The second drawback of the conventional designs stems from the fact that obstructions placed in the path of a moving fluid lead to losses of kinetic energy [7–9]. These losses lead to higher operating costs due to the increase in the power required to deliver water at a given flow rate. The third drawback stems from the difficulty of achieving thorough mixing of the water being

treated to ensure that all pathogens receive a UV dose sufficient for their activation [7–9]. In many systems, the poor mixing is compensated for by increasing the number of UV lamps, but that also leads to increased hydraulic losses. Alternative UV systems to the conventional commercial designs exist. Notable amongst them are the systems developed by, e.g., Reference [10], wherein the UV lamps are placed above the surface of water flowing through an open channel. In this configuration, the problems of "lamp fouling" and hydraulic losses do not occur. However, mixing is usually a limiting factor in these designs, such that the UV dose is delivered to only a thin surface layer. This significantly limits the flow rates that can be accommodated in these designs.

The purpose of this paper is to introduce and demonstrate the efficacy of a novel system that overcomes most of the drawbacks mentioned above. The objective of the research leading to it was to develop a UV system that is robust, reliable, inexpensive to install and operate, and sufficiently maintenance-free to be usable by the non-specialists. The intended end-users were to be private homeowners in under-served communities, but the system is scalable and can be of benefit in other applications. The technical details are presented in the next section. Design details are provided in the Supplementary Materials, from where they can be freely downloaded and replicated.

2. Materials and Methods

2.1. System Development

Details of the system developed in this work are presented in Figure 1. At its core, the system consists of a quartz tube through which flows the water to be treated. Quartz is one of few materials that allow UV radiation in the germicidally-effective C-band to pass through largely unattenuated. In this system, the quartz was supplied by Heraeus (Suprasil 130), whose UV transmission, at wave-length of 254 nm, is rated at 92% of the incident radiation. The UV lamps are now located outside of the quartz tube, seen colored in violet in Figure 1a. Their number is determined by several factors that include the intensity of the emitted UV radiation, the volume of the quartz tube, the rate at which water flows through it, and its UV transmissivity. In this paper, we report the performance of a system that was designed to accommodate a flow rate Q of up to 0.2 L/s. The quartz tube was of length L = 400 mm and inner diameter D = 70 mm, giving a total volume V = 1.54 L. The residence time was thus approximately 8 s. The tests were predominantly performed with two low-pressure UV lamps rated at 30 W each, producing a theoretical lamp intensity of 1.5 W/cm^2. The actual radiation intensity at the axis of the quartz cylinder, where it is expected to be at its lowest value after being attenuated by the quartz walls and the water, was not measured. However, when dry, this was measured at 2.78 $\pm$ 0.127 mW/cm^2. Thus, assuming uniform intensity throughout the quartz tube, the UV dose delivered by each lamp was estimated to be 187 mJ/cm^2. Biodosimetry testing with the bacteriophage MS2 indicated the delivery of a UV dose of 215.6 mJ/cm^2 when both lamps were operated simultaneously. The difference between the theoretical and actual dose is thus quite small.

An important feature of this system is the manner in which water flows into and out of the quartz tube. This is arranged through a diffusor at the inlet (top right of Figure 1a), and a nozzle at the outlet (bottom left of Figure 1a). These are identical in shape and dimensions. Their purpose is to connect the system to an existing water supply pipe in such a way as to minimize the kinetic energy losses that inevitably arise when a flow accelerates or decelerates due to a change in the cross-sectional area. Built into the diffusor and the nozzle are static guide vanes. Their function, in the diffusor, is to impart swirl to the inlet flow, and in the nozzle, is to maintain the swirl which would otherwise decay with distance from the inlet. Two benefits arise from imparting a strong swirling motion to the flow. The first is the amplification of turbulent mixing, which arises from the increased shearing of the flow. This has the effect of ensuring that the pathogens that enter the quartz tube close to its axis do not remain there to eventually leave the tube not having received a sufficient UV dose for complete inactivation but are, instead, well mixed with the flow and are thus brought close to the surface where the UV intensity is at maximum. The second benefit is that, as will be shown in the next section, the presence

of swirl increases the magnitude of the shear stress at the quartz walls. This creates a mechanism for the operating system to be self-cleansing. In effect, the elevated shear stresses continually scrub the inner surface of the quartz tube to thus prevent the establishment of bio-film, or the accumulation of mineral residues.

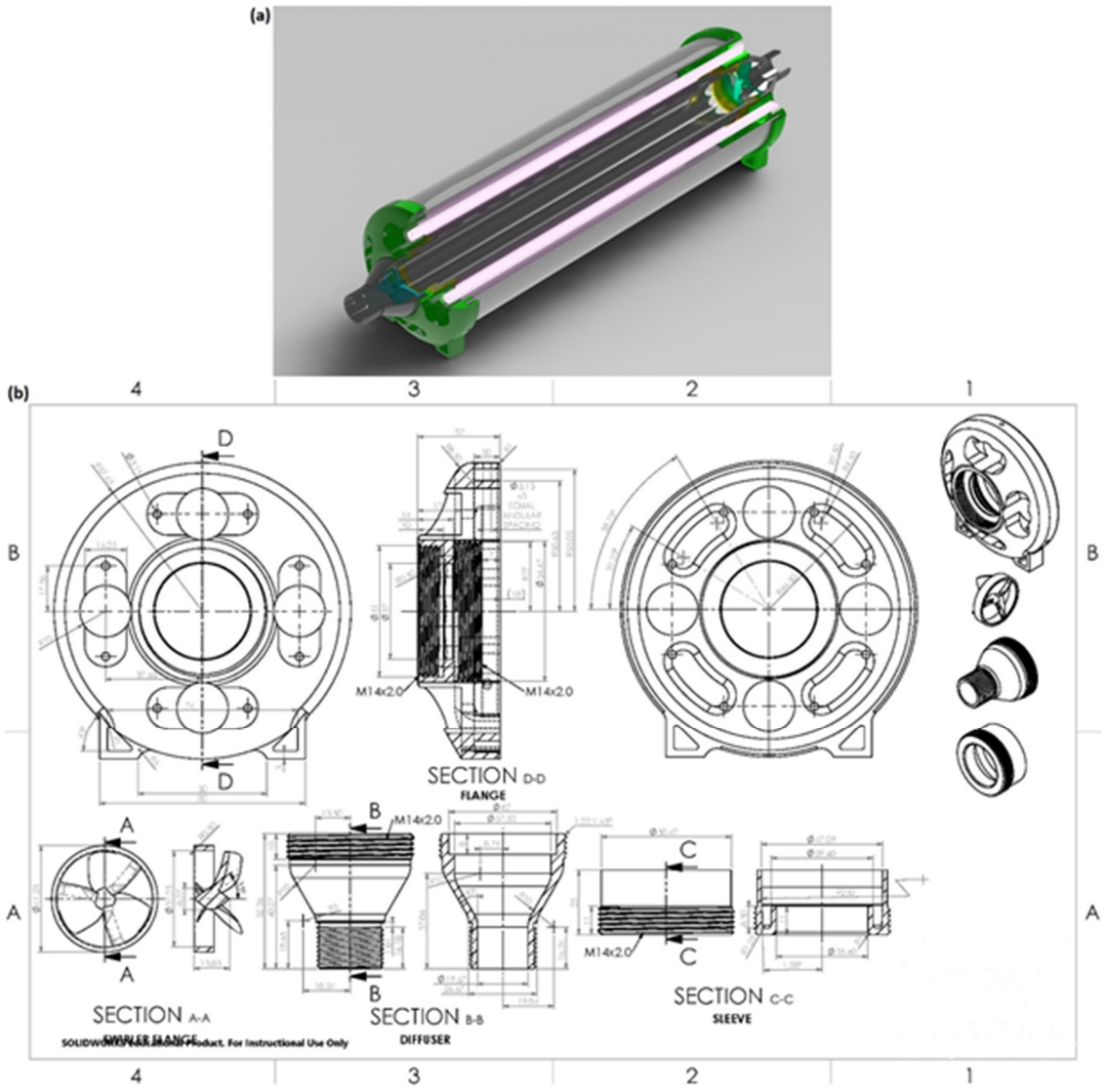

Figure 1. A rendered representation of the UV reactor (**a**) and the design details and dimensions of the various components (**b**).

The detailed design was performed digitally using SolidWorks, the engineering design software. The combined diffusor and the static guide vanes assembly was manufactured by three-dimensional (3D) printing. The printing was done using the Selective Laser Sintering (SLS) 3D technique. SLS is a type of 3D printing that is one of the most common rapid prototyping processes available commercially. It is significantly faster and more affordable than other alternative 3D printing methods, and can produce more complex geometries. The parts produced by this method are robust, of high strength, and resistant to UV radiation.

To complete the design of the inlet and outlet assemblies, each had a flange incorporated into it. Holes in these surfaces, also created by 3D printing, allowed for the UV lamps to be secured into position, parallel to the quartz tube, and at a set distance from its wall. Two circular grooves were created in the flanges: one that allowed the quartz tube to be held in place, and another that held the outer, protective shell in place.

2.2. Computer Modeling

In developing the entry diffusor and exit nozzle, computer simulations utilizing the Fluent software for Computational Fluid Dynamics (CFD) were performed to investigate the patterns of mixing due to the induced swirl. This was done in part to check whether all influent flow was brought sufficiently close to the quartz tube surface where the intensity of the UV radiation was at a maximum. Another objective of the computer simulations was to provide guidance on how to minimize the hydraulic energy losses that occur across the entire system.

Figure 2 shows the computational grid used for the simulations, as well as the coordinates system used. It consisted of 504,544 nodes that were non-uniformly distributed across the domain to resolve the regions of flow where the streamlines are most strongly curved. Uniform flow conditions were assumed at the inlet while, at the outlet, the flow in the exit pipe was assumed to be fully developed and hence gradients of all dependent values were set equal to zero. The effects of turbulence were accounted for by using the two-equation realizable k-ε model of turbulence. The flow close to the wall was assumed to obey the universal logarithmic law of the wall and this provided the boundary conditions for k and ε there (the "wall function" approach). The solution procedure was iterative and the criterion for convergence was set to the sum of absolute residuals for all dependent variables fell to below 10^{-4}, something that was achieved after about 1700 iterations. The simulations were performed using the finite volume methodology. Discretization of the equations governing the conservation of mass, momentum, and turbulence parameters was achieved by the second-order linear upwind scheme. The results of the computer simulations are presented in the next section.

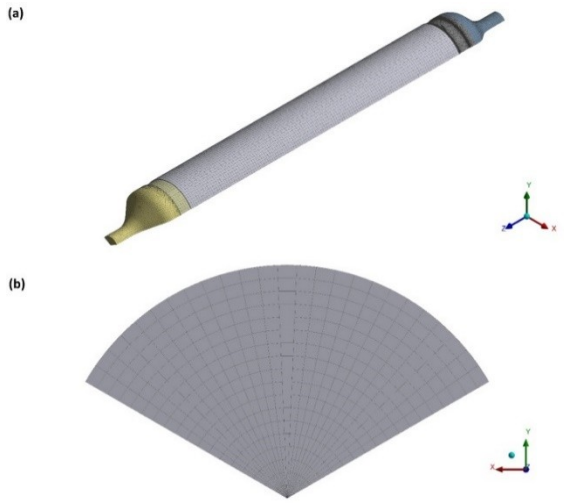

Figure 2. The computational grid used for the computer simulations. View along the side of the system showing the overall arrangement (**a**), and a cross-sectional view of the grid distribution in a sector (**b**).

2.3. UV System Setup

The system was run at 0.16 L/s with two low-pressure mercury UV-C lamps. The quartz tube was treated with a 10% solution of hydrochloric acid before installation to remove deposits on the surface. The UV system was run with water before testing to ensure that the quartz crystal cylinder was filled during operation. In addition, before any test dependent on UV light, the UV lights were first turned on for 5 min before the start of the test.

Initial water quality measurements were taken using a Myron L Company Ultrameter to determine the total dissolved solid (TDS), pH, oxidation reduction potential, and conductivity. UV absorbance (UVA) and UV transmittance (UVT) were assessed at a wavelength of 254 nm using a Cary Win UV-Vis spectrophotometer (Cary Win 1E, Varian Corp., Houston, TX, USA).

2.4. Microbial Propagation

The system was assessed in terms of the removal of *E. coli* and MS2 coliphage. The *E. coli* (ATCC #15597) was propagated with Luria Broth (LB) (Sigma-Aldrich) and a 0.4% inoculation. The solution was incubated at 37 °C for 12 h. The cells in the solution were then concentrated by centrifuging the samples for 20 min at 2500 rpm. The supernatant was then decanted and the pelleted cells were re-suspended in Milli-Q water at room temperature for use during testing so that the color of the LB media did not significantly alter the UVT of the sample water. *E. coli* concentration was determined using the membrane filtration (MF) technique according to standard methods (Method 9132) [11].

The MS2 coliphage (ATCC #15597-B1) was used to determine the UV dose supplied by the system, and its effectiveness at inactivating viral pathogens. A solution of the propagated virus and analysis of samples containing the virus were performed by Biovir Laboratories in Benicia, CA.

2.5. Germicidal Effectiveness

To assess the UV dose applied to the system, the system was spiked with MS2 and assessed at two different UVTs and flow rates. The source water for this testing was unchlorinated City of Davis groundwater at 20 ± 1.2 °C, pH 8.3 ± 0.15, and turbidity 3.8 NTU. The UVTs for this analysis were the original UVT of the groundwater at 95% and another adjusted to 70% using instant coffee (Pampa) per NWRI's UV guidance manual [12]. The UVT was assessed at a wavelength of 254 nm using a Cary Win UV-Vis spectrophotometer (Cary Win 1E, Varian Corp., Houston, TX) and the flow rate was determined using an in-line flow meter (Omega, FL46300 Series). The initial concentrations of MS2 in the source water for the testing were 1.2×10^8 pfu/mL and 3.0×10^8 pfu/mL for UVTs at 95% and 70%, respectively.

For each of the four flow rate and UVT combinations, three samples were collected before and after exposure to the UV radiation for MS2 testing (the MS2 was detected by the host bacterium *Escherichia coli* ATCC 15797). Samples were stored at 4 °C for less than 24 h before being processed at the Biovir Laboratories in Benicia, CA using the double agar over-lay without RNase method for enumeration [13].

