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The Case for LED-UVC as a Primary Disinfectant for Small Sustainable Drinking Water Systems

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Abstract. High loads of natural organic matter (NOM) in source water increase levels of toxic byproducts during disinfection, including trihalomethanes (THMs) which are formed when NOM is chlorinated. This study explores the efficacy of using UVC-LED as a primary disinfectant, with lower concentrations of chlorine used as a secondary disinfectant. Both treatment trains with conventional chlorination and UV irradiation with low chlorination reduced total coliforms and *E. Coli* counts to less than 1 Cfu/100 ml. UV with low chlorination produced approximately 4.6 times less THMs compared to conventional chlorination.

1 Introduction

Global water resources are under severe stress from over-pumping and contamination. Moreover, climate change-induced extreme weather events and unpredictable weather patterns will further deplete existing water resources [1]. While water shortages from droughts have received a lot of attention, such as Day Zero in South Africa, of equal concern is the quality of existing water resources and the means with which to treat them. Flash floods, which are occurring at unprecedented frequencies, can severely contaminate both surface and groundwater resources, increasing levels of bacteria, organic and inorganic contaminants, and nutrients [2, 3]. Moreover, as in the case of India, thousands of water bodies have become cesspools, causing dwindling water stocks to become undrinkable [4].

Additionally, due to degraded source water quality, carcinogenic byproducts, which have to be carefully managed even with relatively pristine source waters, may pose a major challenge. While technologies to treat these contaminants exist, they are costly and not readily available. Even in industrialized nations such as the United States, tens of millions of Americans rely on smaller, conventional water treatment systems that are at risk for violating water quality standards, especially for total coliforms and disinfectant byproduct production [5].

Upgrades of drinking water treatment systems are costly, as was the case for a conventional treatment system in Eastham, Cape Cod, in which \$114.8 million was spent for

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a small town of just 5,000 people [6]. Moreover, the improper application of chemical disinfectants can be disastrous. In Flint, Michigan, the change from chlorine to chloramine contributed significantly to the destabilization of lead scaling in old pipes, thus poisoning the water supply by causing lead to enter customers' taps [7].

The issue becomes more challenging in developing countries, especially in rural, decentralized communities, which are not connected to larger, urban municipal water supply systems. As a result, more resilient and innovative treatment systems that can cost-effectively address a wide range of contaminants are needed, while requiring relatively minimal maintenance.

This study assessed the efficacy of an innovative treatment system that uses readily available materials for conventional treatment, such as sand and activated carbon for filtration, and an LED-based UVC disinfection system to replace chlorination as a primary disinfectant. In comparison to traditional mercury lamps, UVC-LEDs have many unique features that improve inactivation efficiency, including multiple wavelengths and pulsed illumination [8]. Moreover, UVC-LED efficiency can be further enhanced through improved reactor designs, allowing for a wider range of applications than what it is typical available for mercury lamps [8].

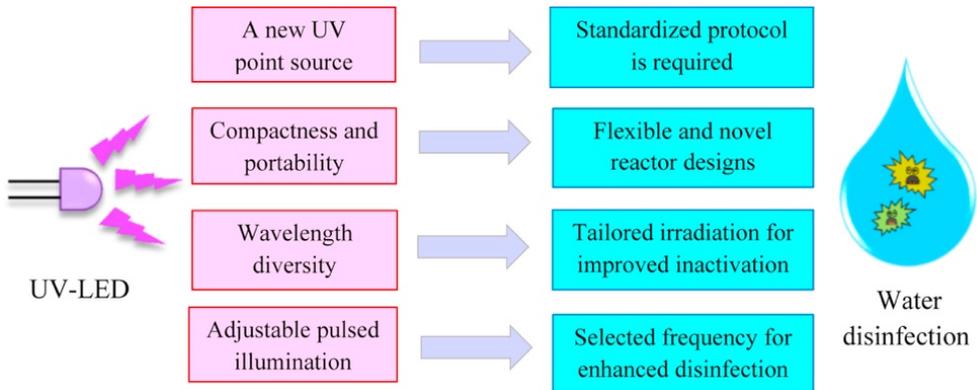


Fig. 1. LED disinfection (from Song et al, 2016)

Currently, most UV disinfection uses high or low-pressure mercury lamps. They require special training, need to be replaced frequently, and pose a severe contamination risk if they break [8, 9]. On the other hand, LED-based UVC systems require minimum maintenance and have a significantly longer lifespan, making them better suited for small, sustainable treatment systems. Moreover, the challenge of disposing spent mercury lamps as hazardous waste is removed, since LED systems are mercury free [8].

