

EFFECTIVENESS AND CARBON FOOTPRINT OF UV-OXIDATION FOR THE TREATMENT OF TASTE AND ODOR-CAUSING COMPOUNDS IN DRINKING WATER

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ABSTRACT

2-methylisoborneol (MIB) and geosmin are two compounds that lead to unpleasant tastes and odors (T&O) in drinking water. These compounds are often detected during or following seasonal algal blooms that can result from a combination of factors including warm temperatures and nutrient loading into water catchments through agricultural run-off. The combined use of ultraviolet (UV)-light and hydrogen peroxide, a process known as UV-oxidation, is a recognized approach to mitigating T&O problems brought on by MIB and geosmin.

To date, a number of water treatment facilities have adopted UV-oxidation for this purpose, and performance data has been collected from a recently completed North American UV-oxidation installation. The results demonstrated that UV-oxidation can remove well over 90% (1-log) of MIB while treatment with hydrogen peroxide alone (no UV) showed negligible levels of treatment. In addition to performance testing, a competitive life cycle analysis (LCA) analysis approach was taken to evaluate the global warming potential (GWP) of various T&O treatment technologies and UV-oxidation had 46.2% lower greenhouse gas (GHG) emissions compared to an alternative treatment approach which used carbon adsorption. The GWP of UV-oxidation was also compared with ozone, and a 7.9% lower GHG emission was observed by using UV-oxidation.

It was also recognized that removal of residual hydrogen peroxide upstream of a distribution system was necessary to ensure ongoing compliance with local drinking water standards. With this in mind, bench scale testing with granular activated carbon (GAC) and biological activated carbon (BAC) filtration demonstrated that empty bed contact times of as low as two minutes were effective at removing greater than 98% of residual H₂O₂ after UV-oxidation treatment with BAC often demonstrating improved residual removal efficiency over GAC. This suggested that frequent change-outs of filter beds are not necessary when using activated carbon for the quenching of residual H₂O₂.

This presentation will highlight the various technical, economic and environmental features and benefits of UV-oxidation when applied for the treatment of T&O compounds.

KEYWORDS

UV-Oxidation, Taste and Odor, Global Warming Potential, Quenching, Activated Carbon

1 INTRODUCTION

More water treatment facilities are taking action to eliminate contaminants which diminish aesthetic water quality. For example, 2-methylisoborneol (MIB) and geosmin are two commonly targeted compounds derived from *Cyanobacteria* (“algae blooms”) and are responsible for unpleasant earthy and musty tastes and odors (T&O) in drinking water.

Drinking water utilities can employ any of several methods to remove T&O-causing compounds like MIB and geosmin. Activated carbon, for example, is capable of removing MIB and geosmin through adsorption to carbon media. Treatment can also be carried out using advanced oxidation methods like ozone or UV-oxidation, the latter using ultraviolet (UV) light in combination with hydrogen peroxide (H_2O_2). This method uses UV to facilitate the dissociation of H_2O_2 into hydroxyl radicals, powerful oxidants which catalyze the breaking of the chemical structures of chemical contaminants including MIB and geosmin.

The objective of this study was to demonstrate the effectiveness of UV-oxidation for the treatment of T&O compounds by presenting performance data from a current North-American installation as well as utilizing life cycle assessment (LCA) methodology to evaluate which processes associated with various T&O treatment methods contribute most significantly to its overall environmental impact, with a specific focus on global warming potential.

2 METHODS

2.1 UV-OXIDATION TESTING

UV-oxidation performance data was collected at an installation owned and operated by the Patoka Lake Regional Water & Sewer District located in Indiana, in the United States. The installation has a design flow rate of 10 MGD (37.8 MLD), water with a UV transmittance (UVT) of 90.5% and a treatment goal of removing >95% (1.5-log) of MIB. The treatment system was composed of six UV reactors with medium-pressure UV lamps equipped with an H_2O_2 dosing system which injected up to 8 mg/L (ppm) H_2O_2 upstream of the UV reactors. Influent and effluent samples were collected and MIB levels were measured by a third-party laboratory. Specific tests are described in Table 1.

