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Impact of biofilter operation on microbial community structure and performance

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ABSTRACT

The objectives of this pilot-scale study were to evaluate biological acclimation of virgin granular activated carbon (GAC), quantify the impact of nutrient (phosphorus and nitrogen) enhancement and to compare the performance of parallel biologically active carbon (BAC) filters operated continuously or cyclically (12 h/day), with respect to removal of dissolved organic carbon (DOC) and disinfection by-product (DBP) precursors. Virgin GAC media outperformed biologically active carbon for an initial 4-month period in terms of DOC reduction (30%), as expected based on the superior performance associated with adsorption compared to biodegradation. Once the adsorptive capacity was exhausted and the media was biologically acclimated, the performance of the new GAC was statistically similar in terms of organic carbon and disinfection by-product precursor removal to a filter containing media harvested from a filter operating biologically for 12 years. Phosphorus addition to the filter influent (0.3 mg PO_4-P/L; C:N:P = 400:1:30) had a small impact on DOC (3 ± 2%) and THM formation potential (5 ± 3%) reduction when compared to biofiltration without nutrient enhancement. Ammonia nitrogen added to the filter influent (0.8 mg NH_4-N/L; C:N:P = 200:40:1) was completely consumed through the biofilter; however, no impact on measured performance parameters was observed. Cyclical operation of full-scale biofilters resulted in a modest, but significant improvement in DOC removal (3 ± 2%) when compared to continuously operated pilot filters. Genotyping of both cyclically and continuously operated biofilters (with varying GAC ages) showed similar community composition; however, differences in the phylogenetic diversity of the samples were evident.

1. Introduction

Granular activated carbon (GAC) is commonly used as a filter-adsorber in drinking water systems. GAC filters have been shown to effectively remove natural organic matter (NOM; [1], disinfection by-product (DBP) precursors [2] and micropollutants including pharmaceuticals [3], as well as taste and odour compounds [4]. Over time general trends show that GAC loses adsorptive capacity while at the same time biofilm development occurs to promote removal of various substances through biodegradation. Previous studies have reported the time required for biological acclimation to occur (~90 days, [5]; however, limited information is available for biofilters which receive water that been pre-treated with ultrafiltration, which remove particulates.

It has been hypothesized that carbon metabolism by biofilters may be limited by the amount of bioavailable phosphorous or nitrogen. An optimal molar uptake ratio of 100:10:1 for carbon:nitrogen:phosphorous has previously been proposed based on the metabolic cycles of aerobic organisms [6]. Phosphorus has been identified as a limiting nutrient in many drinking water sources [7], and correspondingly in drinking water biofilters [8]. Shifting from a phosphorous or nitrogen limitation to a carbon limiting environment has been hypothesized to stimulate carbon utilization by the attached microbiome for cell synthesis and energy production, thereby increasing NOM biodegradation [9]. Mixed consensus exists in the literature regarding the efficacy of nutrient addition on biofilter performance. Lauderdale et al. [6] reported that phosphorus addition (0.02 mg PO_4-P/L) to pre-ozonated biofilter influent increased DOC removal by 75% (0.7 mg/L) compared to a passively operated biofilter (0.4 mg/L) with an EBCT of 6.7 min. In contrast, McKie et al. [10] and Azzeh et al. Azzeh et al. (2014) observed no impact of phosphorus or nitrogen enhancement to the filter influent (0.5 mg/L; C:N:P = 10:1:1) on DOC removal by biologically active anthracite or GAC filters (EBCT = 10 min) receiving waters with or without pre-ozonation.

Although many water treatment facilities operate continuously, some may only be operated to meet demand, or to utilize available

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storage capacity. As a result, treatment systems may be operated cyclically as water is required. Niquette et al. [11] examined the shutdown of biofilters and reported DOC removal to increase once filters were re-started, however, reasons for this improvement were not provided. It is hypothesized that cyclical biofilter operation may preferentially promote the growth of NOM degrading bacteria, providing improved water quality. Such a "feast and fasting" phenomenon is routinely practiced in wastewater treatment, where cyclic aerobic and anaerobic conditions are employed to preferentially select for healthy microorganisms and increase the biodegradation rate of organic matter [12].

In this study, the acclimation period of virgin GAC media was monitored to better understand biofilter start-up as well as the time required to achieve biological versus adsorptive removal. Performance was characterized by pH, temperature, turbidity, dissolved oxygen, DOC and THM and HAA formation potential (FP) to compare both continuous and cyclically operated biofilters as well as the impact of nutrient enhancement. Finally, the biological community composition was examined to identify differences in the microbiome distribution between filters operated cyclically and continuously.

2. Materials and methods

2.1. Full-scale plant configuration

The Georgina Water Treatment Plant (GWTP), Georgina, ON uses Lake Simcoe as its source water and employs biofiltration following ultrafiltration (UF) and ultraviolet (UV) disinfection. Raw water is prechlorinated at the intake (0.2 mg/L residual) to provide zebra mussel control when the water temperature exceeds 10 °C. Any remaining residual chlorine is quenched through UV disinfection such that no detectable residual (< 0.01 mg/L) is present in biofilter influent. Granular activated carbon (Filtrasorb 300, Calgon Carbon, Pittsburgh, PA) was originally installed to provide taste and odour control. The media has not been regenerated and all adsorptive capacity was assumed to be exhausted when this study was conducted (12 years following initial installation). Full-scale biologically active carbon (BAC) filters are operated for approximately 8–12 h per day. Loss of head is minimal due to the low turbidity in the post-UF influent (Table 1). As such, the filters are typically backwashed every 6 months.