2 Methods

2.1 Study Site

A non-urban, forested watershed (Cork Brook) in the northern region of the state of Rhode Island was selected for this study. The Cork Brook is a significant tributary of the Scituate Reservoir, which supplies around 60% of the state's population with drinking water [10].

2.2 Methods

2.2.1. Bacterial Treatment

Experiments were conducted to determine the efficacy of the UV-LED systems for total coliform and *E. coli* inactivation. Natural water was collected from a local river and was filtered through a dual anthracite/sand column to remove turbidity. The effluent was then pumped through the UVC-LED system at a flowrate of 12 ml/min. Total coliform and *E. coli* were analyzed in the source water itself prior to filtration, after filtration, and after irradiation using the IDEXX Colilert-18 method [11].

2.2.1. Bench Scale Experiment

A conventional treatment train modelled after a local water treatment utility formed the basis our experiments, and included flocculation, coagulation, and anthracite/sand filtration. Three benchtop experiments were conducted in parallel:

1. Conventional treatment with higher-dosed chlorine as primary disinfectant (CPD) (2 ± 0.05 ppm).
2. LED-based, continuous UV as a primary disinfectant and lower-dosed chlorine as a secondary disinfectant (UVPD) ($0.5 \text{ ppm} \pm 0.05$ ppm).
3. LED-based, continuous UV as a primary disinfectant with the addition of a granular activated carbon (GAC) filter and lower-dosed chlorine as a secondary disinfectant (GAC + UVPD) (0.5 ± 0.05 ppm).

The primary differences between the three experiments were in the disinfection procedure, as well as the addition of an activated carbon filter in the third treatment train. The ferric sulfate flocculent (75 mg/l) and the dual sand/anthracite filter media used in the experiment were sourced from a local water utility. 50 grams of utility-grade anthracite were packed on top of 25 grams of silica sand in a 16-inch acrylic column. Washed gravel was used to contain the filter media.

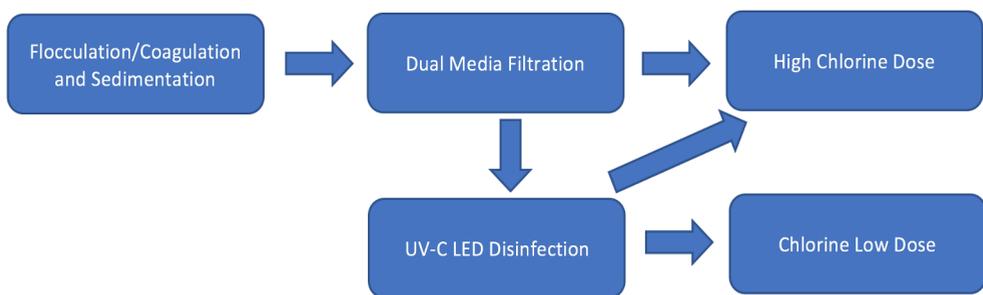


Fig. 2. Schematic of treatment trains

A Lovibond Floc Tester ET 750 was used for flocculation and coagulation. Through jar tests, the addition of 75 mg/l of ferric sulfate and pH adjustment of 5.6 was determined to be the optimal conditions for removing natural organic matter.

After pH adjustment and the addition of ferric sulfate, raw water samples were flocculated at a velocity gradient of 750 sec^{-1} for 30 minutes. After 30 minutes of settling time, samples were coagulated at a velocity gradient of 90 sec^{-1} for an additional 30 minutes. The treated

water was then pumped through the anthracite/sand filter at a flow rate of 12 ml/minute using Teflon tubing.