Table 1: Description of UV-oxidation performance data experiments

Test Description	UV (% Power)	H_2O_2 Dose
No Treatment	NONE	NONE
UV Alone	100	NONE
H_2O_2 Alone	NONE	8 ppm
50% UV+ H_2O_2	50	8 ppm
100% UV+ H_2O_2	100	8 ppm

2.2 QUENCHING STUDIES

H_2O_2 not converted to hydroxyl radicals during the UV-oxidation treatment process often needs to be removed before treated effluent can enter a distribution system. Bench scale studies using three columns (A,B and C) containing three different bituminous coal-derived activated carbon products produced by two manufacturers were carried out to evaluate the capacity of granular activated carbon (GAC) and biological activated carbon (BAC) for this purpose. Specifically, the carbon sources were:

- A. Manufacturer A (Catalytic Coal-Derived Carbon)
- B. Manufacturer A (Non-Catalytic Coal-Derived Carbon)

C. Manufacturer B (Non-Catalytic Coal-Derived Carbon)

To generate BAC, GAC was allowed to remain on a column for greater than 90 days without replenishment with fresh GAC. Biological activity on the GAC was regularly monitored by evaluating total organic carbon (TOC) removal.

Each column contained several sample ports at regular intervals so samples could be collected at various empty bed contact times (EBCT) up to a maximum of 20 minutes. Water used in these experiments was lake water filtered through 5 μL and 1 μL filters and mixed with de-chlorinated and deionized municipal drinking water to maintain a UV-transmittance (UVT) of between 90% and 93%. Various concentrations of H_2O_2 were spiked into the water before application to columns.

2.3 LIFE CYCLE ANALYSIS

For the LCA analysis, global warming potential (GWP) was evaluated for three hypothetical drinking water treatment facilities using different treatment methods for the removal of T&O molecules. These methods included:

- *Powdered Activated Carbon (PAC)*: Using bituminous coal for adsorption/filtration of contaminants.
- *Air-Fed Ozone*: Oxidative destruction of contaminants using ozone generated with ambient air onsite and dosed into raw water.
- *UV-Oxidation*: Oxidative destruction of contaminants using a combination of UV-light and H_2O_2 dosed upstream of UV reactors.

It was assumed that all facilities were located in New Zealand and each had a design flow rate of 10 MGD (37.8 MLD) and an average flow rate of 5 MGD (19.0 MLD). For each facility, MIB and geosmin were treated to remove 0.7-log (63%) and 0.9-log (81%) of each contaminant respectively. Since algae blooms are a seasonal event, it was assumed that each facility would function to remove T&O molecules for two months and carry out standard drinking water disinfection for the remainder of the year.

The LCA study described herein applied a “cradle to gate” framework (Figure 1). Specifically, the GWP of each facility was evaluated by accumulating the GWPs of the individual processes associated with the extraction of raw material, the manufacture of raw material into useable supplies and equipment, transportation, as well as processes associated with plant operation (e.g. energy consumption). Processes involved with equipment disassembly and disposal at the end of the project’s lifetime were not within the scope of the cradle to gate study. All GWPs were expressed in units of emitted carbon dioxide equivalents (CO_2e) which is the cumulative release of three common greenhouse gases: carbon dioxide (CO_2), methane and nitrous oxide. Each greenhouse gas was converted to an equivalent amount of CO_2 emissions by applying an established multiplier (Table 2).

Table 2: Specific greenhouse gas emissions accounted for in LCA analysis with respective CO_2e multipliers (Solomon, 2007)

Greenhouse Gas	CO_2e Equivalent Multiplier
Carbon Dioxide	1
Methane	21
Nitrous Oxide	310

3 RESULTS AND DISCUSSION

3.1 UV-OXIDATION PERFORMANCE AND QUENCHING

Treatment with H₂O₂ alone demonstrated negligible levels of MIB removal and treatment with UV-light (without H₂O₂) resulted in an approximate 0.5-log reduction of MIB (Figure 2). However, neither of these scenarios were capable of achieving the desired MIB reduction required by the facility (1.5-log). Conversely, UV in combination with H₂O₂ demonstrated significantly higher levels of MIB removal with over 2.2-log and 1.4-log MIB removal being observed with UV lamps operating at 100% power and 50% power respectively.

Table 3: H₂O₂ concentrations measured in water spiked with H₂O₂ and sampled at various EBCTs from the indicated GAC columns.