2.6. Hydraulic Tracer Test

A tracer study was conducted to determine the hydraulic performance of the reactor. A solution of methyl green (Sigma-Aldrich) and Milli-Q water was used as a conservative tracer using the absorbance at 615 nm as the tracer monitor. Approximately 25 mL at 150 mg/L was spiked into the inlet upstream of the pump, and was thereafter monitored as it passed through the system. The reactor was operated using unchlorinated City of Davis groundwater at 20 ± 1.2 °C and pH 8.3 ± 0.15. A 100-mL sample was collected every 2 s and the system was operated at 0.16 L/s. The absorbance at 615 nm was measured using a UV/Vis spectrophotometer (Cary Win 1E, Varian Corp., Houston, TX, USA).

2.7. Analysis of Scaling

To assess how scaling develops in the system, synthetic water types were continuously circulated through the system for 60 h under several conditions, including three irradiation conditions (two lamps on/one lamp on/both lamps off) and two types of synthetic water. The constituent concentrations for the synthetic waters are shown in Table 1. These solutions were made in 20-L batches with Milli-Q and operated at room temperature, 20 ± 1.4 °C. The pH of the first trial was 7.1 ± 0.17 and the pH of the second trial was 10.55 ± 0.13. Each trial was performed in triplicate.

Table 1. Initial concentration of constituents in feed water.

Type	Constituent	Concentration (mg/L)
1	Iron, as ferric chloride (Sigma-Aldrich)	1.0
	Magnesium, as magnesium chloride (Sigma-Aldrich)	200
	Calcium, as calcium chloride (Sigma-Aldrich)	300
2	Calcium, as calcium chloride (Sigma-Aldrich)	300
	Carbonate, as sodium carbonate (Sigma-Aldrich)	100

All experiments were performed using continuous-flow and non-stop UV irradiation. For each trial, two 100-mL samples in amber glass bottles were collected. These samples were of the initial feed water and final water sample of treatment. Samples were stored at 4 °C for less than 48 h before being processed. Standard methods were followed after the samples were collected to assess the change in alkalinity [11].

A UV intensity meter was used to profile radiation intensity and temperature changes after the 60-hour treatments. Measurements of UV intensity were taken along the center, top, and bottom surface of the quartz cylinder. Visual inspection of the quartz was performed at 60-hour intervals to quantify changes of the inner surface with regards to color, fouling and scaling patterns, smoothness of surface, and session of irradiation with severe/medium/light fouling.

Analysis of how the fouling due to 60 h of operation with two lamps switched on has impacted the disinfection performance of the system was performed via introducing water spiked with *E. coli* to the system before and after the completion of the scaling test. The water for this test was Milli-Q operated at a pH of 7.1 ± 0.18 and a temperature of 20 ± 1.1 °C. Each trial was repeated in triplicate and samples were stored at 4 °C for less than 24 h before being processed.

2.8. Analysis of the Impact of Turbidity

To assess the impact of turbidity on the system, activated carbon at various concentrations was added to the system to generate the following levels of turbidity: 0.16 ± 0.05, 3.53 ± 0.85, 6.62 ± 1.51, 13.3 ± 1.67, and 17.83 ± 2.13 NTU. To ensure a small particle size, the activated carbon was first crushed, added to the Milli-Q water at a pH of 7 ± 0.16 and a temperature of 20 ± 1.4 °C, and then screened with a 20-µm cartridge filter before use. The solutions of activated carbon were also dosed with concentrated solutions of *E. coli*. The number of *E. coli* cells that were in the system before and after UV treatment were then assessed using the membrane filtration technique [12]. Each turbidity level was assessed three times and three samples were collected before and after the UV treatment for *E. coli* testing from each trial.

3. Results and Discussion

3.1. Computer Simulations

An overview of the flow generated within the system and, in particular, of the strong swirl generated by the guide vanes is presented in Figure 3. Shown there are the tracks of massless particles released at the inlet to the system (at top left) and then tracked as they were convected by the flow to the outlet (at bottom right). The particles follow a helical path under the combined effect of axial and tangential motions. The extent of swirl near the cylinder walls is quite pronounced, and hence acts as a self-cleansing mechanism preventing the fouling of the inner walls. The color scale gives the flow velocity in m/s.

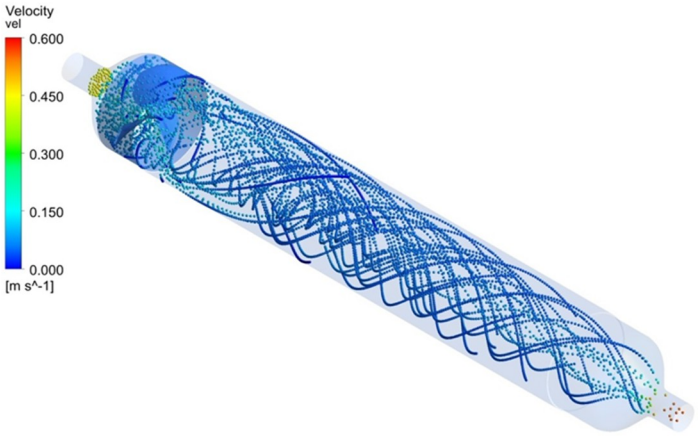

Figure 3. Computed tracks of massless particles released at the inlet to the UV system. The strong swirling motion responsible for enhanced mixing and wall cleansing is evident.

Figure 4a–d show the variation, in the direction of flow, of the centerline values of axial velocity, the static pressure, the turbulence kinetic energy, and the ratio of turbulent (eddy) to molecular viscosity. Plotted there are results obtained for three different angles characterizing the skewness of the guide vanes with respect to the flow direction. The predicted axial velocity shows an initial rise indicating that the flow in the entry pipe develops from the assumed uniform inlet conditions. Once the diffusor section is encountered, the velocity drops in response to the increase in the cross-sectional area while the pressure rises, creating conditions for flow reversal due to adverse pressure gradients. Figure 4a indicates that a small region of recirculating flow was indeed generated for the case of the 75° guide vanes. Downstream of the diffusor, the flow recovers as it develops in the constant area tube, only to accelerate when the outlet nozzle is reached. There, the velocity increases fairly rapidly in response to the reducing area, while the pressure drops to a value below that at the inlet. The difference in pressure between the inlet and outlet represents the total pressure drop in the reactor—a measure of the hydraulic losses. Our aim in these studies was to minimize this quantity to the greatest extent possible while ensuring that turbulent mixing is enhanced. The ratio of turbulent to molecular viscosity is a good indicator of the extent of turbulent mixing in the flow. In our predictions, this ratio initially drops from the high value that was assumed at the inlet where the rate of turbulence generation was negligibly small due to the assumption of uniform flow, only to rise downstream of the guide vanes due to flow development and the imposition of swirl. At the outlet, turbulence mixing is reduced due to flow acceleration; this is manifested in a drop in the eddy viscosity ratio there.

The computed contours of axial velocity, static pressure, turbulence kinetic energy, and the eddy viscosity ratio are shown in Figure 5a–d. These contours, which are presented at a cross-section located at $x/L = 0.25$ from the inlet, show the effects of swirl on the main features of the flow. Of particular interest are the plots of the eddy viscosity ratio. Very close to the cylinder walls, this ratio is of the order of 10, signifying that the mixing due to turbulence is one order of magnitude greater than its laminar counterpart. Further from the walls, this ratio significantly increases due to the enhancing effects of swirl. Initially, this increase is confined to the regions behind the guide vanes where the swirling motion is at its most intense. Further downstream (not shown), the regions of high eddy viscosity ratio expand to fill the entire cross-section.

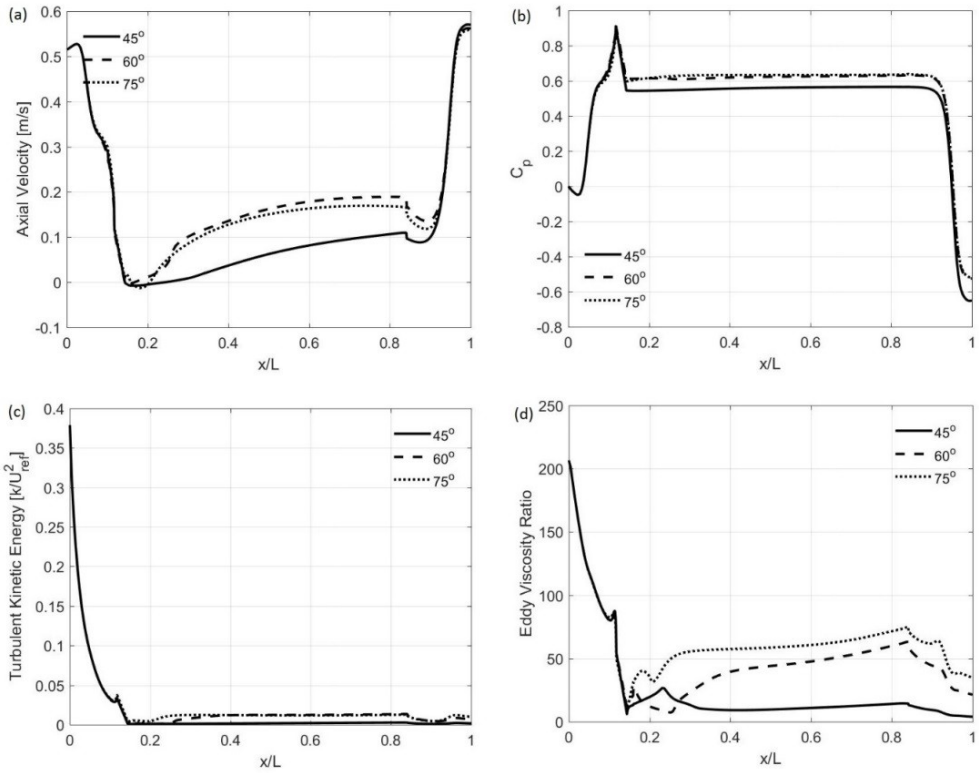

Figure 4. Predicted variation along the reactor centerline of the mean axial mean velocity (**a**), the pressure coefficient (**b**), the turbulence kinetic energy (**c**), and the eddy-viscosity ratio (**d**). Results are plotted for three different values of blade pitch.

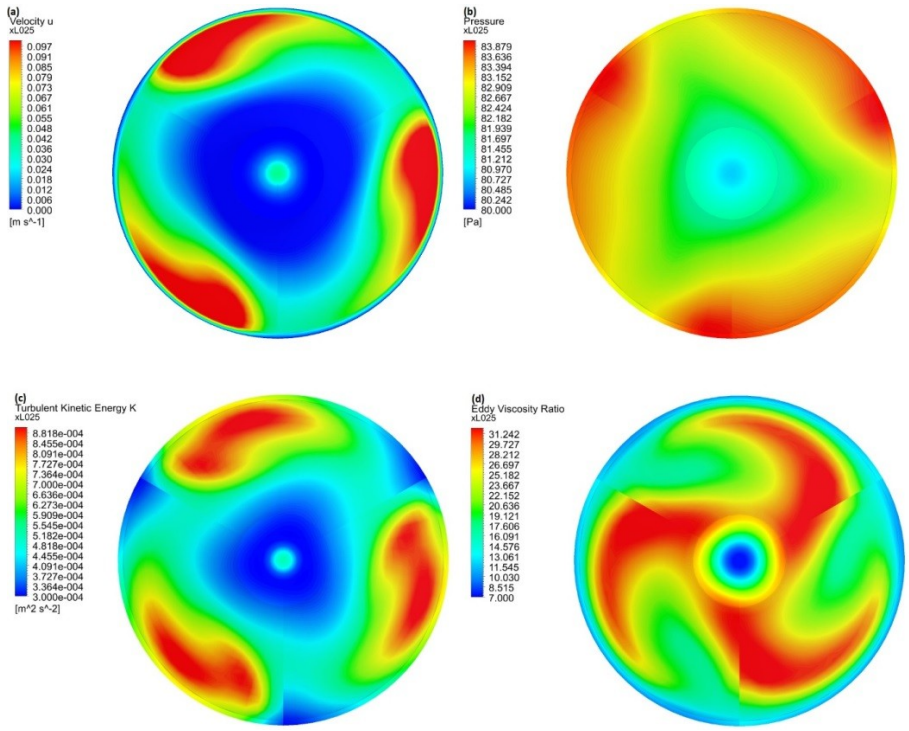

Figure 5. Predicted cross-sectional contours of the mean axial velocity (**a**), the static pressure (**b**), the turbulent kinetic energy (**c**), and the ratio of turbulent to molecular viscosity (**d**). The enhanced levels of turbulence kinetic energy and thus of turbulent mixing due to swirl are evident.

3.2. Hydraulic Tracer Results

A hydraulic tracer test was conducted to estimate the residence time in the system. Knowledge of this parameter yields a reasonable estimation of the overall hydraulic efficiency: too short a time would imply that an insufficient UV dose is being delivered, while too long a value would imply an oversized volume, or a low flow rate. In this test, a tracer, methyl green (with an initial concentration of 0.02 mg/L), was introduced at the inlet to the system and its concentration was measured at the exit. The outcome is shown in Figure 6. Using this data, the hydraulic residence time was calculated to be 1.6 s, which is slightly lower than expected [5]. By this method, the system efficiency was estimated to be 73% (see Table 2) which is quite encouraging considering that the actual velocity profile was significantly different from the plug-flow profile assumed in this analysis.

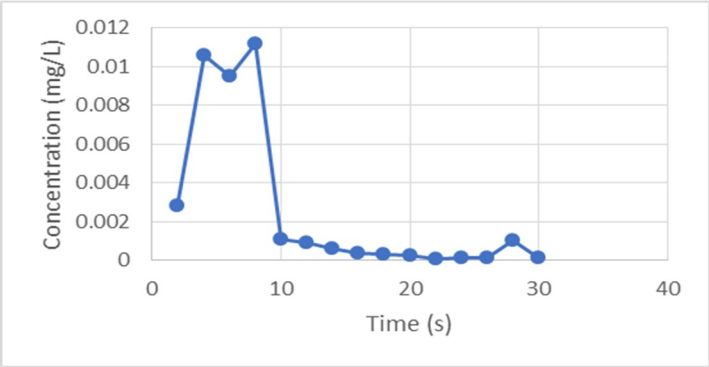

Figure 6. Measured concentration of methyl green tracer at the outlet from the reactor used to determine the hydraulic residence time.

