Engineered Biofiltration for Drinking Water Treatment: Optimizing Strategies to Enhance Performance

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The use of biological drinking water treatment processes for the treatment of surface water and groundwater has recently been increasing in North America. Biofiltration can simultaneously remove a wide range of dissolved organic and inorganic contaminants, while achieving particle removal goals. Organic compounds, including color and taste and odor (T&O)-causing compounds, are not only removed but also destroyed in this process. This can limit the formation of disinfection byproducts (DBPs) and lower regrowth potential in the distribution system. Operation of biofilters requires low energy input, minimal chemicals, and little waste production. Although biofiltration can provide numerous benefits, biofilter systems can be susceptible to hydraulic and water quality challenges, such as shortened runtimes, biological clogging, and breakthrough of contaminants such as T&O, manganese (Mn), and organic carbon.

Drinking water biofilters are often designed and operated similarly to conventional granular media filters, and backwashing is the primary means of biofilm control. However, backwash protocols can be ineffective at restoring clean-bed headloss and preventing underdrain fouling, even with the addition of chlorine or chloramines. These disinfectants may not effectively remove extracellular polymeric substances (EPS), which are a primary foulant of biofilters (Lauderdale et al., 2011). Adding chlorine or chloramines to biofilters can also harm the biology needed for achieving water quality goals. The EPS are significant to both fouling and headloss issues because they can occupy as much as 1,000 times the void space of filter media compared to bacteria (Mauclaire et al., 2004). An alternative approach for biofilm control is to manage microbial EPS production through 1) nutrient supplementation, and/or 2) direct removal of EPS through hydrogen peroxide (H_2O_2) supplementation.

Pilot studies, which spanned two Water Research Foundation (WRF) tailored collaboration (TC) projects (#4215 and #4346), focused on investigating enhancement strategies for drinking water biofilters. Pilot tests were conducted at three surface water plants in Florida and Texas. The TC project #4215, *Engineered Biofiltration for Improved Hydraulic and Water Treatment Performance*, identified two "engineered biofiltration" strategies (nutrient and peroxide enhancement) that provided multiple water quality and hydraulic benefits with minor implementation requirements (Lauderdale et al., 2011). The follow-up study, TC #4346, *Optimizing Engineered Biofiltration*, provided essential studies to validate, optimize, and explore these strategies to achieve sustained performance.

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Background

A purposefully operated biological system (i.e., engineered biofiltration) includes biological treatment objectives as important aspects of biofilter design and operation. The goal of this work is to shift the practice of biofiltration from a passive process, designed and operated around conventional filtration objectives, to an intentionally operated biological system. The studies described here include pilot-scale studies of two strategies to meet this goal: nutrient and peroxide enhancement.

Nutrient Enhancement

Optimal microbial growth relies on a proper balance of carbon, nitrogen, and phosphorus. The typical target ratio of assimilable carbon: ammonia-nitrogen: orthophosphate-phosphorus (C:N:P) is 100:10:1 (USEPA, 1991). This molar ratio converts to a concentration ratio of 1 mg/L C: 0.117 mg/L N: 0.026 mg/L P. The biological filter feed at typical water treatment facilities has nondetectable amounts of phosphorus (<0.01 mg/L), due to removal through enhanced coagulation and/or source water limitation. This phosphorus-limiting condition can be unfavorable for biofilter operation because phosphorus is an essential nutrient to maintain a healthy microbial population. In addition, phosphorus deficiency may lead to increased microbial production of EPS, which are strongly adhesive and may cause clogging of biofilter media or underdrains. For that reason, adding phosphorus to the biofilter feed water may improve the "type" of biogrowth in the filters to minimize clogging, decrease headloss, and maintain uniformity of flow.

Peroxide Enhancement

Low doses of hydrogen peroxide (≤1 mg/L) effectively oxidize and remove EPS and inactive biomass without negatively affecting the biological activity desired for water treatment. Hydrogen peroxide may also improve biofilter treatment performance by causing certain microorganisms to express oxidoreductase enzymes that produce free radicals. These free radicals can also remove EPS, as well as oxidize recalcitrant organic compounds.