Column	H ₂ O ₂ Concentration (mg/L)		
	Initial (EBCT = 0 min)	EBCT = 2 min	EBCT = 4 min
A	1.8	0.02	N/S
B	1.8	0.03	N/S
C	1.8	0.03	N/S
A	3.73	Not Sampled	0.01
B	3.73	Not Sampled	0.01
C	3.73	Not Sampled	0.01
A	1.5	Not Sampled	0.01
B	1.5	Not Sampled	0.01
C	1.5	Not Sampled	0.01

Regardless of the type of activated carbon used, the bench-scale column tests demonstrated that the majority of H₂O₂ was removed at EBCTs between two and four minutes (Table 3). Further, column A showed no discernable improvement in H₂O₂ removal over column B suggesting that modifying activated carbon to allow for heightened catalytic activity did not enhance removal of H₂O₂ from treated effluent of UV-oxidation treatment.

Table 4: H₂O₂ concentrations measured in water spiked with H₂O₂ and sampled at various EBCTs from the indicated BAC columns.

Column	H ₂ O ₂ Concentration (mg/L)		
	Initial (EBCT = 0 min)	EBCT = 2 min	EBCT = 4 min
A	8.15	0.01	ND
B	8.24	0.03	0.01
C	8.31	0.02	0.01
A	9.24	0.02	0.02
B	9	0.03	0.02
C	10.6	0.3	0.02

Removal of H₂O₂ using BAC demonstrated similar levels of removal (Table 4) suggesting that the loss of catalytic sites on GAC due to the presence of biofilms does not negatively influence the ability of the media to remove H₂O₂ after UV-oxidation treatment.

3.2 LCA STUDY

With regards to the LCA analysis, the total GWP, taking into account all individual processes for all three hypothetical treatment facilities are provided in Table 3. PAC carried a significant GWP of 1.07×10^7 kgCO₂e, greater than any of the oxidation based methods while ozone and UV-oxidation carried GWPs of 3.07×10^6 kgCO₂e and 3.10×10^6 kgCO₂e respectively. It was further determined that the process contributing most significantly to the overall GWP of PAC was the production of raw material, namely the carbon activation step (Figure 3) while GWP of both ozone and UV-oxidation were most heavily influenced by electrical energy use and other operational processes.

4 CONCLUSIONS

The UV-oxidation (UV + H₂O₂) performance data successfully demonstrated 1.5-log MIB reduction, providing a valuable precedent of a full-scale UV-oxidation installation being able to carry out advanced oxidation of T&O causing contaminants. Quenching studies further revealed that removal of residual H₂O₂ could be carried out with a minimum contact time using activated carbon both with and without biological activity. This shows that in the event that the catalytic sites vital to the decomposition of H₂O₂ on GAC become inaccessible due to biological activity, subsequent BAC can continue to remove residual H₂O₂. The latter process is driven by catalase, an enzyme naturally produced by aerobic (oxygen-dependent) organisms present within biofilms (Urfer and Huck, 1997). Collectively, these results highly suggest that activated carbon columns can be applied for extended periods of time to carry out residual H₂O₂ quenching, potentially reducing operating costs associated with the quenching process of UV-oxidation treatment.

When evaluating environmental impact, UV-oxidation carried a GWP of 3.10×10^6 kgCO₂e, 70% less than the GWP of the PAC alternative. Figure 4 provides a detailed break-down of the individual processes contributing to the overall GWP of the hypothetical UV-oxidation facility. Electricity production to power UV lamps was the most significant overall contributing factor to this GWP with other processes making much lower impact. It is mentionable that the production of H₂O₂ made less than a 12% overall impact on UV-oxidation GWP.