Table 2. Hydraulic tracer test results.

Parameter	Value
Hydraulic Residence Time (s)	1.6
Variance (s2)	0.86
Standard Deviation (s)	0.93
t10 (s)	2.3
t50 (s)	7.3
t90 (s)	13.6
Morrill Dispersion Index	1.4
Volumetric Efficiency (%)	73%

3.3. Germicidal Effectiveness

The UV dose delivered by a system (mJ/cm^2) can be obtained as the sum of the product of the UV intensity and the exposure time. In practice, this is not easily done due to departure from plug-flow conditions and non-uniform intensity distributions. Instead, the UV dose is estimated using biodosimetry. Biodosimetry uses a known response pattern that an organism has to a specified level of radiation (typically generated using a collimated beam) and correlates it to the response pattern seen in the system. Thus, the dose assigned to a UV system after validation testing is really a "reduction equivalent dose" or the UV dose found in the collimated beam for the equivalent amount of microbial inactivation achieved in the system [12]. The dose-response curve was generated with the collimated beam, using UC Davis industrial water as the substrate and MS2 coliphage as the microbial organism. The analyses were performed by BioVir Laboratories Inc., who reported that the dose response data can be fitted by the straight line (R^2 = 0.979):

$$L = 0.26 + 0.0297\ D \quad (1)$$

where L is the MS2 $\log_{10}$ reduction and D is the UV dose (mJ/cm^2).

By evaluating the actual $\log_{10}$ removal of MS2 from the measurement of its concentration in the influent and effluent streams, and by assuming that the dose response curve given by Equation (1) remains linear, it becomes possible to estimate the UV dose delivered by our system at various flow rates and UVT values. The results are shown in Table 3. The UV dose of 215.6 mJ/cm^2 delivered at a flow rate of 0.16 L/s and a UVT of 95% is sufficient to inactivate most pathogenic bacteria, protozoa, fungi, and viruses of common concern. Moreover, given that the delivered UV dose exceeds twice the NSF standard, the system may be operated using only one of the two lamps.

Table 3. UV dose for the system at various flow rates and UV transmittance (UVT) values.

Flow (L/s)	UVT (%)	$\log_{10}$ Influent MS2 Conc.	$\log_{10}$ Effluent MS2 Conc.	$\log_{10}$ Removal of MS2	UV Dose (mJ/cm^2)
0.16	95	8.18 ± 0.10	1.60 ± 0.12	7.12 ± 0.93	215.6 *
0.16	70	8.60 ± 0.05	5.59 ± 0.09	3.01 ± 0.09	93.9
0.22	95	8.18 ± 0.10	2.72 ± 0.08	5.46 ± 0.08	173.3 *
0.22	70	8.60 ± 0.05	6.38 ± 0.13	2.22 ± 0.13	64.5

* Assuming the linearity of the dose response curve.

3.4. Analysis of Scaling

Fouling of the inside of the system impairs the penetration of the UV radiation and reduces the UV dose applied to the water. Fouling can occur due to a number of mechanisms that include scaling, chemical reaction, corrosion, and bio-film fouling [14,15]. In this work, we focus on scaling due to its frequent occurrence in UV systems. Scaling (sometimes called precipitation or crystallization fouling) is the process by which inverse volubility salts in water, such as $CaCO_3$, $CaSO_4$, and $Ca_3(PO_4)_2$, precipitate onto surfaces. The mechanisms by which UV radiation promotes scaling are not well understood but are thought to involve ferric hydroxide precipitation ($Fe(OH)_3$) and calcium organic species releasing calcium followed by the precipitation of iron, magnesium, and calcium carbonate, all of which have been found to be the primary contributors to the scaling of UV systems [16]. The thermal output of the UV lamps can accelerate this process, while the hydrodynamics of the flow within the system can either aid or inhibit it. Thus, for example, the flow velocity influences scaling by modifying the diffusional and removal rates of constituents in the water, and by altering the quality of the scale formed. Scale formed at low velocities (<0.3 m/s) tends to be more porous and less tenacious than scale formed at higher velocities (>0.5 m/s) [17]. Moreover, the patterns of flow within the system influence the scaling process via the induced wall shear stresses. In the present system, these stresses are significantly magnified by the presence of the strong vortex generated by the guide vanes; hence, it is reasonable to expect that the formation of scale will be inhibited. The outcome of tests on scaling can be seen in Table 4. The results there are from continuous testing with hard water containing calcium, iron, and magnesium. They show the change in alkalinity and reduction in UV transmittance for the case when the system was filled with stationary water, and when water was pumped through at a rate of 0.16 L/s corresponding to a velocity of 2 cm/s. This velocity is lower than the 10 cm/s threshold suggested by Lin et al. [18,19] for the point above which thermal output of the UV lamps has a minimal impact on UV fouling. This suggests that the presence of swirl and consequent increase in wall shear stress has limited the thermal impact of the UV lamps, and of the sedimentation of suspended particulates.

To help isolate the impact of velocity on the system, a second test was performed with feed water containing just calcium and carbonate. This showed that while the finite velocity decreased scaling when the UV lamps were off, the reduction in transmittance went from 63% to 12%. However, with the lamps on, less scaling was formed when there was no flow than with a flow rate of 0.16. This indicates that for this scenario, temperature is not a main contributor to the formation of scale in the system and

another mechanism, such as sedimentation, governs scaling in the system. Scaling was also dominated by precipitation on the bottom of the quartz rather than on the sides opposite the lamps, suggesting that particulate fouling, where the scaling salts are developed in solution and then attach onto the heat transfer surface, is the dominate form of scaling in the system. This is beneficial, since when scaling does not mainly form on the sides of the reactor, less UV radiation is inhibited, thereby preserving the UV dose applied to the system for a longer time period and lengthening the periods between which the system needs to be serviced.

Table 4. Reduction in transmittance and change in alkalinity due to hard water over 96 h operating at an initial UV dose greater than 120 mJ/cm^2 and a UVT of 98%.

Water Type	Number of Lamps	Flow Rate (L/s)	Transmittance Reduction (%)	Change in Alkalinity (%)
Feed (Ca+Fe +Mg)	1	0	22	53
	2	0.16	10	67
Feed ($CaCl_2$+Na_2CO_3)	0	0	63	49
	0	0.16	12	18
	2	0	34	30
	2	0.16	43%	22%

Table 5 shows that the disinfection capability of the system is not significantly impacted by the accumulation of scale. The $\log_{10}$ removal of *E. coli* was not diminished after the system was run for 96 h with hard water, with both lamps on and at a flow rate of 0.16 L/s.

Table 5. Change in $\log_{10}$ removal after 96 h, with two lamps on, a 0.16 L/s flow rate, and $CaCl_2$ and Na_2CO_3 feed water.

Sample	$\log_{10}$ Influent *E. coli* Conc.	$\log_{10}$ Effluent *E. coli* Conc.	$\log_{10}$ Removal of *E. coli*
Pre-fouling	7.32 ± 0.04	0.35 ± 0.28	6.9 ± 0.50
Post-fouling	6.97 ± 0.58	-0.11 ± 0.34	6.9 ± 0.58

3.5. Impact of Turbidity

Turbidity is a measurement of the number of suspended particles in a water sample. It is an important parameter to quantify, because these particles can embed pathogenic microorganisms and act as a shield for free-floating microorganisms, thereby preventing these organisms from being exposed to the UV radiation [12]. Understanding how turbidity impacts the system informs the user on what type of upstream filtration is needed for the system and serves as a guide for suitable water types for the system to treat. As shown in Table 6, the disinfection capacity of the system was not significantly impacted when tested with water containing turbidity levels from 0 to 18 NTU, and the disinfection of *E. coli* in all scenarios remained above 5 $\log_{10}$ removal. The absence of an impact of turbidity suggests that this system would be suitable for operation with upstream filters that have a nominal opening of 20 µm, the size used to screen particles for this analysis. Similarly, the UV system would also be suitable to be operated with waters that contain higher turbidities, such as surface water, sandy groundwater wells, or recycled water.

Table 6. Impact of turbidity on disinfection performance.

Turbidity (NTU)	Log_{10} Influent *E. coli* Conc.	Log_{10} Effluent *E. coli* Conc.	Log_{10} Removal of *E. coli*
0.16 ± 0.03	7.17 ± 0.12	1.45 ± 0.17	5.5 ± 0.3
3.53 ± 0.11	7.02 ± 0.16	1.55 ± 1.16	5.1 ± 1.0
6.62 ± 0.21	7.15 ± 0.12	1.24 ± 0.86	5.6 ± 1.0
13.30 ± 0.53	6.91 ± 0.42	0.35 ± 0.49	6.8 ± 0.9
17.83 ± 0.32	6.93 ± 0.06	1.80 ± 0.21	5.1 ± 0.2

4. Conclusions

Our aim in performing the research reported here was to develop a system for water disinfection with UV radiation that is not prone to the problem of lamp fouling while being effective for use in water with high turbidity levels and low UVT. The proposed design achieves these aims by locating the UV tubes outside the water-conveying quartz tube, and by imparting a strong swirling motion to the inlet flow that ensures uniform exposure to UV radiation and provides a self-cleansing mechanism that prevents the accumulation of bio-film and residues on the inside of the quartz. Future research will focus on the adaptation of the UV system for use in conjunction with an oxidant to form an Advanced Oxidation Process (AOP) [20]. The aim will be to reduce the chemical contaminants and the toxicity from highly-polluted waters conveyed at low to moderate flow rates. In particular, we plan to devise a method to collect the ozone which is naturally generated by the operation of the UV lamps in air, and inject that into the influent stream to provide the hydroxyl radicals needed for the AOP. We envision that introducing ozone into the influent stream can be done using a Venturi nozzle, wherein the water is accelerated to the extent that the resulting reduction in static pressure will be sufficient to draw in the ozone without the need for a complex mechanical apparatus.

Supplementary Materials: The following are available online at http://www.mdpi.com/2073-4441/10/9/1275/s1.

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References

1. Berndt, E.C.; Creighton, H.M. Method for irradiating substances with active rays. US Patent 2072417A, 2 March 1934.
2. Bolton, J.R.; Linden, K.G. Standardization of methods for fluence (UV dose) determination in bench-scale UV experiments. *J. Environ. Eng.* **2003**, *129*, 209–215. [CrossRef]
3. Gates, F.L. A study of the bactericidal action of ultra violet light: III. The absorption of ultra violet light by bacteria. *J. Gen. Physiol.* **1930**, *14*, 31–42. [CrossRef] [PubMed]
4. Linden, K.G.; Shin, G.; Sobsey, M.D. Comparative effectiveness of UV wavelengths for the inactivation of Cryptosporidium parvum oocysts in water. *Water Sci. Technol.* **2001**, *43*, 171–174. [CrossRef] [PubMed]
5. Tchobanoglous, G.; Stensel, H.; Tsuchihashi, R.; Burton, F.; Abu-Orf, M.; Bowden, G.; Pfrang, W. *Wastewater Engineering: Treatment and Resource Recovery*, 5th ed.; Metcalf & Eddy I AECOM; McGraw-Hill Book Company: New York, NY, USA, 2014.
6. Oliver, M. Validation of Cleaning Methods for UV Disinfection Systems. *Proc. Water Environ. Federation* **2002**, *1*, 564–579. [CrossRef]

7. Sultan, T. Numerical study of the effects of lamp configuration and reactor wall roughness in an open channel water disinfection UV reactor. *Chemosphere* **2016**, *155*, 170–179. [CrossRef] [PubMed]
8. Wols, B.A.; Hofman, J.A.M.H.; Beerendonk, E.F.; Uijttewaal, W.S.J.; Van Dijk, J.C. A systematic approach for the design of UV reactors using computational fluid dynamics. *AIChE J.* **2011**, *57*, 193–207. [CrossRef]
9. Li, W.; Li, M.; Bolton, J.R.; Qiang, Z. Configuration optimization of UV reactors for water disinfection with computational fluid dynamics: Feasibility of using particle minimum UV dose as a performance indicator. *Chem. Eng. J.* **2016**, *306*, 1–8. [CrossRef]
10. Brownell, S.A.; Chakrabarti, A.R.; Kaser, F.M.; Connelly, L.G.; Peletz, R.L.; Reygadas, F.; Lang, M.J.; Kammen, D.M.; Nelson, K.L. Assessment of a low-cost, point-of-use, ultraviolet water disinfection technology. *J. Water Health* **2008**, *6*, 53–65. [CrossRef] [PubMed]
11. APHA. *Standard Methods for the Examination of Water and Wastewater*; Rice, E.W., Baird, R.B., Eaton, A.D., Clesceri, L.S., Eds.; American Public Health Association: Washington, DC, USA, 2012.
12. NWRI. *Ultraviolet Disinfection Guidelines for Drinking Water and Water Reuse*, 3rd ed.; National Water Research Institute: Fountain Valley, CA, USA, 2012.
13. Adams, M.H. *Bacteriophages*; Interscience Publishers: New York, NY, USA, 1959.
14. Taborek, J.; Aoki, T.; Ritter, R.; Palen, J.; Knudsen, J. Fouling: the major unresolved problem in heat transfer. *Chem. Eng. Prog.* **1972**, *68*, 69–78.
15. Hasson, D.; Bramson, D. Effectiveness of magnetic water treatment in suppressing calcium carbonate scale deposition. *Ind. Eng. Chem. Process Design Dev.* **1985**, *24*, 588–592. [CrossRef]
16. Nessim, Y.; Gehr, R. Fouling Mechanisms in a Laboratory-Scale UV Disinfection System. *Water Environ. Res.* **2006**, *78*, 2311–2323. [CrossRef] [PubMed]
17. Sheikholeslami, R.; Watkinson, A. Scaling of plain and externally finned heat exchanger tubes. *J. Heat Trans.* **1986**, *108*, 147–152. [CrossRef]
18. Lin, L.-S.; Johnston, C.T.; Blatchley, E.R. Inorganic fouling at quartz: water interfaces in ultraviolet photoreactors: I. Chemical characterization. *Water Res.* **1999**, *33*, 3321–3329. [CrossRef]
19. Lin, L.-S.; Johnston, C.T.; Blatchley, E.R. Inorganic fouling at quartz: water interfaces in ultraviolet photoreactors—II. Temporal and spatial distributions. *Water Res.* **1999**, *33*, 3330–3338. [CrossRef]
20. Glaze, W.; Kang, J.-W.; Chapin, D.H. The Chemistry of water treatment processes involving ozone, hydrogen peroxide and ultraviolet radiation. *Ozone Sci. Eng.* **1987**, *9*, 335–352. [CrossRef]

Control of algal blooms using a novel UV water disinfection system

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Control of algal blooms using a novel UV water disinfection system

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Abstract

Algal blooms and bacterial growth are a considerable problem in many natural waterways leading to degradation of the local ecosystem. Several methods have been proposed to mitigate and prevent these blooms including the use of ultraviolet (UV) radiation. However, existing commercial UV systems have generally proved unsuited for use in waters with heavy algae content due to their vulnerability to the problem of lamp fouling. This paper introduces a novel UV system in which this problem does not arise. The research reported herein consisted of laboratory tests for proof of concept with the dual purposes of assessing the performance of the new system in water that is severely impaired by the presence of algae, and for determination of the minimum UV dose required for effective algae control. Significant reductions in turbidity and in chlorophyll were obtained with no evidence of lamp fouling.