2.2. Pilot configuration and experimental design

The biofiltration pilot treatment train used in this study consisted of four parallel filters (diameter = 7.62 cm; depth = 100 cm) receiving post UF and UV treated water (average UV dose = 24.6 ± 6.6 mJ/cm^2) and operated at an EBCT of 10 ± 1 min to simulate maximum flows reached at full-scale. The facility utilizes GE Zenon 500C membranes (nominal pore size = 0.04 μm). Three of the filters contained biologically active media (BAC; in service 12+ years) harvested from full-scale biofilters. If all of the DOC was biodegradable (~4 mg/L) the addition of 0.48 mg N/L and 0.1 mg P/L, respectively, would achieve a C:N:P ratio of 100:10:1 described by Lauderdale et al. [6] as being required for microbial growth. To ensure that these nutrient needs were satisfied, one pilot filter was enhanced with nitrogen (BAC_N; 0.8 mg/L NH_4-N; C:N:P = 200:40:1), another with phosphorus (BAC_P; 0.3 mg/L PO_4-P; C:N:P = 400:1:30), with the third filter serving as a control (BAC_{CTRL}; no additional nutrients; C:N:P = 400:1:2). Nutrient doses were determined by increasing the concentration over a period of 4 weeks, until maximum uptake was observed. The fourth pilot filter (BAC_{VIR}) contained virgin GAC (Filtrasorb 300; Fig. 1). Finally, the cyclically operated full-scale filter (BAC_{FS}) was monitored in parallel to the continuously operated pilot filters. Biological acclimation of the virgin GAC was observed over a period of seven months. The filter was deemed to be biologically active when DOC removal plateaued, and was approximately that observed at full-scale.

Table 1
Pilot biofilter and full-scale influent characteristics.

Parameter	Range
TOC (mg/L)	3.7–4.7
DOC (mg/L)	3.7–4.6
Temperature (°C)	5–17
pH	6.7–8.1
DO (mg/L)	8.8–14.1
Turbidity (NTU)	0.025–0.05
Alkalinity (mg/L as $CaCO_3$)	102–113

All trials evaluating the impact of nutrient enhancement were conducted when the water temperature was consistently above 10 °C (11–17 °C), as lower water temperatures (< 10 °C) have been shown to negatively impact biofiltration performance [13]. Filters were provided with increasing concentrations of additional nutrients (N and P) over a period of six weeks, until maximum uptake was observed. Nutrient concentrations were measured twice per week, and concentrations were increased each week until breakthrough was observed. Filters were then dosed N (0.8 mg/L as NH_4-N) and P (0.3 mg/L as PO_4-P) to satisfy maximum uptake; samples were collected over a six-week period and analyzed weekly for pH, temperature, dissolved oxygen (DO), organic carbon (DOC), UV_{254} absorbance and DBP formation potential (FP). Nutrient concentrations in biofilter influent and effluent were measured twice a week to assess uptake and ensure consistent dosing. Media samples were collected from a sampling port located 5 cm from the top of the filters and analyzed monthly for ATP concentration on the media during acclimation. ATP was also monitored before and after nutrient enhancement. Finally, media samples were collected from 5 cm and 45 cm depths to evaluate bacterial community composition and quantify changes in biomass density, as measured by ATP.

2.3. Analytical methods

Dissolved organic carbon (DOC) was measured using a wet oxidation method based on Standard Method 5310 D using an O-I Corporation Model 1010 analyzer (College Station, TX) with a Model 1051 Vial Multi-Sampler [14]. Ultraviolet absorbance at 254 nm (UV_{254}) was measured using a CE 3055 Single Beam Cecil UV/Visible Spectrophotometer (Cambridge, England) equipped with a 1 cm quartz cell (Hewlett Packard, Mississauga, ON). ATP analyses were conducted using a LuminUltra Biofilm Deposit Surface Analysis™ Test Kit (DSA-100C, Fredericton, NB) as per the manufacturer's instructions.

DBP FP was examined following chlorination of the pilot influent, biofilter and full-scale filter effluents. The target 24-h free chlorine residual was 1.5 ± 0.5 mg/L, representing the maximum chlorine residual observed in a downstream reservoir. Samples were incubated at 20 ± 2° C for 24 h after which chlorine residuals were quenched with L-ascorbic acid (100 mg/L) and measured using Standard Method 4500-Cl G [14]. Trihalomethanes (THMs) including chloroform (trichloromethane, TCM), bromodichloromethane (BDCM), dibromochloromethane (DBCM), and bromoform (tribromomethane, TBM) were analyzed using a liquid–liquid extraction gas chromatographic method based on Standard Method 6232 B [14]. Haloacetic acids (HAAs) including monochloroacetic acid (MCAA), monobromoacetic acid (MBAA), dichloroacetic acid (DCAA), trichloroacetic acid (TCAA), bromochloroacetic acid (BCAA), dibromoacetic acid (DBAA), bromodichloroacetic acid (BDCAA), dibromochloroacetic acid (DBCAA), and tribromoacetic acid (TBAA) were analyzed using a liquid–liquid extraction gas chromatographic method based on Standard Method 6251 B [14]. Both analyses were performed using a Hewlett Packard 5890 Series II Plus Gas Chromatograph (Mississauga, ON) equipped with an electron capture detector (GC-ECD) and a DB 5.625 capillary column (Agilent Technologies Canada Inc., Mississauga, ON). Quality