The relatively large GWP observed with PAC (Table 3) has also been demonstrated in other reports including Johnson et al. (2005) and Swaim et al. (2010) and is primarily the result of the GWP associated with the burning of fossil fuels (usually natural gas) to activate carbon and convert it from bituminous coal into a porous state capable of adsorbing contaminants. This activation process encompasses over 91% of the total GWP of using PAC for T&O removal with the remaining GWP being made of a combination of infrastructure, operational and transportation processes. The GWP of oxidation-based methods in contrast, were less dependent on the direct burning of fossil fuels and more dependent on electricity as mentioned previously for UV-oxidation. It is also worth mentioning that UV-oxidation and ozone can effectively be installed to inactivate microorganisms during times of the year when T&O causing compounds are less prevalent. PAC facilities on the other hand are less recognized for disinfection and are traditionally active exclusively when T&O events are occurring. As a result, manufactured PAC must often be stored on-site between T&O events. Producing the materials required to construct PAC storage facilities could potentially increase the overall GWP of a PAC-based facility but this assumption was not made for the LCA herein. PAC facilities also inherently have operational and disposal processes which are not required for ozone or UV-oxidation treatment. Such processes would further increase the GWP of PAC-based systems but were also not included in the cradle to gate scope of this LCA.

With regards to the electricity production demands for oxidation-based treatment methods, it was observed that ozone generators and UV lamps required the most electrical energy for ozone and UV-oxidation methods respectively. Inherently, operational processes heavily dependent on electricity have a GWP which can fluctuate depending on the methods employed to produce electricity. For example, electricity produced through nuclear energy or renewable energy such as hydroelectricity and wind energy would have lower GWP than methods dependent on fossil fuel combustion. In contrast, water treatment methods whose operation is dependent on direct combustion of fossil fuels as in the case of PAC will have consistent GWP throughout various geographies. It can be argued that with the introduction of new renewable energy solutions and future improvements in the efficiency of existing methods of electricity production that the gap between oxidation-based and PAC adsorption-based T&O treatment methods could be more significant.

With increasing pressure being placed on various industries to evaluate environmental impact and pursue environmentally-friendly operation, evaluating which processes influence environmental impact categories like GWP through methods like LCA will become more significant.

Figure 1: Diagram of cradle to gate LCA analysis categories with processes incorporated into the LCA within the red box.

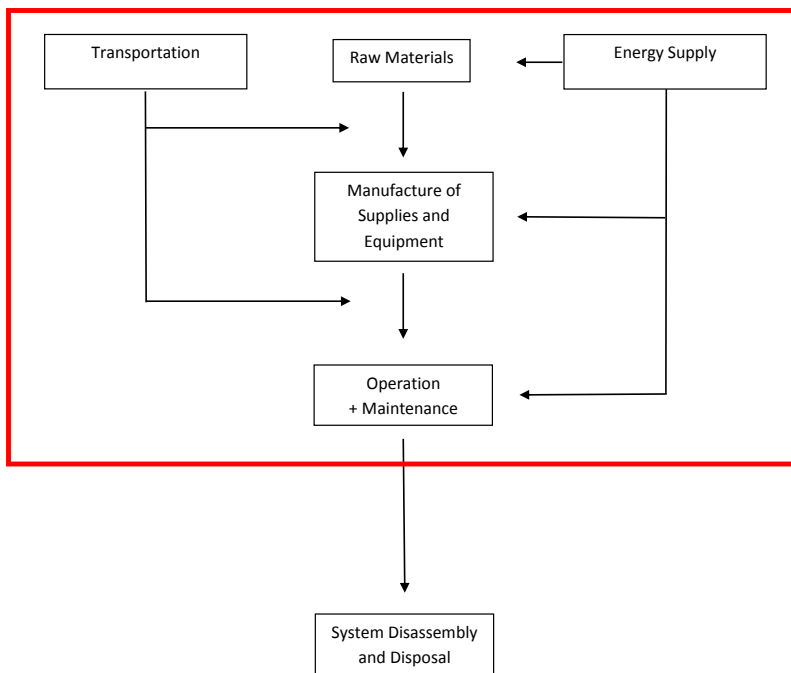


Figure 2: Evaluated MIB reductions (log) with indicated UV and H₂O₂ treatment. H₂O₂ dose = 8 ppm