Samples were transferred to 950 ml amber jars, in which they were chlorinated with a sodium hypochlorite solution. CPD was dosed at 2 mg/l, while both UVPD and GAC + UVPD were dosed at 0.5 mg/l. The samples were then incubated at a constant temperature for $20^{\circ}\text{C} \pm 1^{\circ}\text{C}$ for 24 hours.

Afterwards, samples were transferred to 40 ml amber vials pretreated with sodium thiosulfate to neutralize chlorine and were sent to the Department of Civil and Environmental Engineering at the University of Massachusetts Amherst for trihalomethane analysis. A modified version of the EPA 551.1 method for analyzing trihalomethanes was used.

Additionally, effluent samples along every step of the treatment train were taken and analyzed for DBP precursors, including non-purgable organic carbon (NPOC) and UV-254 absorbance, which were determined using the combustion oxidation catalytic method and EPA Method 415.3, respectively [10]. NPOC was used instead of total organic carbon/dissolved organic carbon since some samples had levels of inorganic carbon that would interfere with results [13]. SUVA was derived by dividing UV-254 by NPOC.

3 Results and Discussion

3.1 Bacterial Inactivation

Raw river water had initial concentrations of 35 CfU/100 ml and 5 CfU/100 ml for total coliforms and *E. coli*, respectively. After filtration, bacterial concentrations remained mostly unchanged, with total coliforms remaining at 35 CfU/100 ml and *E. coli* reduced to 4 CfU/100 ml. After both conventional treatment and irradiation by UVC-LED, total coliform and *E. coli* concentrations were reduced <1 CfU/100 ml, meeting the drinking water standards [14].

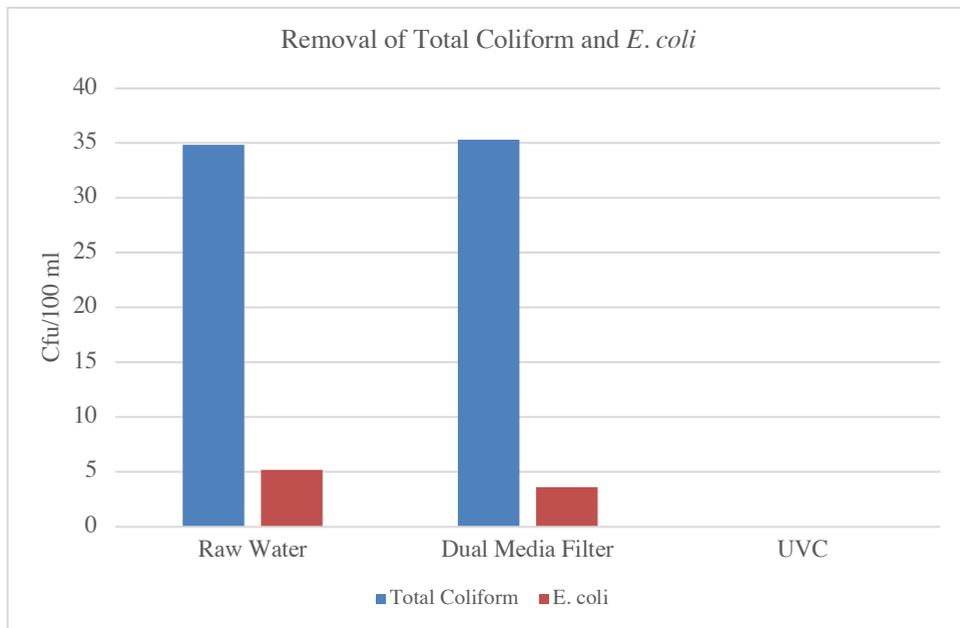


Fig. 3. Total coliform and *E. coli* inactivation using UVC-LED.

3.2 Trihalomethane Formation

There was a background concentration of 5.7 $\mu\text{g/l}$ of total trihalomethanes (TTHMs) in the source water, with chloroform being the dominant species. Removal rates for NPOC and reduction of UV254 absorbance were similar for the two conventional treatment trains. NPOC decreased by 70%, from an initial concentration of 5.7 mg/l in the raw source water to 1.7 mg/l for both the CPD and UVPD treatment trains. Reduction achieved was below the 2 mg/l EPA limit [14]. The addition of the GAC filter to the dual media sand/anthracite filter further reduced levels by 93% to 0.93 mg/l.