Keywords: Algal bloom; Constructed waterway; UV inactivation; Lamp fouling

1. Introduction

Algal blooms and bacterial growth are a considerable problem in many natural and constructed waterways. One such waterway has provided the motivation of the present study: it is a 1.7-mile constructed waterway, located south of the Arboretum of the University of California campus in Davis, California. Frequently in past summers, and especially over five consecutive summers (2012-2017), this waterway has been eutrophic (UCD, 2016). Eutrophication is the excessive accumulation of nutrients in a waterway leading to a bloom of algae and bacteria. This impairment has severely impacted the local ecosystem and the aesthetics of the campus, and diminished the usability of this living classroom (Dodds et al., 2009).

Several methods have been developed to control or prevent algae blooms in small waterways. Some of these methods aim to alter elements within the system, such as diverting nutrient rich water that promotes algal and bacterial growth, or mixing water free of algal species into the system (Grover et al., 2017; Qin et al., 2015). Other methods target the organisms directly for example by utilizing ultrasonic radiation to lyse the cells, or by flocculation and precipitation of cells to alter the cellular structure of algal and bacterial species (Dai et al., 2015; Lee et al., 2001). The method used in this study is exposure to UV radiation which has been shown to achieve reductions in algal biomass by more than 80% (Barrado-Moreno et al., 2017). UV radiation in the UV-C range (with wavelength of around 254 nm) treats water by altering the DNA and RNA in the cells of microorganisms thereby preventing their replication. This technique is commonly used to control viral and bacterial populations in discharges from

wastewater treatment plants (Metcalf & Eddy, et al., 2014). To date, its use in controlling algae growth in large waterways has been very limited due, in part, to certain features that are inherent to the design of commercially-available UV systems. In such systems, the algae-impaired water is introduced into a vessel (an open channel or a closed pipe) where it is exposed to the UV radiation. The sources of this radiation are UV lamps that are themselves located inside the vessel. With time, these lamps become covered with mineral residue and bio-film that significantly reduce the intensity of radiation – the 'lamp fouling' problem. The presence of algae in the water accelerates this process as it is found to adhere more rapidly to the lamps thereby providing an anchoring mechanism for the accumulation of other matter. The overall result is the frequent disruption of operations due to the need to shut-down the system for the purpose of cleaning the lamps. This paper reports on results obtained with a novel UV system in which the lamp fouling problem does not arise. The objectives of the study were to assess the performance of this system in water with heavy algal content, and to determine the UV dose necessary to inhibit the replication of the algal cells. In this regard, the outcome of this study serves as proof of concept of the novel design, and an essential prerequisite to pilot-plant scale studies to evaluate the utility and effectiveness of the design under small lake conditions.

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2. Materials and methods

The UV system under consideration, shown in isometric view in Figure 1 (a), was developed at the University of California – Davis (Younis et al., 2018). It consists of a quartz tube through which the untreated water flows. Quartz is one of very few materials that allow UV radiation in the germicidal UV-C band (around 254 nm) to pass through with little attenuation. Outside this quartz tube, a number of UV lamps are installed which, when operated, serve to irradiate the water without coming into contact with it. Thus the lamp fouling problem does not arise. To prevent the fouling of the inside of the quartz tube, the flow at inlet is imparted with a strong swirling motion produced by stationary guide vanes. This swirling motion increases the wall shear stress levels inside the quartz thereby providing a mechanism for self-cleansing. The swirling motion also ensures that all contaminants that enter with the water are uniformly exposed to the radiated light. The inlet and outlet are designed in the form of a diffuser and nozzle, respectively. Their geometries were optimized to keep the hydraulic losses to a minimum. The inlet and outlet assemblies, the guide vanes, and the flanges that hold the UV lamps and the quartz tube in place were all manufactured using 3D printing. The quartz tube and UV lamps are enclosed inside an outer shell to prevent damage to the users. The inner wall of this shell is lined with aluminum foil which is very effective in reflecting the incident light back into the quartz tube. In designing this system, extensive use was made of Computational Fluid Dynamics (CFD) to simulate the behavior of the resulting turbulent swirling flow inside the quartz tube to ensure uniform exposure of all contaminants to the UV light. Sample results are presented in Figure 1 (b) which shows the simulated patterns of the resulting flow as visualized by the tracking of massless particles released at entry to the system. Further details of the system design and the CFD results can be found in Younis et al. (2018).

Biodosimetry testing with the bacteriophage MS2 indicated that with one 30 W low-pressure Hg UV tube, the supplied UV dose was 215 mJ/cm^2 when the UV transmissivity (UVT) of the water at 254 nm was 95%. This produced a 7.12 $\log_{10}$ reduction in MS2. At UVT of 75%, the supplied UV dose was 94 mJ/cm^2. A dose of 215 mJ/cm^2 is about five times greater than that required to meet minimum standard for drinking water (e.g. NSF 55).

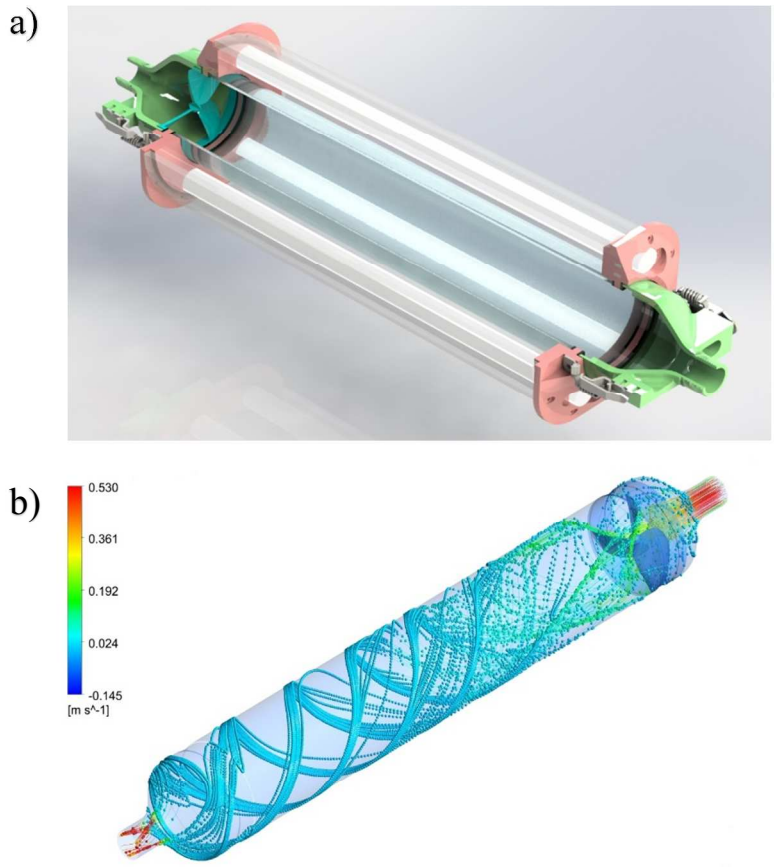

Figure 1. *Isometric view (a) and particle tracking through the UV system (b).*

In performing the current tests, the system was operated in continuous recycle loop in 190 liter barrel (50 gallons) at 9.5 liters/minute (2.5 gallons per minute) over a period of two weeks. As controls, the study also tracked water quality from a 190-liter tank recirculating water without UV treatment, and a 190-liter tank with no recirculation and no treatment. The water from the system was 50% tap water, 40% Arboretum water, 9.5% water from an algae-impacted local lake, and 0.5% concentrated suspension of *Chlorella sp*. ATCC #50258. For the intermittent operation study, three 190-liter tanks were used to compare 100% Arboretum water treated with the following conditions: a single pass through the system, two passes through the system and no treatment.

To assess water quality and performance each of the studies tracked the following parameters: pH, oxidation reduction potential (ORP), conductivity, total dissolved solids (TDS), temperature, dissolved oxygen (DO), UV absorbance (UVA), turbidity, chlorophyll a concentration (Chl a), total nitrogen (TN) and total phosphorus (TP). Water samples were taken 8 cm below the free surface and 15 cm above to the bottom of the tank (hypolimnion). The tanks were 1.07 m tall.

As shown in Table 1, the pH ORP, TDS, Conductivity, Temperature, and pH were measured at the sampling location with the Myron L Company Ultrameter III and followed the method described in APHA (2012) standard methods in conjunction with the instrument manufacturer's instructions (APHA, 2012). Similarly, DO was measured onsite with YSI 55 Dissolved Oxygen Meter and followed the method described in APHA (2012) in conjunction with the instrument manufacturer's instructions. The turbidity and the UVA were assessed in the lab using the Hach 2100AN Turbidimeter and the Cary 1E UVvisible Spectrophotometer, respectively, and followed the method in APHA (2012) in conjunction with the instrument manufacturer's instructions. The determination of the Chl a concentration followed the APHA (2012) method without modification. Sampling was performed in duplicate as a quality assurance measure. The measurement of TN and TP used Lachat Instruments QuikChem FIA+: 8000 Series in conjunction with Lachat methods 10-107-04-4-A and 10-107-04-4-B, respectively. Similarly, sampling was for TP and TN performed in duplicate as a quality assurance measure.

To assess water quality and performance the study tracked: pH, oxidation reduction potential (ORP), conductivity, total dissolved solids (TDS), temperature, dissolved oxygen (DO), UV absorbance (UVA), turbidity, chlorophyll a concentration (Chl a), total nitrogen (TN) and total phosphorus (TP). Water samples were taken 2 inches below the water surface and 75% to the bottom of the water body.

3. Results and discussion

3.1 Proof of Concept

Our objective here was to check the performance of the system with regards to its ability to treat algae-impacted water without being affected by fouling. The tests were performed on identical amounts of water samples placed in three barrels: one received no treatment, one was continuously recirculated using the pump but with no UV, and one was also continuously recirculated but with the UV lamp turned on. The no treatment scenario served at the negative control for the system and is the baseline against which the UV system was assessed. The barrel that had recirculation with just the pump served as a control that served to isolate the impact of the mechanical disruption arising from the passage of the water through the pump.

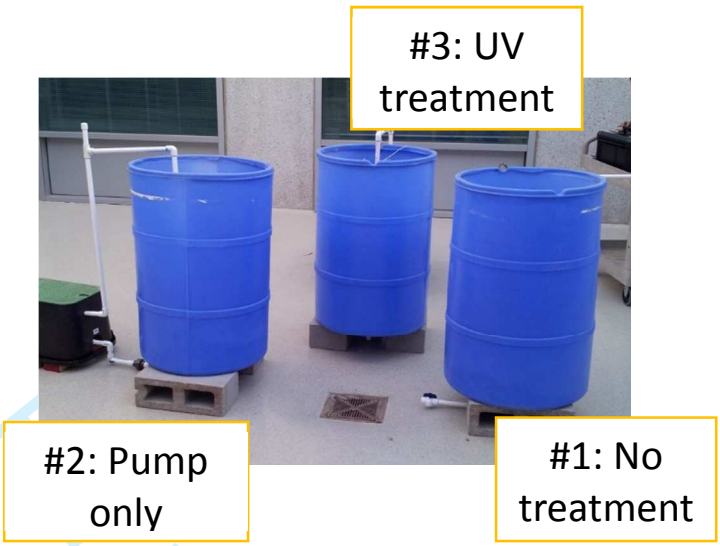

***Figure 2**. Experimental treatment and number for each basin.*

As shown in Figure 3, pH, UVA, turbidity, and average Chl a concentration increased over the two-week test period for all treatment conditions except for the barrels that received UV treatment. This exception is seen in more detail when looking at each graph. Clear peaks in average Chl a concentration and turbidity, Figure 3b and Figure 3d, indicate an algal bloom occurred in barrel that received no treatment. While no bloom occurred in the recirculation only barrel, the recirculation barrel showed a similar increase in pH and UVA. Algae increase the surrounding water's pH when they photosynthesize, and their presence also increase the UVA, an indication of the concentration of dissolved organics in the water. Therefore, while the recirculation barrel prevented the algal bloom, the water quality in the system still diminished (Figure 3a and Figure 3c). The barrel containing the water that received the UV treatment was the only one in which the algal bloom was totally inhibited. It was also the one in which the water quality parameters were closest to the initial values. Inspection of the inside of the quartz tube showed that, after two weeks of continuous operation, the problem of fouling did not occur.