Materials and Methods

Pilot Biofilters

Pilot studies were conducted at three surface water treatment plants (WTPs): John Kubala WTP in Arlington, Texas; Tampa Bay Regional Surface WTP in Tampa; and Bachman WTP in Dallas. Each pilot skid (Intuitech, Salt Lake City, Utah) included four parallel biofilters (6-in. diameter columns). The pilot biofilter columns contained the same media configuration as the full-scale system at the host site (Table 1). Biofilter feed (from upstream ozonation and coagulation processes) were supplied to the pilot

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Table 1. Pilot Plant Setup and Operating Parameters

Sponsor Utility	Arlington, Texas	Tampa Bay Water, Fla.	Dallas Water Utilities, Texas[1]
Project	WRF TC #4215	WRF TC #4346	WRF TC #4346
Host Site	John Kubala WTP	Tampa Bay Regional Surface WTP	Bachman WTP
Pilot Duration	9 months	14 months	14 months
Biofilter Feed			
Upstream Processes	Preozonation, Coag/ Floc/Sed, Intermediate Ozonation	Actiflo™ Process, Ozonation	Preozonation, Enhanced Coagulation
Coagulant Type	Alum	Ferric	Ferric
Filter Feed pH	7.0	7.5	7.1
Pilot Plant			
No. of Pilot Filters	4	4	4
Media Configuration	40-in. Granular Activated Carbon (GAC) 8-in. sand	48-in. GAC or Anthracite, 6-in. sand	24-in. GAC or Anthracite, 12-in. sand
Underdrain	Leopold IMS® cap	Leopold IMS® cap	Leopold IMS® cap
Filter Loading Rate	4.5 gpm/ft^2	2.5 – 4 gpm/ft^2	2.5 gpm/ft^2
Backwash Triggers[2]	Runtime > 18 hrs Headloss > 13.5 ft Turbidity > 1 NTU	Runtime > 24-48 hrs Headloss > 9 ft Turbidity > 1.2 NTU	Runtime > 24 hrs Headloss > 8-16 ft Turbidity monitored[3]

Notes:
1. Dallas Water Utilities' pilot system included a flocculation/sedimentation (Floc/Sed) pilot unit to treat ozonated water from the full-scale plant prior to the biofiltration pilot. All of the pilot-scale biofilters at Dallas were operated to simulate future full-scale conditions after conversion from conventional filters to biofilters.
2. Automatic backwash triggers included runtime, headloss, and effluent turbidity.
3. Effluent turbidity was continuously monitored and logged for each biofilter, but was not used as an alarm limit to automatically initiate a backwash cycle.