Table 1. Results for water treatment trains

Sample Name	Turbidity (NTU)	UV 254	SUVA (L/mg-M)	NPOC (mg/l)	TTH M ($\mu\text{g/l}$)	Total Coliform (Cfu/100ml)	<i>E. coli</i> (cfu/100 ml)
Raw	0.5	0.18	3.16	5.70	5.70	104.4	22.8
CPD	0.4	.02	1.16	1.72	8.54	0	0
UVPD	0.4	.02	1.23	1.62	6.13	0	0
GAC + UVPD	.07	.002	0.22	0.93	6.05	0	0

Although NPOC removal rates for CPD and UVPD treatment trains were similar, TTHM production was different. The addition of the higher chlorine dose (2 mg/l) in the CPD experiment increased TTHM production to 8.54 $\mu\text{g/l}$, which was a 33% increase from background levels. On the other hand, the lower chlorine dose (0.5 mg/l) for UVPD increased TTHM to just 6.13 $\mu\text{g/l}$, or a 7% increase from background levels. Though NPOC removal for UVPD with the addition of a GAC filter was higher than just UVPD, TTHM production was still very similar at 6.05 $\mu\text{g/l}$ or a 5.8% increase from background levels. The low SUVA levels were between 0.22 – 1.16 L/mg-M, suggesting that the NOM is hydrophilic in nature.

A study by Bougeard et al. (2009) on DBP formation potential in the United Kingdom showed similar results, in which low SUVA and NPOC levels of 1.5 L/mg-M and 0.2 mg/l, respectively, produced 11 $\mu\text{g/l}$ of TTHMs [13]. However, low TTHMs were only produced when both NPOC and SUVA were low [13]. In the same study, while effluent collected from various water treatment plants post coagulation/filtration had NPOCs levels between 1.4-1.6 mg/l, SUVA levels were as high as 2.7 L/mg-M, resulting in THM levels as high as 47 $\mu\text{g/l}$ [13]. In contrast, while NPOC in the conventional treatment train in this study was similar to Bougeard et al at 1.72 mg/l, SUVA was less than half at 1.16 2.7 L/mg-M, resulting in a TTHM concentration of 8.54 $\mu\text{g/l}$.

The lower NPOC and SUVA levels in this study may have been due to the high coagulant dose of 75 mg/l, which is almost 4.5 times higher than some conventional plants. Moreover, since ferric sulphate is one of the most effective coagulants, it is not surprising why the higher doses in this study achieved such an efficient DBP precursor removal, resulting in lower DBPs overall [15].

Therefore, this study is consistent with other literature, in which both low NPOC and SUVA levels together contribute to lower DBP production. Furthermore, although the treated water was not entirely precursor-free, a study by Rossman et al. (2001) showed that water that has been heavily pretreated and then chlorinated will produce low TTHMs [16]. Both the dose and the resulting THM levels in the Rossman study were 2.3 mg/l and 11 $\mu\text{g/l}$, respectively, similar to that of the conventional treatment train in this study [16].

4 Conclusion

All treatment trains were effective at inactivating total coliform and *E. coli*. UVPD and UVPD + GAC produced less TTHMs than conventional treatment. However, they were not significantly lower since TTHM formation for all treatment trains was near background levels and almost a tenth of the EPA's 80 µg/l MCL for TTHMs. DBP precursors, namely SUVA and NPOC, were reduced significantly due to the high dose of ferric sulphate, resulting in low TTHM formation for both conventional treatment and unconventional treatment with low chlorination. The results are consistent with other studies that show that both low SUVA and NPOC levels result in lower DBP formation potential.

More variation in DBP formational potential across the treatment trains may be observed when influent water is less pristine than the samples used in this study. This research project will be expanded to include other watersheds in particularly in agricultural and urban areas, where major DBP precursors are expected to be significantly higher.

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