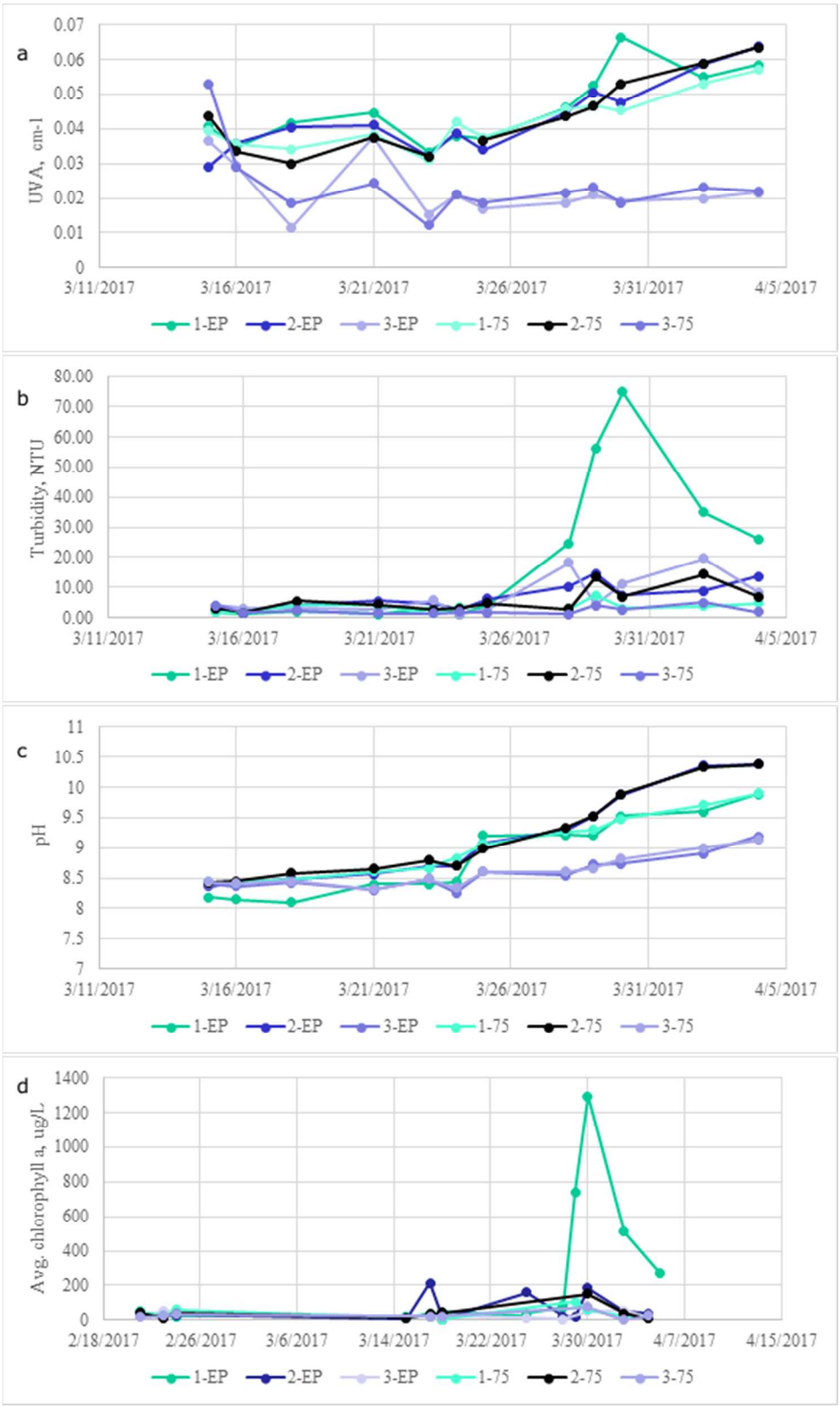

Figure 3. *Change in UVA (a), turbidity (b), pH (c), and avg chlorophyll a concentration (d) over time. The number refers to the treatment barrel, EP refers to sampling at the water surface, and 75 refers to sampling at 75% to the bottom of the barrel.*

3.2 Establishing the minimum required treatment level

Sampling was performed at the beginning of this study and after two weeks of treatment. The two-week timeline was established from the proof of concept stage of this study as the time needed to achieve an algal bloom. The results are presented in Table 1. The number of passes there represents the number of times that the entire contents of a barrel have passed through the pump. From this analysis, the study determined that two passes through the system are needed to prevent and algal bloom. Two passes resulted in a 92% decrease in turbidity and a 22% decrease in Chl a. While in the one pass and no treatment scenarios, a bloom resulting in a 356% and 34% increase in turbidity and 808% and 858% increase in Chl a.

***Table 1**: Change in water quality parameters after two weeks after zero, one, or two passes through the treatment system.*

Parameter	Initial Quality (4/21/2017)	2 Pass (5/5/2017)	1 Pass (5/5/2017)	No Pass (5/5/2017)
pH	9.15 ±0.03	9.71±0.61	10.02±0.61	9.17±0.01
Cond, μS	625.2±11.96	693.25±88.6	818.8±531.96	679.7±73.68
TDS, ppm	430.3±5.30	475.9±55.30	563.7±70.64	466.05±45.89
ORP, mV	115.7±5.69	100.5±17.68	104±24.04	109±1.41
Temp, C	26.2±0.17	28.3±7.35	32.5±6.79	27.55±7.00
UVA, cm-1	0.084±0.003	0.128±0.001	0.175±0.001	0.132±0.002
Turbidity, NTU	14.15±3.65	12.15±15.49	64.5±29.42	20.8±2.55
DO, mg/L	12.42±2.39	13.22±0.057	11.54±0.50	10.78±1.56
Total N, mg-N/L	7.05±0.11	6.46±0.064	6.335±0.054	6.89±0.059
Total P, mg-P/L	0.85±0.026	0.95±0.006	0.81±0.014	0.95±0.021
Chl a, μg/L	39.7±4.67	61.72±8.16	498.39±345.88	529.69±476.59

To confirm that the results from each of the trials were different, a two-sided t-test was performed on the Chl a testing results. A shown in Table 2 and Table 3, there is a 90.17% of confidence that the no pass and 2 pass results are from separate populations and a 84.62% of confidence that the 1 pass and 2 pass results are from separate populations.

***Table 2:** Chlorophyll a Confidence Intervals*

Sample	No. of Samples	Average, μg/L	Standard Dev. μg/L	95% CI, μg/L
2 Pass	2	61.716	8.16	62±11
1 Pass	4	498.39	345.88	498±340
No Pass	4	529.692	476.59	529±470

***Table 3:** Confidence level that the two populations are different.*

	No Pass and 2 Pass	1 Pass and 2 Pass
T-Score	1.68	1.31
Degrees of Freedom	4	4
% Confidence	90.17%	84.62%

This difference in water quality can also be seen in Figure 4. The apparent water clarity after two weeks in the system that received two passes remains clear and free of suspended matter.

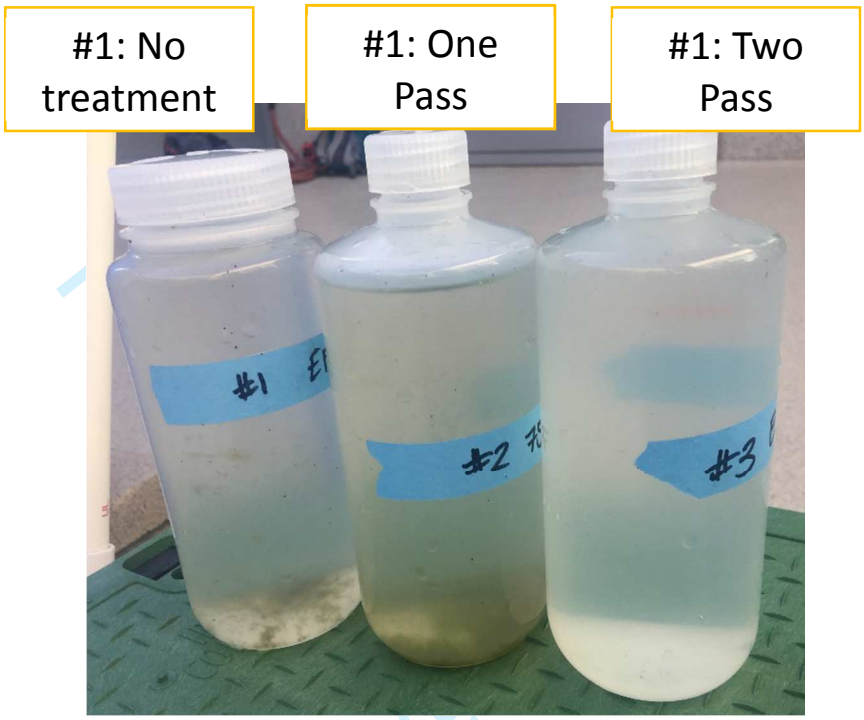

Fig. 4 *Water clarity after two weeks for each treatment barrel. Barrel one received no treatment, barrel two received one pass through the UV system and barrel three received two passes.*

Based on previous testing of the system, two passes in the system is calculated to be equivalent of a UV dose of 430 mJ/cm^2 and 188 mJ/cm^2 when the transmissivity at 254 nm (UVT) of the water are 95% and 75%, respectively. The UVT supplied to the system can be determined from the UVA using the following equation (Metcalf & Eddy et al., 2014):

$$UVT, \% = 100\% \; x \; 10^{-UVA} \qquad (1)$$

The UVT of the Arboretum water at the beginning the trial was 82.34%. Thus, using linear interpolation, the two passes through the system received a UV dose of 276.8 mJ/cm^2 and the single pass through the system received a UV dose of 138.4 mJ/cm^2. Based on these findings, it is estimated that, depending on the number and capacity of the UV systems deployed, a full-scale system installed at the Arboretum would be required to deliver a dose in the range 138.4 mJ/cm^2 - 276.8 mJ/cm^2 to prevent algal bloom.

4. Concluding remarks

This study was conceived as a proof of concept to demonstrate the utility of a novel system for water disinfect with UV light for the control of algae in water that is heavily impacted by algal growth. The key features of the UV system that posed it as being potentially suitable for large-scale deployment were its ability to remain free of the fouling problem that is present in most commercial systems, and its ability to uniformly expose the untreated water to the incident

UV radiation. These features arise from locating the UV tubes outside the untreated water, and from the imposition of strong swirling motion to the inlet flow. Under the flow conditions tested in this study, the system proved to be effective in inhibiting the growth of algae in water obtained from a constructed waterway that was severely impacted by algal growth. No fouling of the inner walls of the quartz cylinder was observed in any of the tests performed, while the treated water remained clear of algae for a period of at least two weeks after exposure to the UV radiation. The UV dose required for preventing the algal growth was determined and was found to be in the range 138.4 mJ/cm^2 - 276.8 mJ/cm^2, depending on the number of times that the impacted water passes through the system. In future work, the effectiveness of the system under small lake conditions will be assessed via field deployment in impacted water where various algal and microbial assemblages will be present.

Acknowledgements

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References

APHA. (2012). Standard Methods for the Examination of Water and Wastewater (Vol. 22). Washington DC, USA: American Public Health Association.

Barrado-Moreno, M., Beltrán-Heredia, J., & Martín-Gallardo, J. (2017). Degradation of microalgae from freshwater by UV radiation. Journal of Industrial and Engineering Chemistry, 48, 1-4.

Metcalf & Eddy, Inc., Tchobanoglous, G., Stensel, H. D., Tsuchihashi, R., & Burton, F. L. (2014). Wastewater engineering: treatment and Resource recovery, 5th Edition, McGraw-Hill, Boston.

Dai, G., Zhong, J., Song, L., Guo, C., Gan, N., & Wu, Z. (2015). Harmful algal bloom removal and eutrophic water remediation by commercial nontoxic polyamine-co-polymeric ferric sulfate-modified soils. Environmental Science and Pollution Research International, 22(14), 10636.

Dodds, W. K., Bouska, W. W., Eitzmann, J. L., Pilger, T. J., Pitts, K. L., Riley, A. J., Thornbrugh, D. J. (2009). Eutrophication of US freshwaters: analysis of potential economic damages. Environ Sci. Technol., 43(1), 12-19.

Grover, J. P., Roelke, D. L., & Brooks, B. W. (2017). Population persistence in flowing-water habitats: Conditions where flow-based management of harmful algal blooms works, and where it does not. Ecological Engineering, 99, 172-181.

Lee, T., Nakano, K., & Matsumara, M. (2001). Ultrasonic irradiation for blue-green algae bloom control. Environmental Technology, 22(4), 383-390.

Qin, B., Li, W., Zhu, G., Zhang, Y., Wu, T., & Gao, G. (2015). Cyanobacterial bloom management through integrated monitoring and forecasting in large shallow eutrophic Lake Taihu (China). Journal of Hazardous Materials, 287, 356-363.

UCD. (2016). UC Davis Arboretum: About Us. Retrieved from http://arboretum.ucdavis.edu/about_us.aspx

Younis, B. A., Mahoney, L., & Palomo, N. (2018). A novel system for water disinfection with UV light. In review (text available from the Corresponding Author).

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Field evaluation of a novel UV water disinfection system for use in underserved rural communities

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Abstract

Reliable, robust, and inexpensive disinfection systems are needed to expand water security in remote and underserviced areas. This paper reports on the deployment and evaluation of a novel UV water disinfection system in a remote rural community. Prior laboratory tests indicated a 7.12 log10 reduction of the bacteriophage MS-2 at a flow rate of 9.46 L/min, which corresponds to a supplied UV dose 215 mJ/cm^2. Further tests in water containing turbidity levels up to 18 NTU showed *E. coli* removal remaining above the 5 log10 level. Field testing was performed at a Native American reservation in Northern California where the system was used to treat groundwater obtained from a well with a known fecal contamination. The system was powered by solar panel and was operated on-demand for extended periods. Tests on the treated water showed that the system exceeded the standard of disinfection required for drinking water. © 2018 Water Environment Federation

Practitioner points

- A novel system for water disinfection with UV light is described.
- Laboratory and field tests showed high levels of disinfection achieved even at low UVT and high turbidity.
- System is robust, reliable and inexpensive to produce thus suitable for use in underserved communities.

Key words

underserved communities; UV disinfection; water safety

Introduction

Centralized services typically found in major cities, such as drinking water and wastewater treatment, are expensive and unattainable for many small cities and remote locations (Cherunya, Janezic, & Leuchner, 2015; Huang et al., 2018). This is true in many places other than in the developing world. For example, as of 2014, over 1 million Californians still did not have safe drinking water either because their publicly supplied water contains constituents over the regulated Maximum Contaminant Level (MCL) or because they rely on insecure private wells that receive no treatment at all (SWRCB, 2016). Similarly, as of 2014, 432 public water systems have been unable to supply safe drinking water to their communities for years and sometimes even decades in California's San Joaquin Valley (SWRCB, 2016). Therefore, these communities must rely on either purchasing bottled water or treating their own water onsite.