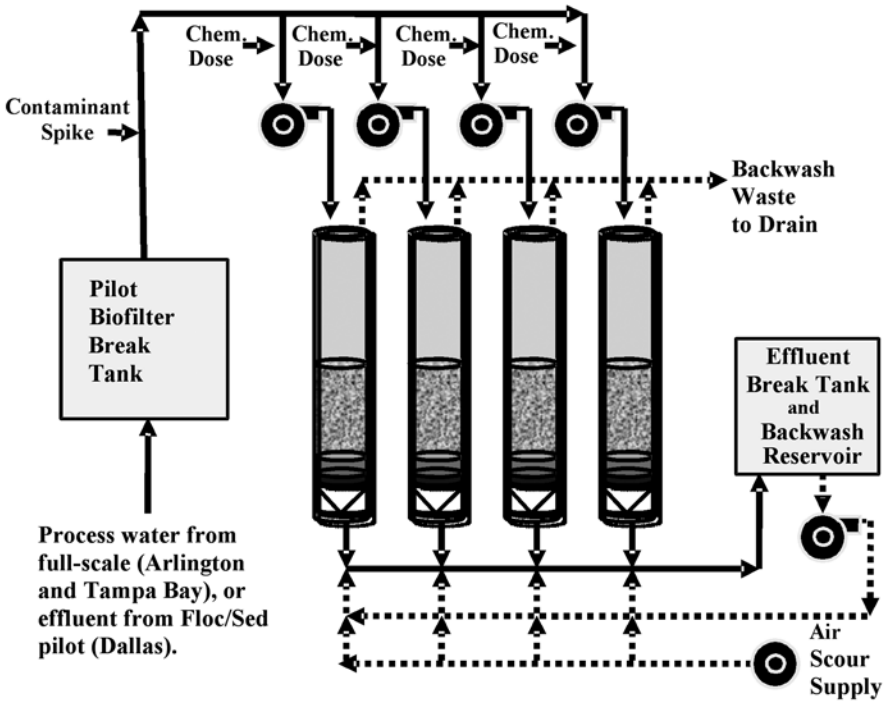

Figure 1. Biofilter Pilot Process Flow Schematic

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equipped with progressive cavity feed pumps (one dedicated pump per column) with automatic flow control. Peristaltic feed pumps allowed flow-paced chemical injection to the combined biofilter feed water for spiking contaminants, such as 2-Methylisoborneol (MIB) and Mn. Biofilter effluent was pressure-fed to a backwash water storage tank. Each pilot included a backwash system with dedicated pump and air-scour system. Backwash protocols simulated that of the hosting full-scale facility. Pilot instrumentation included on-line effluent turbidimeters, flow transmitters, and pressure sensors for monitoring headloss. Each pilot was equipped with an automatic data logger, which recorded the following data every 10 min for the duration of the study: headloss, effluent turbidity, biofilter underdrain pressure, backwash underdrain pressure, filtration rate, runtime, and run volume.

Chemical Feed

Contaminants were spiked to the pilot biofilter feed water using a peristaltic pump and 40-L chemical tank. To promote mixing, a static mixer was located downstream of the injection point. Contaminant spiking tests were performed to characterize Mn and T&O (e.g., MIB) removal performance. Manganese spiking of the pilot biofilter feed water was performed using reagent-grade manganese chloride from Sigma Chemical (St. Louis, Mo.); the MIB (gas chromatography-grade in methanol) was also purchased from the chemical company.

For testing of the enhancement strategies, nutrients or peroxide were fed to the top of the specified biofilter using dedicated peristaltic pumps supplied by 40-L chemical tanks. Phosphorus (PO_4-P) supplementation was performed using NSF-60-certified 83 percent phosphoric acid. Caustic (50 percent sodium hydroxide) was used for the biofilter feed pH adjustment at Tampa Bay and Dallas. Peroxide supplementation used food-grade 3 percent hydrogen peroxide (Arlington pilot) or technical-grade 20 percent hydrogen peroxide (Tampa Bay and Dallas pilots).

Analytical Methods

Water quality samples of the pilot biofilter feed and effluent streams were collected twice per week throughout the pilot study period. Results were used to verify operation (e.g., dosed nutrient and hydrogen peroxide concentrations) and to evaluate water treatment performance of the pilot biofilters. Analytical methods for key parameters are:

- *Turbidity*. In-line nephelometers (Hach or ThermoScientific) were used for continuous turbidity measurement of pilot filter effluents.

- *Hydrogen Peroxide.* Hydrogen peroxide concentration of the biofilter feed water was measured on site using a CHEMets Colorimetric Hydrogen Peroxide Test Kit (Chemtech International, Media, Pa.).
- *Total Organic Carbon (TOC) and Dissolved Organic Carbon (DOC).* Both TOC and DOC were performed using Standard Method 5130B.
- *Manganese (Mn).* Total Mn measurements were performed in accordance with Standard Method 311B.
- *Ammonia-nitrogen (NH_4-N).* The NH_4-N measurements were performed in accordance with Standard Method 4500.
- *Orthophosphate-phosphorus (PO_4-P).* The PO_4-P measurements were performed in accordance with U.S. Environmental Protection Agency (USEPA) Method 300.0.
- *2-Methylisoborneol (MIB).* The MIB analyses were performed in accordance with Standard Method 6040D.

Pilot biofilter media samples from the top 6 in. of each biofilter column were collected twice per month. Each sampling event included two samples: (1) after a backwash (i.e., clean bed), and (2) at the completion of the subsequent filter run (i.e., dirty bed). The media samples were used for microbial characterization, including:

- *Adenosine triphosphate (ATP).* The ATP analysis on biofilter media was conducted using a Deposit and Surface Analysis Test Kit (LuminUltra, Fredericton, N.B.) and a luminometer (Kikkoman, Tokyo, Japan) following the manufacturer protocols.
- *Scanning Electron Microscopy (SEM).* Biofilter media samples were imaged using a JEM 6490 LV scanning electron microscope (Peabody, Mass.).
- *EPS.* Sugars from EPS polysaccharides were measured using the method described by Dubois et al. (1956).