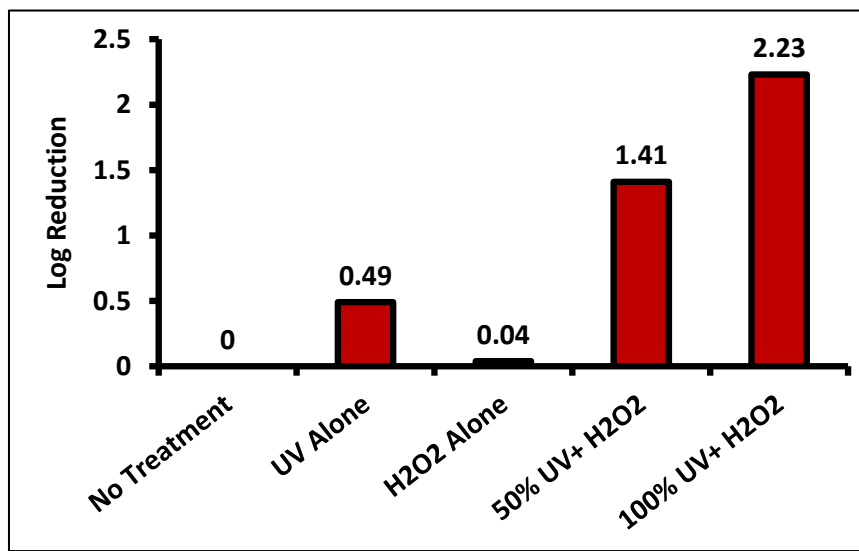


Figure 3: Break-down of how various processes contribute to overall GWP of T&O treatment methods.

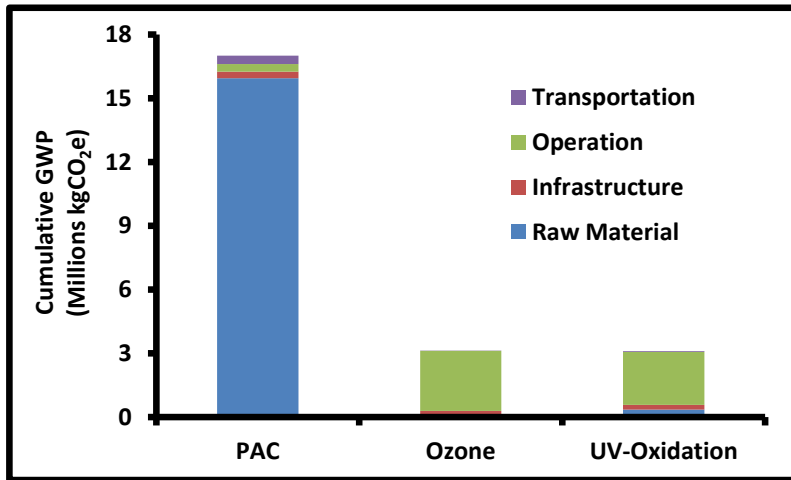
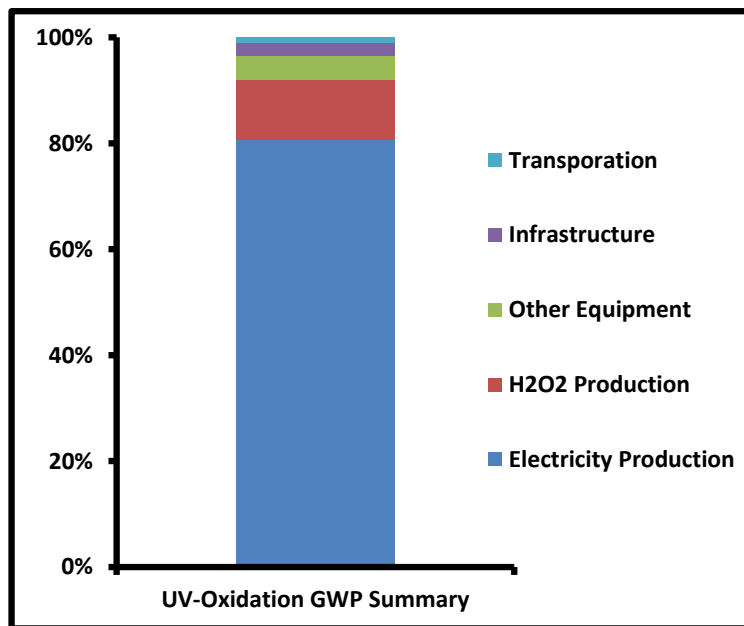


Figure 4: Break-down of the individual processes contributing to the overall GWP of the hypothetical UV-oxidation T&O compound treatment facility



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