An essential part of the onsite, point-of-use disinfection of the drinking water is to prevent the consumption of fecally contaminated water thus reduce the risk of transmission of enteric viral and bacterial diseases (Firth et al., 2010; Sobsey, Stauber, Casanova, Brown, & Elliott, 2008). Personal and household water treatment devices and chemical treatment devices have been developed to meet this need (Clasen, 2015; Sobsey, 2004). For example, chemicals, such as chlorine and iodine, have a long history of use to treat water, but these treatment methods can negatively alter the taste of the water and can also create harmful disinfection by-products. Filtration systems are also available; however, many fail to remove viruses, dramatically reduce the flow rate, and require the water to be treated in batches. Treatment with UV light is an attractive alternative treatment option

because it is effective at treating waterborne pathogens, provides rapid and continuous treatment, and does not create any disinfection by-products (Metcalf & Eddy, Inc. et al., 2013). However, existing commercial UV systems are expensive to purchase and operate and, moreover, require a degree of technical ability that is not available in many underserved communities. Many of these drawbacks to the commercial systems arise from their basic design. This consists of one or more UV lamps that are inserted inside quartz tubes and placed within the body of water being treated. As a result, the problem of "fouling" occurs wherein the quartz tubes become covered by organic and inorganic residues that significantly reduce the intensity of UV radiation and eventually lead to failure to achieve adequate inactivation. Anecdotal evidence indicates that many operators of such systems are not aware of the extent of the "fouling" problem, or of the rapidity of its occurrence. Even when the importance of frequent cleaning of the quartz tubes is emphasized, issues of lack of resident technical expertise in underserved communities arise, giving rise to a false sense of security associated with the consumption of water that has flowed through the UV system without receiving adequate UV dose to inactivate target pathogens.

In recent years, a number of studies have been performed to investigate various aspects related to the use of UV disinfection in underserved communities (Anon., 2009; Brownell et al., 2008; Lui et al., 2014; Reygadas, Gruber, Ray, & Nelson, 2015; Sun, Liu, Cui, & Liu, 2013). Vidal et al. (1999) and Vidal and Diaz (2000) examined the potential use of compound parabolic reactors to disinfect water supplies in rural communities and reported successful inactivation of coliforms by UV-A from incident sunlight at competitive costs. In this paper, we introduce a UV system that has been developed to provide a better alternative to the commercially available system, specifically with regard to its suitability for use in underserved communities. Details of this system, and of both the laboratory and field tests conducted for its evaluation, are reported next.

Materials and methods

The UV system

Two features distinguish the new system from those available commercially: The UV lamps do not come in contact with the water, and hence, the problem of "fouling" does not occur, and the water that flows through it does so in the form of a strong swirling motion that ensures exposure of all pathogens present in the untreated water to the appropriate UV dose and, also, ensures that the system is self-cleaning, thereby eliminating the need for frequent maintenance. The way in which these distinguishing features are obtained can be seen from Figure 1, which shows a computer-aided design rendering of the system. The core of this system consists of a quartz tube whose diameter and length are sized according to the expected flow rate of water to be treated. Quartz is one of the few materials suitable for this application since it allows for 96% of the incident UV radiation at the germicidally effective wave length of 254 nm to pass through it. The UV lamps, the number of which again depends on the flow rate and on the pathogenic load in the untreated water, are arranged outside the quartz tube. When operated, the lamps operate without being in contact with the water. Also, with the lamps placed outside the water means that they can be replaced without the entire system being disconnected and drained.

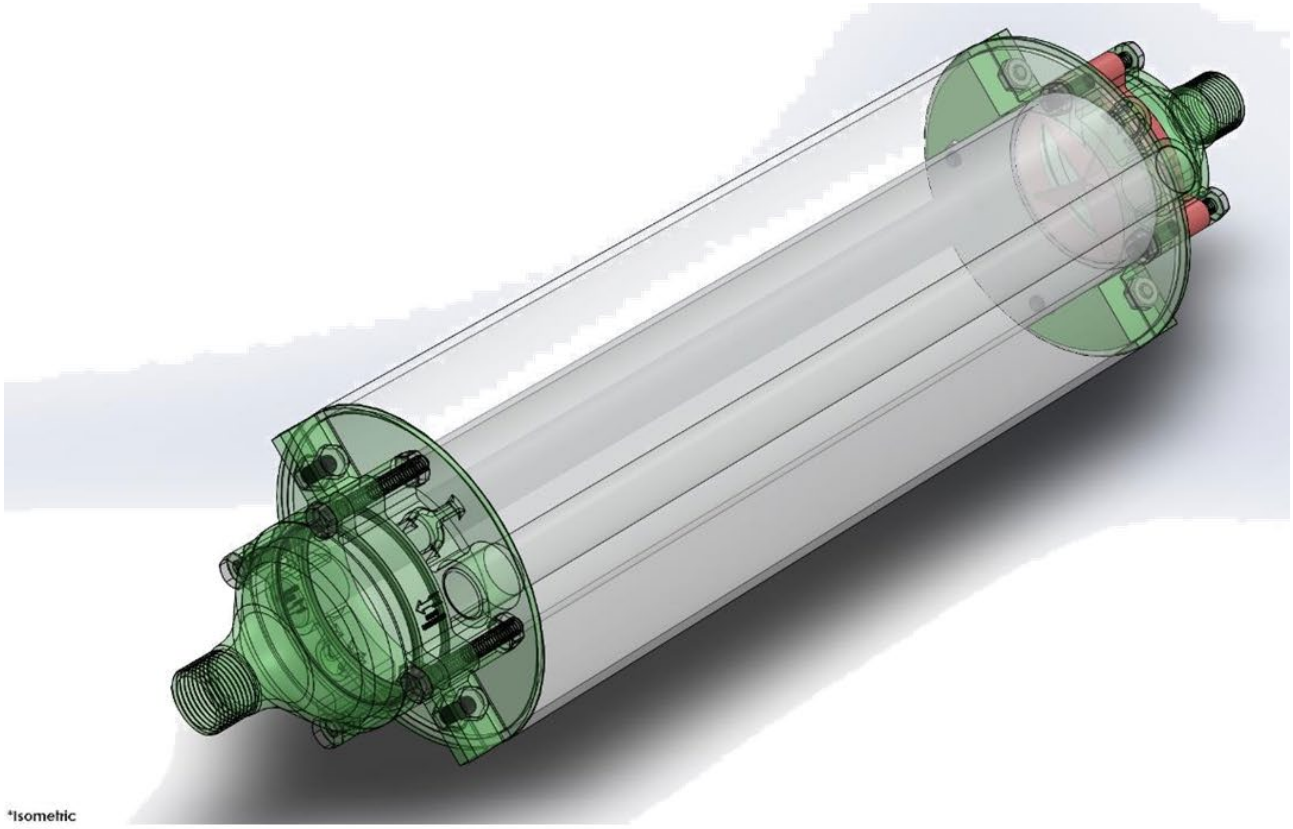
The quartz tube was of length L = 400 mm and inner diameter D = 70 mm giving a total volume of 1.54 L. The residence time was thus approximately 8 s. The tests were predominantly performed with two low-pressure UV lamps rated at 30 W each producing a theoretical lamp intensity of 1.5 W/cm^2. The actual light intensity at the axis of the quartz cylinder, where it is expected to be at its lowest value after being attenuated by the quartz walls and the water, was not measured. However, when dry, this was measured at 2.78 ± 0.127 mW/cm^2. Thus, assuming uniform intensity throughout the quartz tube, the UV dose delivered by each lamp is estimated to be 187 mJ/cm^2.

At inlet to the quartz tube, a diffuser having an included angle of 45° is installed so as to transition of flow from a pipe having the dimensions of a domestic water-supply system, to the larger diameter of the quartz tube to gradually reduce the flow velocity, thereby keeping the hydraulic energy losses associated with the velocity change to a minimum. Within this diffuser, static guide vanes are inserted. Their task is to impart a strong swirling motion to the inlet flow. As previously mentioned, this has the dual benefit of enhanced turbulent mixing, and the provision of a mechanism for self-cleaning due to the high levels of shear stress generated at the inside walls of the quartz tube. At outlet, a nozzle, also having an included angle of 45°, is installed to conveniently connect the large-diameter quartz tube to the domestic water supply system. Within this nozzle, another set of static guide vanes is installed for the purpose of enhancing the swirling motion induced at inlet. Finally, the entire assembly of quartz tube and UV lamps is encased within a PVC cylinder to prevent leakage of UV radiation. The inside of this cylinder is lined with aluminum foil to reflect incident radiation back into the enclosure.

The fabrication of this system was made possible only by the availability of 3D printing technology. This was used to manufacture the key components of this system, specifically the inlet and outlet assemblies, and the guide vanes. Figure 1 gives details of these, and the relevant dimensions. Not only was 3D printing essential for creating the complex shapes involved, but it also allowed for rapid and cost-effective experimentation with alternative configurations to ultimately—an optimal design which maximized the swirling motion while keeping the hydraulic losses at a minimum. With the increasing availability and decreasing cost of 3D printing, it is envisioned that the cost to manufacture the key components of this system will become quite modest.

Laboratory evaluation

The National Sanitation Foundation (NSF) and the US Environmental Protection Agency (USEPA) have recommended performance standards for UV disinfection system to ensure a minimum level of performance for the removal of pathogens. The NSF standard requires the removal of at least 99.99% (4-log10 inactivation) of the bacterial coliphage MS-2 (NSF, 2002). Similarly, the USEPA's Long Term 2 Enhanced Surface Water Treatment Rule and Ground Water Rule require 4-log10 removal of viruses, 3-log10 removal of *Giardia lamblia* cysts, and 2-log10 removal of cryptosporidium (USEPA,



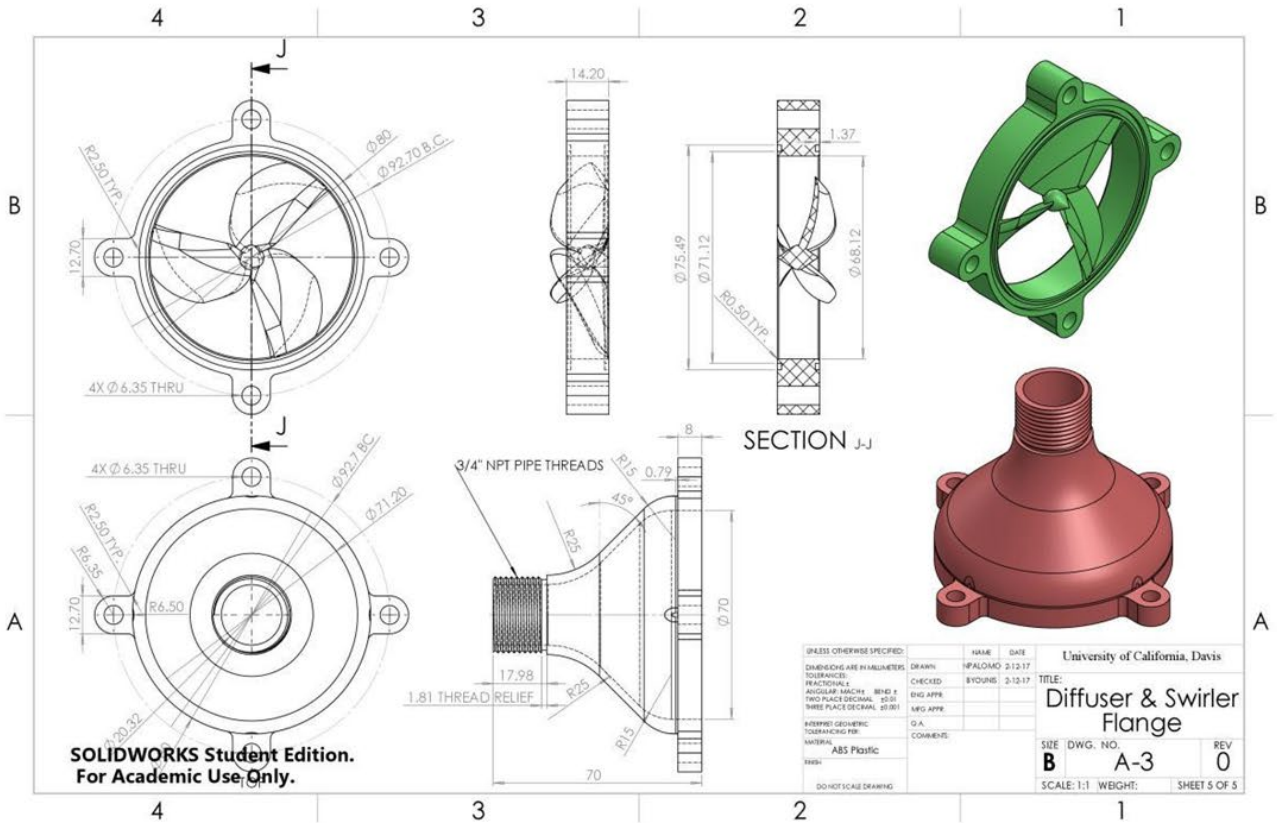


Figure 1. A rendered representation of the UV reactor.

2006a, 2006b). Determination of the UV dose (or fluence) supplied by the system was based on the NWRI recommendations complied in "Ultraviolet Disinfection Guidelines for Drinking Water and Water Reuse."

Test water and test conditions

To assess the UV dose applied to the system, the system was spiked with the MS-2 and assessed at two levels of Ultra-Violet Transmissivity (UVT) namely 70% and 90%, and for two flow rates namely 9.46 and 12.9 liters/min. The source water for this testing was unchlorinated City of Davis groundwater at 20 ± 1.2°C and pH 8.3 ± 0.15. The UVTs for this analysis were the original UVT of the City groundwater at 95% and another adjusted to 70% using instant coffee (Pampa) per NWRI's UV guidance manual (NWRI, 2012). The UVT was assessed at wavelength of 254 nm using a Cary Win UV-Vis spectrophotometer (Cary Win 1E, Varian Corp., Houston, TX), and the flow rate was determined using an in-line flow meter (Omega, FL46300 Series). The initial concentration of the MS2 in the source water for the testing was 1.2×10^8 and 3.0×10^8 pfu/ml for a UVTs of 95% and 70%, respectively. For each of the four flow rates and UVTs combinations, three samples were collected before and after the UV for MS-2 testing. Samples were stored at 4°C for <24 hr before being processed at the Biovir Laboratories in Benicia, CA, using the Adam's double agar overlay without RNase method for enumeration (Adams, 1959).