Results and Discussion

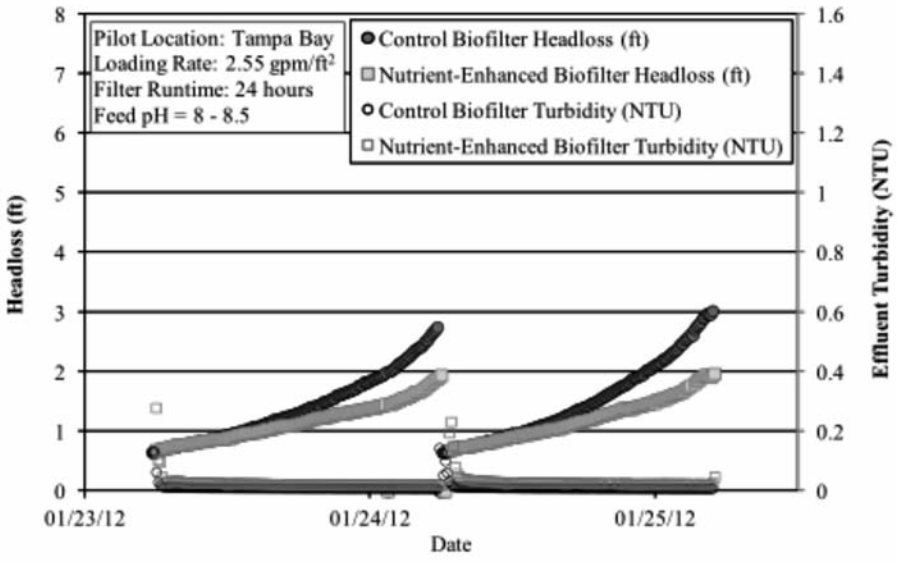
Nutrient Enhancement Studies

The biofilter feed water at the pilot sites was typically phosphorus (PO_4-P)-limited due to source water limitation and/or PO_4-P removal through upstream coagulation processes. Nutrient enhancement of biofilters initially targeted a total (background + dosed) bioavailable C:N:P molar ratio of 100:10:1. The PO_4-P and/or NH_4-N were used to supplement nutrient deficiencies in select biofilters.

Nutrient supplementation testing at the Arlington pilot included PO_4-P supplementation (0.02 mg/L as P) to satisfy the nutrient deficiency. Multiple benefits were achieved, including improved hydraulics, water quality performance, and microbial characteristics (Lauderdale et al., 2011; Lauderdale et al., 2012):

- *Hydraulic Performance.* The PO_4-P supplementation to the nutrient-enhanced biofilter feed decreased terminal headloss (at an 18-hour filter runtime) by approximately 15 percent, relative to the control biofilter. This improvement in hydraulic performance translates to energy savings and reduced chemical usage to retreat backwash water.
- *Water Treatment.* Performance was tracked across multiple parameters, including turbidity, DOC, Mn, and MIB. The PO_4-P supplementation improved the removal of DOC and Mn compared to the control. The DOC removal across the filter bed was 19 percent for nutrient-enhanced biofilter compared to 11 percent for the control. Removal of background Mn was observed for both the nutrient-enhanced and control biofilters. High concentrations of Mn were also spiked to the biofilter feed (224 µg/L). Effluent Mn concentrations were nondetect (< 2.4 µg/L) for the nutrient-enhanced biofilter, whereas the control biofilter effluent averaged 25 µg/L. During simulated long-term, moderate MIB spiking to the pilot biofilter feed, mean effluent MIB concentrations remained below the T&O threshold (< 10 ng/L) for the nutrient-enhanced and control biofilters. All pilot biofilter effluent turbidities maintained compliance with the USEPA Surface Water Treatment Rule.
- *Microbial Characteristics.* Compared to the control biofilter, the nutrient-enhanced biofilter media had lower-measured biofilter EPS concentrations (corresponding to the decrease in headloss relative to the control), 30 percent higher terminal (end of filter run) ATP concentrations (corresponding to higher biomass concentrations), and more morphological diversity and cell abundance.