Viral and bacterial analysis

Viral analyses were performed using the MS-2 coliphage (ATCC #15597-B1) to determine the UV dose supplied by the system, and its effectiveness at inactivating viral pathogens (Bolton & Linden, 2003). A solution of the propagated virus and analysis of samples containing the virus were performed by Biovir Laboratories in Benicia, CA. Bacterial analysis were performed using IDEXX Colilert Quanti-Trays to determine total coliform and *E. coli* counts.

The concentrated solutions of *E. coli* used for the turbidity testing and the analysis of the impact of the type of water were prepared in the following manner. The *E. coli* (ATCC #15597) was propagated with Luria Broth (LB; Sigma-Aldrich) and at a 0.4% inoculation. Then, the solution was incubated at 37°C for 12 hr. The cells in the solution were then concentrated by centrifuging the samples for 20 min at 2,500 rpm. The supernatant was decanted, and the pelleted cells were re-suspended in Milli-Q water at room temperature for use during testing so that the color of the LB media did not significantly alter the UVT of the sample water.

Analysis of the impact of water quality

In addition to water from Covelo site, the testing also assessed the performance of the system to disinfect water from a campground in the Mokelumne River Canyon (9/5/2016) and a campground next to Lake Tahoe (9/18/2016). At the Mokelumne River Canyon site, water was collected from the river, the local nonpotable groundwater source, and the potable water line piped in from Pine Grove, CA. The campsite had to move their drinking water from the local groundwater source to the source from Pine Grove, because of iron concentrations exceeding the MCL of 0.3 mg/L. This is important for our testing, since high iron concentrations colors the water and reduces the transmission of the UV light. At the Lake Tahoe campsite, water was collected from the lake at two separate locations adjacent to the campsite. The water was collected by rinsing a sterile bottle three times with the sample water before collecting the sample. For each water type, 38 L of water was collected and then transported to the UCD campus for testing within 12 hr. Once on campus, the samples were stored at 4°C before being processed over the following 7 days.

To determine the impact of the different water qualities, first the water was assessed based on their background characteristics. The oxidation-reduction potential (ORP), conductivity, total dissolved solids (TDS), conductivity, temperature, and pH of the water were measured at the sampling location with a Myron L Company Ultrameter III using the method described in Standard Methods (AWWA) and in conjunction with the instrument manufacturer's instructions. The turbidity and the UVT were assessed on campus using a Hach 2100AN Turbidimeter and a Cary 1E UV visible Spectrophotometer, respectively, in accordance with Standard Methods (AWWA) and manufacturer's instructions.

To assess disinfection performance of the system with each water type, each water type received a dosed of a concentrated solution of *E. coli*. The number of *E. coli* cells that were inactivated in the system before and after passing through it were then assessed using the membrane filtration technique described in Standard Methods (AWWA). Each turbidity level was assessed three times, and three samples were collected before and after the UV for *E. coli* testing from each trial. Samples were stored at 4°C for <24 hr before being processed.

Analysis of susceptibility to turbidity

To assess the impact of turbidity on the system, various concentrations of activated carbon were added to Milli-Q water. To ensure a small particle size, the activated carbon solutions was first crushed, added to the Milli-Q water at a pH of 7 ± 0.16 and a temperature of 20 ± 1.4°C, and then screened with a 20-μm cartridge filter. The activated carbon solution was then added to the system to generate the following levels of turbidity: 0.16 ± 0.05, 3.53 ± 0.85, 6.621.51 ±, 13.3 ± 1.67, and 17.83 ± 2.13 NTU. Each solutions of activated carbon also received a dosed of a concentrated solution of *E. coli*. The number of *E. coli* cells that were inactivated in the system before and after passing through then assessed using membrane filtration technique described in Standard Methods (AWWA). Each turbidity level was assessed three times, and three samples were collected before and after the UV for *E. coli* testing from each trial. Samples were stored at 4°C for <24 hr before being processed.

Field testing location and test conditions

The field tests were carried out at Covelo—CA. This community is located 64 km Northeast of Willits, CA along the I-162

in Mendocino County and is about 22 km from the middle fork of the Eel River. Covelo is located in the Round Valley Indian Reservation and is home to 99 inhabitants (US Census 2000). The test site draws water from the Round Valley Groundwater Basin, which is in the Central Northeastern part of Mendocino County and is about 8 miles long and 4 miles in width. The total capacity of the groundwater basin is about 284×10^6 m^3, and the water is characterized as being a calcium–magnesium bicarbonate type. The TDS typically range between 38 and 116 mg/L, and water can be high in hardness, magnesium, iron, and calcium concentration (EPA, 2016). The typical range in domestic well depths for this area is 9.7–91 m, with an average depth of 30 m. For the groundwater well at the test site, no disinfection treatment was in operation at the time of testing.

Results and discussion

UV dose determination

The results obtained from the laboratory tests are considered first. Table 1 lists the flow rates tested, the percentage UVT for each flow rate, the log10 concentration of MS-2 in the influent and effluent streams, the log10 removal of MS-2 achieved by the system, and the UV dose delivered by the system under these operating conditions. As can be seen in Table 1, the UV dose delivered by the system is significantly higher dose than the 40 mJ/cm^2 of dose >120 or 215.6 mJ/cm^2 assuming continued linearity of dose–response curve. This elevated dose ensures the inactivation of pathogenic bacteria, protozoa, fungi, and viruses. Given the delivered UV dose is more than twice the NSF standard, it may be possible to operate the system with only one of the two lamps and extend the service life of the system (NSF, 2002). Similarly, a lower power UV lamp could also be used, which would lower energy consumption and reduce the cost of materials.

Impact of water quality assessment

To determine the maximum, contaminate load of *E. coli* the system could treat, challenge tests were also performed at UCD using water from Covelo, a campground in the Mokelumne River Canyon, and a campground next to Lake Tahoe. A "challenge test" is when a disinfection system is dosed with a high volume of a microorganism to determine how well the system removes or inactivates the microorganism. The influent characteristics of the source water can influence the penetration of the UV light into the water column and diminish the disinfection performance of the system. Thus, a challenge test to the system is essential to confirm the effectiveness of the system at any particular location. The water quality characteristics from each site are summarized in Table 2.

As shown in Table 3, the minimum log10 removal was 5.9 and it occurred at the Mokelumne River Canyon Campground. However, the average log10 removal from these test was 7.24, which is well beyond requirements from the NSF and USEPA.

Turbidity assessment

Turbidity is a measurement of the number of suspended particles in a water sample. It is an important parameter to quantify in tests of this type because the suspended particles can embed pathogenic microorganisms and thus act as a shield to free floating microorganisms in such a way that prevents these organisms from receiving the required UV dose. Understanding how turbidity impacts the system informs the user on what type of upstream filtration is needed for the system, and serves as a guide for identifying the type of water that can be treated by the UV system. As shown in Table 4, the disinfection capacity of the system was not significantly impacted when tested with water containing turbidity levels from 0 to 18 NTU. In all the samples tested, the disinfection of *E. coli* in all scenarios remained above 5 log10 removal. That this was the case is due to the strong swirl that is imparted to the influent stream. This leads to intense mixing of the flow inside the quartz tube, thereby ensuring that pathogens that may have become attached to suspended particles receive UV radiation as they rotate and tumble towards the outlet. This tolerance to elevated levels of turbidity suggests that the present system would be suitable for operation with upstream filters that have a nominal opening of 20 μm, the size used to screen particles for this analysis. Similarly, the UV system would also be suitable to be operated with waters that contain higher turbidity, such as surface water, sandy groundwater wells, or recycled water.

Field testing

The main concern regarding the quality of the groundwater produced in the well in the Covelo community is fecal coliform contamination, namely *E. coli,* and hence, the subsequent analyses were limited to assessment of the UV system efficacy for bacterial contamination only. The system was powered and operated using a single 100 W solar panel (WindyNation) to demonstrate the system's utility for deployment at off-grid locations.

In order to determine the background microbial concentration for each test, samples were taken from the community's groundwater well at source to be tested for the presence of total coliform and *E. coli*. Results were positive for each round

Table 1. UV dose for the system at various flows and UVTs

FLOW (L/MIN)	UVT (%)	LOG10 INFLUENT MS2 CONC.	LOG10 EFFLUENT MS2 CONC.	LOG10 REMOVAL OF MS2	UV DOSE (MJ/CM^2)
9.46	95	8.18 ± 0.10	1.60 ± 0.12	7.12 ± 0.93	215.6
9.46	70	8.60 ± 0.05	5.59 ± 0.09	3.01 ± 0.09	93.9
12.9	95	8.18 ± 0.10	2.72 ± 0.08	5.46 ± 0.08	173.3
12.9	70	8.60 ± 0.05	6.38 ± 0.13	2.22 ± 0.13	64.5

Table 2. Summary of water quality parameter from each site

ASSESSMENT PARAMETERS	COVELO REC. CENTER AVERAGE	MOKELUMNE CAMP GROUNDWATER AVERAGE	MOKELUMNE CAMP RIVER WATER AVERAGE	MOKELUMNE CAMP POTABLE WATER AVERAGE	TAHOE CAMPSITE #1 AVERAGE	TAHOE CAMPSITE #2 AVERAGE
pH	6.9	7.4	6.62	8.17	6.7	6.61
Turbidity, NTU	2.9	0.25	8.12	1.05	1.52	0.41
Conductivity, $\mu S/cm^2$	188.4	535.5	23.05	232.2	118.9	113.4
TDS, ppm	119.7	369.9	14.77	152.6	78.25	74.5
Alkalinity, mg/L	66.7	212	8.9	69	50	53
Calcium, mg/L as $CaCO_3$	23.7	192	8.6	52	25	35
Magnesium, mg/L as $CaCO_3$	15.3	51	11.6	110	15	50
Hardness, as $CaCO_3$ mg/L	39	243	19	162	40	85
UVT, %	99.9	95.5	94.7	95.3	99.4	99.7

Table 3. Summary of results from the *E. coli* challenge tests

SAMPLE	INFLUENT, CFU/100 ML	EFFLUENT, CFU/100 ML	LOG REMOVAL
Covelo Rec. Center	6.00E+09	1.65E+02	7.6
Mokelumne Camp Groundwater	6.00E+09	4.91E+03	6.1
Mokelumne Camp River Water	1.62E+10	0.00E+00	10.2
Mokelumne Camp Potable Groundwater	1.11E+09	1.34E+03	5.9
Tahoe Campsite 1	6.50E+09	3.94E+02	7.2
Tahoe Campsite 2	3.33E+09	1.22E+03	6.4

Table 4. Impact of turbidity on disinfection performance

TURBIDITY (NTU)	LOG10 INFLUENT *E. COLI* CONC.	LOG10 EFFLUENT *E. COLI* CONC.	LOG10 REMOVAL OF *E. COLI*
0.16 ± 0.03	7.17 ± 0.12	1.45 ± 0.17	5.5 ± 0.3
3.53 ± 0.11	7.02 ± 0.16	1.55 ± 1.16	5.1 ± 1.0
6.62 ± 0.21	7.15 ± 0.12	1.24 ± 0.86	5.6 ± 1.0
13.30 ± 0.53	6.91 ± 0.42	0.35 ± 0.49	6.8 ± 0.9
17.83 ± 0.32	6.93 ± 0.06	1.80 ± 0.21	5.1 ± 0.2

Table 5. Bacterial concentration before and after treatment. Results are for groundwater samples collected from the Round Valley Indian Reservation Recreation Center in Covelo, CA

SAMPLE	AVG. TOTAL COLIFORM (MPN/100 ML)	AVG. *E. COLI* (MPN/100 ML)
Outside	68.05	43.3
Kitchen	81.6	44.35
Women's bathroom	145.85	52.85
Post-UV treatment	ND	ND

Note. ND: None detected.

of testing for the sampling period of 8/5/2016–8/7/2016. As per EPA guidelines, results were repeated for confirmation. Additional samples were collected 8/22/2016 and processed 8/24/2016 using IDEXX quanti-trays. The results of these tests are presented in Table 5, which lists the results for each sampling point in the community center. In all the tests performed, the bacterial concentration in the treated water fell to below the detection limit.

In the course of evaluating the UV system's performance in inactivating pathogens, an opportunity arose to evaluate the system's utility in the sense of its adaptability for use in other areas where disinfected water was in demand. This opportunity was provided by the coincidence of the tests there with the presence a team of veterinary surgeons who operated a mobile spay and neuter clinic setup in the community center on temporary basis. The clinic was operated over a period of 48 hr. While no water samples were taken for analysis, it was found that the UV system, due to its compact and robust design, integrated seamlessly into the regular

operations of this clinic, primarily as part of the scrubbing-in station where it met the needs for disinfected water pre- and post surgeries.

Cost analysis

At the time of performing this study (May, 2017), the cost of the material (PLA) used in the 3D printing of the key system components was $6.20. The PLA resin was bought in bulk at a cost of $22/kg. The retail price of a 30 W UV lamp was $26.00 though similar lamps, purchased from the manufacturer in bulk, would cost around $7.00/lamp. The cost of the quartz tube was $45.00, while the cost of the PVC pipe that formed the outer casing was $3.00, thereby bringing up the total cost of the unit just under $90.00. An equivalent commercial system having similar flow rate retails at around $600.00 though such systems are fitted by a clock and a UV sensor which was not the case in our system. The lamp manufacturer indicates that the lifetime of the lamp, when operated continuously, is 10,000 hr. The retail cost of electric power for a domestic household is $0.13/kW.hr, and thus, the daily operating cost of this system with 2 30 W UV lamps is just under $0.20 when running at the full capacity of 9.46 L/min, $0.015/$m^3$. These costs obviously do not include the initial costs of construction and material, or the cost of pumping the water through the system which would be necessary in most cases.

Conclusions

The search for an economic, robust, and practical method for water disinfection in underserved communities is a worthwhile objective considering the great proportion of the world's inhabitants without a safe and secure access to drinking water, and the significant economic hardship that arises due to the consumption of untreated water. In this paper, a novel system for water disinfection with UV light was introduced. The principal components of this system were manufactured using 3D printing—a technology whose costs are decreasing at a fast rate. The system offers many benefits that are not available from commercial systems. Amongst the most significant of these is the avoidance of the problem of lamp fouling and all the complications that arise from it such as the need to install a mechanical wiper that traverses the length of the lamps scraping off residues. The presence of strong swirl in the influent flow ensured that the inner surface of the quartz cylinder remained free of fouling due to the elevated levels of wall shear stress produced by swirl. Moreover, the presence of swirl enhanced the turbulent mixing, thereby ensuring that all pathogens that enter into the system receive the UV dose that is required for their inactivation. Laboratory tests showed that at a flow rate of 9.4 L/min, the system delivered a UV dose of 215 mJ/cm^2 which is sufficient to inactivate most common pathogenic bacteria, viruses, and protozoa. In addition, at the relatively low UVT of 75%, the system delivered a dose of 94 mJ/cm^2 which is also sufficient for inactivation of all common pathogens (USEPA, 2003). Tests performed in situ at a remote and underserved community indicate that the new system, that was powered by a single 100 W solar panel, can be relied upon to provide water that is free from the pathogens of concern. It is hoped that the details provided in this paper can contribute to ongoing efforts directed toward the provision of a sustainable and affordable means for widening access to safe drinking water in underserved communities.

Acknowledgments

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References

Adams, M. H. (1959). *Bacteriophages*.

Anon., (2009). UV treatment: A mobile water solution for Native American tribes. *Filtration & Separation*, *46*(3), 37–39.

Bolton, J. R., & Linden, K. G. (2003). Standardization of methods for fluence (UV dose) determination in bench-scale UV experiments. *Journal of Environmental Engineering*, *129*(3), 209–215. https://doi.org/10.1061/(ASCE)0733-9372(2003)129:3(209)

Brownell, S. A., Chakrabarti, A. R., Kaser, F. M., Connelly, L. G., Peletz, R. L., Reygadas, F., … Nelson, K. L. (2008). Assessment of a low-cost, point-of-use, ultraviolet water disinfection technology. *Journal of Water and Health*, *6*(1), 53–65. https://doi.org/10.2166/wh.2007.015

Cherunya, P. C., Janezic, C., & Leuchner, M. (2015). Sustainable supply of safe drinking water for underserved households in Kenya: Investigating the viability of decentralized solutions. *Water*, *7*(10), 5437–5457. https://doi.org/10.3390/w7105437

Clasen, T. (2015). Household water treatment and safe storage to prevent diarrheal disease in developing countries. *Current Environmental Health Reports*, *2*(1), 69–74. https://doi.org/10.1007/s40572-014-0033-9

EPA (2016). *Safe Drinking Water Information System (SDWIS)*. Retrieved from https://sdwis.waterboards.ca.gov/PDWW/index.jsp

Firth, J., Balraj, V., Muliyil, J., Roy, S., Rani, L. M., Chandresekhar, R., & Kang, G. (2010). Point-of-use interventions to decrease contamination of drinking water: A randomized, controlled pilot study on efficacy, effectiveness, and acceptability of closed containers, *Moringa oleifera*, and in-home chlorination in rural South India. *American Journal of Tropical Medicine and Hygiene*, *82*(5), 759–765. https://doi.org/10.4269/ajtmh.2010.09-0206

Huang, J., Huang, G. H., An, C. J., He, Y., Yao, Y., Zhang, P., & Shen, J. (2018). Performance of ceramic disk filter coated with nano ZnO for removing Escherichia coli from water in small rural and remote communities of developing regions. *Environmental Pollution*, *238*, 52–62. https://doi.org/10.1016/j.envpol.2018.03.008

Lui, G. Y., Roser, D., Corkish, R., Ashbolt, N., Jagals, P., & Stuetz, R. (2014). Photovoltaic powered ultraviolet and visible light-emitting diodes for sustainable point-of-use disinfection of drinking waters. *Science of the Total Environment*, *493*, 185–196. https://doi.org/10.1016/j.scitotenv.2014.05.104

Metcalf & Eddy, Inc., Tchobanoglous, G., Stensel, H. D., Tsuchihashi, R., & Burton, F. L. (2013). Wastewater engineering: Treatment and resource recovery. New York, NY: McGraw-Hill.

NSF (2002). NSF international standard/American national standard for drinking water treatment units— ultraviolet microbiological water treatment systems, NSF/ANSI 55-2002. Ann Arbor, MI: National Sanitation Foundation International.

NWRI (2012). Ultraviolet disinfection guidelines for drinking water and water reuse. In G. M. Vartanian (Ed.). Retrieved from http://nwri-usa.org/documents/UVGuidelines3rdEdition2012.pdf

Reygadas, F., Gruber, J. S., Ray, I., & Nelson, K. L. (2015). Field efficacy evaluation and post-treatment contamination risk assessment of an ultraviolet disinfection and safe storage system. *Water Research*, *85*, 74–84. https://doi.org/10.1016/j.watres.2015.08.013

Sobsey, M. (2004). *Managing water in the home: Accelerated health gains from improved water supply*. World Health Organization Report WHO/SDE/WSH/02.07.

Sobsey, M. D., Stauber, C. E., Casanova, L. M., Brown, J. M., & Elliott, M. A. (2008). Point of use household drinking water filtration: A practical, effective solution for providing sustained access to safe drinking water in the developing world. *Environmental Science and Technology*, *42*(12), 4261–4267. https://doi.org/10.1021/es702746n

Sun, W. J., Liu, W. J., Cui, L. F., & Liu, L. B. (2013). The biological safety of distribution systems following UV disinfection in rural areas. *Water Science and Technology – Water Supply*, *13*(3), 854–863. https://doi.org/10.2166/ws.2013.077

SWRCB (2016). *State water resources control board – CA annual compliance report*. Retrieved from https://www.waterboards.ca.gov/drinking_water/certlic/drinkingwater/documents/dwdocuments/2016/2016_acr_fnl070717.pdf

USEPA (2003). *Ultraviolet disinfection guidance manual*. EPA report 815-D-03-007.

USEPA (2006a). *National primary drinking water regulations: Ground water rule; Final Rule*. Federal Register.

USEPA (2006b). *National primary drinking water regulations: long term 2 enhanced surface water treatment rule; Final Rule*. Federal Register, 71(3), Retrieved from https://www.gpo.gov/fdsys/pkg/FR-2006-01-05/pdf/06-4.pdf

Vidal, A., & Diaz, A. I. (2000). High-performance, low-cost solar collectors for disinfection of contaminated water. *Water Environment Research*, *72*(3), 271–276. https://doi.org/10.2175/106143000X137473

Vidal, A., Dıaz, A. I., El Hraiki, A., Romero, M., Muguruza, I., Senhaji, F., & González, J. (1999). Solar photocatalysis for detoxification and disinfection of contaminated water: Pilot plant studies. *Catalysis Today*, *54*(2–3), 283–290. https://doi.org/10.1016/S0920-5861(99)00189-3

UNIVERSITY OF CALIFORNIA AT DAVIS / DEPARTMENT OF CIVIL AND ENVIRONMENTAL ENGINEERING

A solar-powered system for water disinfection with UV light for use in underserved communities

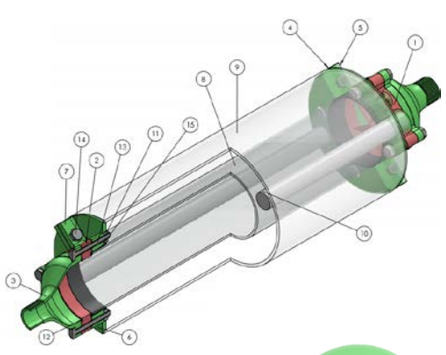
Bassam A. Younis, Laura E. Mahoney, Nicholas J. Palomo, and Shiyun Yao

ABSTRACT

We developed a novel system for drinking water disinfection using UV light. The new system, which is specifically intended for use in underserved communities, is more robust, easier to install, cheaper to acquire and safer to operate than the commercially-available alternatives. The system was designed using advanced computer simulations of fluid flow, and was manufactured in part using 3D printing technology. Tests performed under controlled laboratory conditions and independently analyzed showed that the system was capable of delivering a UV dose of 215.6 mJ/cm^2, which significantly exceeds the requirements of 40 mJ/cm^2 set by the National Sanitation Foundation (NSF) for drinking water. The tests also showed that the system's performance was not significantly impacted by scaling from hard water or turbidity. Field trials were performed at a remote rural community in California in which the system was entirely power by a single solar panel. The results of these trials indicate that the system is ready and suitable for deployment in underserved communities to ensure the safety of their drinking water.

SYSTEM DEVELOPMENT

Fig. 2: Vortex Diffuser Assembly



1. Inlet Swirler Flange
2. Outlet Swirler Flange (No blades)
3. Inlet/Outlet Diffuser
4. Inlet Split Flange 1
5. Inlet Split Flange 2
6. Outlet Split Flange 1
7. Outlet Split Flange 2
8. Quartz Tube (75mm ID X 2.5mm NOM X 1/8" TH X LG 13-5/8")
9. Radiation Shield
10. UV Lamps (20mm Dia X 38.2cm LG)
11. ¼"-20 HEX NUT
12. O-Ring 1/16" TH X 2.75" ID
13. ¼"-20 Cap Screw (Thread LG 1-7/8 Full, Head: WD 7/16", HT. 5/32")
14. ¼"-20 Cap Screw (Thread LG 5/8" Full, Head: WD 7/16", HT. 5/32")
15. Rubber Seal

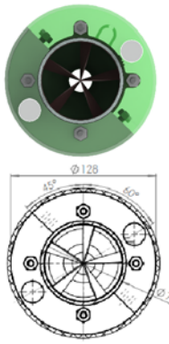
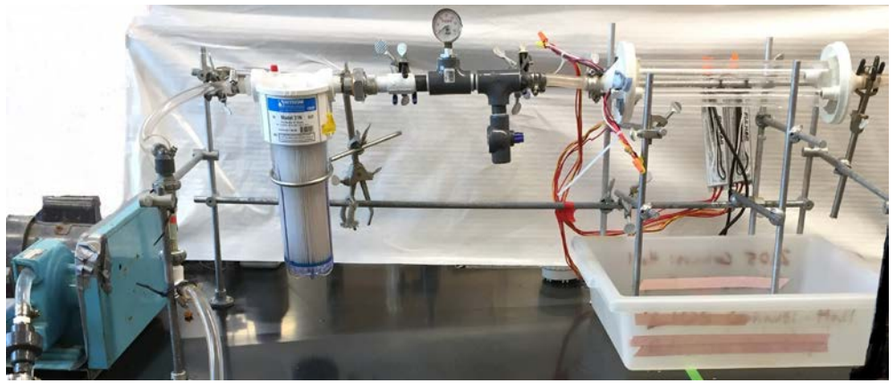


Fig. 1: UV system set-up in the CEE lab at UC Davis



METHODS

The system was assess for the following parameters:

- CFD was used to predict hydraulic performance to optimize the system design before construction
- An tracer test was used to assess hydraulic performance of the completed system
- Biodosimetry was used to established the UV dose supplied by the system
- Germicidal efficiency was determined using *E. coli* and MS2 coliphage
- The performance of the system was measured when subjected to hard water and various levels of turbidity
- *In situ* testing was used to assess ease of use and maintenance needs

RESULTS

- CFD analysis was used to ensure the diffusor kept the hydraulic energy losses associated with the velocity change through the system to a minimum.
- UV system delivers a UV dose of 215 mJ/cm^2 - sufficient to inactivate most pathogenic bacteria, viruses, and protozoa.
- On average, the system achieved a 7.2 log reduction of E. coli and 6.6 log reduction of MS2.
- Fouling due to hard water was dominated by particulate fouling on the lamp facing sides of the system; however, this did not significantly impact the disinfection capability of the system.
- Also, turbidity levels from 0 to 18 NTU did not impact disinfection performance.
- *In situ* testing established that the system was able to completely inactivate the bacterial contamination in a rural community groundwater well and to seamlessly integrated with the routine operations of a veterinary medical facility.

Fig. 3: CFD Analysis (Cross-sectional contours of: (a) Turbulent viscosity, (b) static pressure and (c) eddy viscosity ratio).

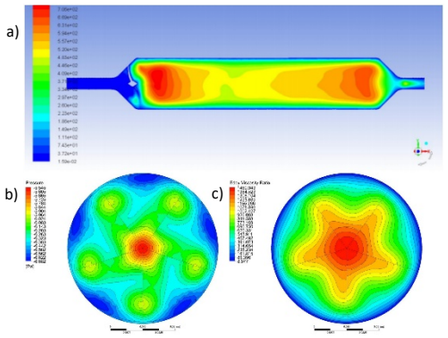
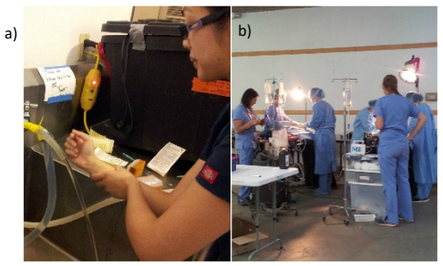


Fig. 4: (a) UV treatment system and (b) Solar Panel.

Fig. 5: Testing in Covelo, CA: (a) a veterinarian using the system to scrub-in for surgery and (b) surgery tables in use at the facility.



CONCLUSIONS

The system is characterized by the absence of contact between the UV lamps and the untreated water thereby avoiding the problem of lamp fouling. Tests conducted in an environmental laboratory showed that at a flow rate of 2.5 GPM the UV system was able to deliver a UV dose of 215 mJ/cm^2 - sufficient to inactivate most pathogenic bacteria, viruses, and protozoa. In addition, at the relatively low UVT of 75%, the system delivered a dose of 94 mJ/cm^2 which is also sufficient for inactivation of all common pathogens. The outcome of these tests, and others conducted in situ at a remote, underserved community indicate that the new system goes some way towards achieving the goal of the provision of an effective, robust, sustainable and affordable means for widening access to drinking water.

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