Figure 2. Profiles of the Control and Nutrient-Enhanced Biofilter at Optimized pH Conditions



Follow-up nutrient enhancement studies at Tampa Bay and Dallas using PO_4-P supplementation and pH adjustment of the biofilter feed water improved hydraulic performance (>18 percent decreased terminal headloss relative to the control) and had no significant effect on water treatment performance (e.g., DOC, MIB, Mn removal). Figure 2 presents example headloss and turbidity profiles for the control and PO_4-P-enhanced biofilter at the optimal pH.

Optimization of the biofilter feed pH (8.0 to 8.5) proved to be an important parameter to achieve hydraulic improvements at the Tampa Bay and Dallas pilots. At ambient biofilter feed pH (7.1-7.5), nutrient supplementation did not improve biofilter performance. This was unexpected due to the results of the previous study, where nutrient addition showed hydraulic and water quality improvements. One notable difference was the type of coagulant used in upstream processes (alum versus ferric). Without pH adjustment, chemical modeling suggested removal of bioavailable PO_4-P by ferric hydroxide carried over from upstream flocculation/sedimentation processes prior to penetrating the media bed (Figure 3). Increasing biofilter feed pH above

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the isoelectric point of the carryover floc (i.e., creating a positive surface charge) inhibits adsorption of negatively charged PO_4-P onto ferric hydroxide carryover. As a result, the PO_4-P stays in solution and is available for microorganisms in the filter bed. Thus, the biofilter feed pH was adjusted to approximately 8.0 at Dallas and 8.5 at Tampa Bay. This process adjustment resulted in decreased headloss across all filters at Dallas, and further improvement in the hydraulic performance of the nutrient-enhanced column relative to the control at both Dallas and Tampa Bay.

Peroxide Enhancement Studies

The pilot studies at both the Florida and Texas utilities showed that peroxide supplementation significantly improves biofilter hydraulic performance. The strategy was first identified at the Arlington pilot when biofilter terminal head loss (at 24 hours) decreased from 6.5 ft (n = 1) to an average of 2 ft (n = 6) after initiating a continuous 1 mg/L peroxide dose to the biofilter feed water (Lauderdale et al., 2011; Lauderdale et al., 2012). These results showed a promising trend and provided the basis for further study.

Validation testing of the peroxide enhancement strategy was conducted by initially augmenting the peroxide biofilter feeds at Tampa Bay and Dallas with 1 mg/L of peroxide. Following preliminary confirmation of the hydraulic benefits associated with peroxide supplementation, the peroxide dose was optimized by adjusting the biofilter feed concentrations to between 0.1 mg/L and 2 mg/L.

At Tampa Bay, hydraulic improvements were observed for the peroxide doses tested (0.5 to 2 mg/L), as shown in Figure 4. The optimum peroxide dose was 0.75 to 1 mg/L. At these concentrations, headloss improved by an average of 25 and 27 percent, respectively, at 24-hour filter runtimes. Algae growth was also inhibited by peroxide addition, as illustrated in Figure 5. Peroxide feed robustness tests showed that hydraulic performance improved during a period of "overfeeding" peroxide (10 mg/L), and hydraulic performance degraded to match control biofilter headloss trends when a peroxide feed failure was simulated. Effluent water quality (e.g., DOC, turbidity, Mn, and MIB) from the peroxide-enhanced biofilter was similar to the control at all peroxide doses tested.

The peroxide dose that provided the best hydraulic improvement at the lowest cost differed for Tampa Bay (0.75 mg/L) and Dallas, where a 0.1 mg/L peroxide dose resulted in 33 percent lower headloss. These results demonstrate the need to evaluate and optimize peroxide feed for hydraulic improvement on a case-by-case basis, as biofilter peroxide demand is likely dependent on multiple factors, including temperature, source water, microbial ecology, and upstream treatment.

Figure 3. Photo of Carryover Ferric Floc Accumulated on the Top (Feed Side) of the Biofilter

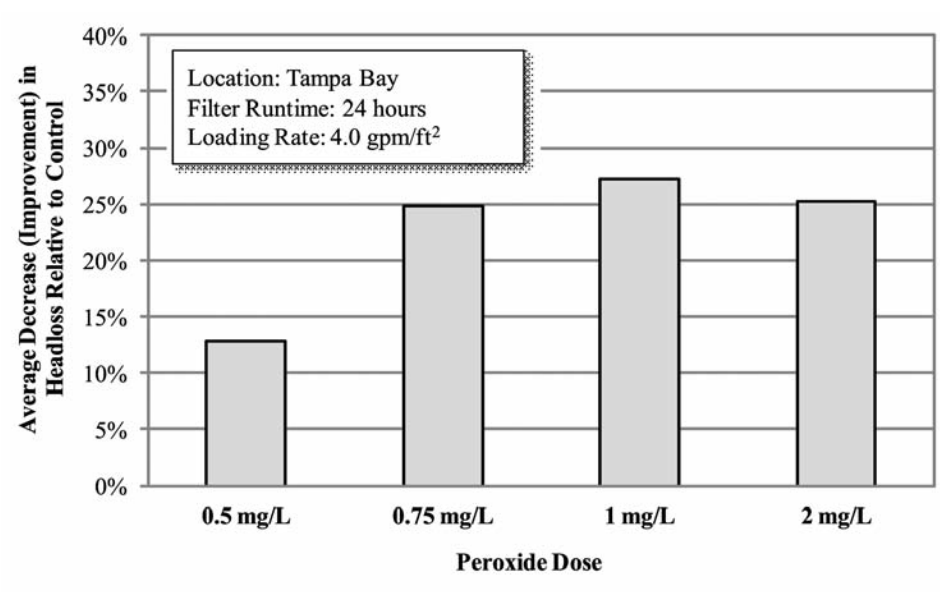

Figure 4. Average Hydraulic Performance of GAC Biofilters Supplemented With Varying Doses of Hydrogen Peroxide Relative to the Control Biofilter (No Peroxide)

Biofilter Media Type

The parallel operation of anthracite and GAC media in the pilot studies provided a comparison of treatment and hydraulic performance of each media type. The nutrient and peroxide enhancement strategies improved anthracite biofilter hydraulic performance over the control GAC filters. However, anthracite biofilter water treatment performance was inferior to the GAC biofilters for both Tampa Bay and Dallas under all test conditions (e.g., control, peroxide enhancement, and nutrient enhancement).

The ATP analysis of GAC media collected from the control and peroxide-supplemented biofilters showed that the peroxide supplementation (0.1 – 10 mg/L) did not significantly impact microbial activity. However, ATP concentrations in the anthracite biofilter decreased during periods of peroxide supplementation (0.5 – 2 mg/L). These results indicate that GAC may be a more robust support media to support biological growth.

Pretreatment (Coagulation) Optimization Testing

Pilot-scale-enhanced coagulation pretreatment optimization was performed concurrently with the biofiltration pilot at the Dallas pilot site. The pilots were tested for ho-

listic, multiprocess optimization. At coagulant doses of 60 mg/L and 30 mg/L (as $Fe_2(SO_4)_3*9H_2O$), results showed the same level of combined DOC removal through the coagulation and biofiltration processes. This demonstrates synergy between the coagulation and biofiltration processes. This test result also presents a significant opportunity for cost savings on chemical costs, while achieving organic carbon and DBP precursor removal goals.

Conclusions

Pilot testing spanning two Water Research Foundation projects (TC #4215 and #4346) identified, validated, and optimized two "engineered biofiltration" strategies with minor implementation requirements: (1) nutrient enhancement and (2) hydrogen peroxide supplementation. These studies identified conditions that allow nutrient enhancement to be applicable across multiple water sources and treatment schemes. The pH was identified as an important parameter for biofilter nutrient optimization, which may broaden the applicability of this enhancement strategy. Pilot-scale optimization of the peroxide enhancement strategy at Tampa Bay Water and Dallas Water Utilities showed that the optimal dose for biofilter performance improvement was site-specific, indicating that biofilter peroxide demand is likely dependent on multiple factors. Optimization studies for the biofiltration process and upstream coagulation process identified a synergy between the processes. The results of this pilot-scale test showed that biofilters decreased coagulant requirements by >50 percent, while achieving organic carbon and DBP precursor removal goals. This highlights the importance of holistic, full-process evaluations for optimizing water treatment facility operation and performance.

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Figure 5. Photo Showing Inhibition of Algae Growth in the Biofilter Supplemented With Hydrogen Peroxide (Third Column From the Left)