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Microfiber filtration of lake water: impacts on TEP removal and biofouling development

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ABSTRACT

Biofouling is a major and very expensive problem for the water industry. An Amiad Automatic Microfiber Filter (AMF) was tested as a pretreatment for biofouling growth inhibition using a lake water source. The filtration efficiency of the AMF in reducing Transparent Exopolymer Particles (TEP) and chlorophyll (Chl) levels in the feedwater was measured in 24 experiments during 2010–2011. These experiments showed significant reductions in TEP (mean 47 ± 21%), Chl (mean 90 ± 6%), total suspended solids (67 ± 7%), NTU turbidity (89 ± 5%), and >3 μm particle count (93 ± 4%) concentrations in the AMF filtered water. In parallel, four tests were conducted over one year to compare details of biofilm development on the surfaces of Robbins devices exposed for 30 days to AMF filtered or unfiltered lake water. Confocal laser scanning microscopy (CLSM) showed that the volume and thickness of extracellular polymeric substances of the biofilm that formed on the surfaces was markedly inhibited when the feedwater was filtered through the AMF. Taken together, these results show that microfiber filtration has good potential as a pretreatment technology upstream of surfaces sensitive to biofouling.

Keywords: Microfiber filtration; Biofilm; TEP; Pretreatment

1. Introduction

Biofouling is a major and very expensive problem for the water industry [1–3]. Consequently, much effort is currently being invested in finding effective means of pretreatment to minimize the development of biofilm on sensitive surfaces such as UF and RO membranes in desalination and water treatment plants. For example, rapid sand filtration (RSF), based on granular gravity filtration, is presently the most common pretreatment technology used in large-scale Sea Water Reverse Osmosis Desalination facilities due to its relative simplicity, low-energy consumption, and relatively low operational costs [4]. An alternative pretreatment approach has been the recent introduction of self-cleaning, microfiber filters to reduce the concentrations of biofilm forming substances and bacteria in feedwater reaching sensitive surfaces [5].

Recently, Transparent Exopolymer Particles (TEP) have been implicated as an important factor in

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the development of aquatic biofilm on filtration membranes and other surfaces [6–8]. TEP are ubiquitous and numerous in oceans, lakes, rivers, and reservoirs as well as in recycled effluents. Like the extracellular polymeric substances (EPS) that form the matrix of aquatic biofilms, these planktonic microgel particles, ranging in size from ~0.4 to >200 μm, are mostly composed of polysaccharides, although nucleic acids and proteins may also be present. In fact, TEP may be regarded as planktonic form of EPS. In aquatic environments, TEP form abiotically from dissolved organic polymers and colloids by processes of coagulation and gelation [9,10] or by turbulence and bubble adsorption [11]. Considerable amounts of TEP are also produced from the gelatinous envelopes that surround diatoms and other algae [12] and from bacterial mucous [13]. TEP may also be formed during senescence by algae and cyanobacteria [14,15]. Many TEP in natural waters are extensively colonized by bacteria and other micro-organisms that find them a convenient and nutritional platform on which to grow [16]; these microgel particles have been termed "protobiofilm" and have recently been shown to be very effective in facilitating aquatic biofilm formation [8].

Here, we present the results of three series of tests run with an Amiad Automatic Microfiber Filter (AMF) on a lake water source to evaluate the potential of this technology to inhibit biofouling. Particular attention was given in these experiments to the efficiency of microfiber filtration in lowering concentrations of TEP in the filtrate. We also measured the efficiency of microfiber filtration in removing chlorophyll (Chl) from the feedwater. Chl is an easily measured proxy for algae and cyanobacteria in marine and freshwater that can often cause significant fouling [17]. Strangely, until recently, Chl was rarely monitored in water treatment or desalination facilities.

The first series of 24 experiments was run to determine the filtration efficiency of the AMF in reducing TEP and Chl levels in the lake water. In this series, we also determined the efficiency of the AMF filter in reducing the levels of total suspended solids (TSS), turbidity, and >3 μm particle counts in the feedwater. In the second experimental series, four tests were conducted over one year and to compare details of biofilm development on glass coupons of Robbins devices [18] that were exposed for ~30 days to AMF filtered or untreated lake water.

2. Methods

2.1. Experimental site and setup

All tests were carried out with coastal water taken at a pumping station at Kibbutz Ginnosar on the western shore of Lake Kinneret. The feedwater was passed directly over the glass coupons in Robbins devices or was first filtered through an Amiad Water Systems AMF filter before reaching the Robbins devices. A schematic representation of the experimental setup is shown in Fig. 1.

2.2. Amiad microfiber filter (AMF)

The AMF was based on a microfiber technology that combines highly effective cartridge filtration with a self-cleaning capability [5]. The basic component of microfiber technology was the thread cassette, which consists of a grooved rigid plastic plate over which multilayer textile threads have been wound (Fig. 2(a)). The type of thread and other winding parameters define the filtration degree, which can range from <2 to 20 μm. The cassettes are attached to a circular holder connected to a collector pipe; these holders are attached to one another to form a complete cartridge (Fig. 2(b)), which was then installed in the filter housing (Fig. 2(c)).

Source water containing inorganic and organic particles such as silt, TEP, algae, and bacteria, is filtered through the threads into the cassette grooves and passed through the collector pipe to the outflow. Larger particles, (e.g. most algae and larger sized TEP) were immediately blocked on the surface of the multiple layers of thread while finer particles, (e.g. bacteria and smaller TEP) penetrated the surface and were trapped deeper inside the thread layers. The self-cleaning sequence begins when the differential pressure across the filter elements reaches a preset level. Cleaning was accomplished by injection of high-pressure water jets through the thread layers of the cassette. The jets hit the plastic base of the cassette and were forced backwards creating a powerful back flush that carried the trapped particles out of the thread layers to the outflow [5].

2.3. Biofilm formation in Robbins devices

Biofilm development and formation was measured using modified Robbins devices [18] that are made of

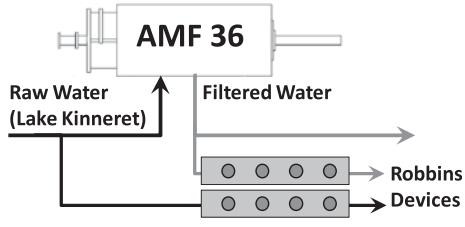

Fig. 1. Schematic representation of the experimental setup at Ginnosar showing paths of feedwater flows.

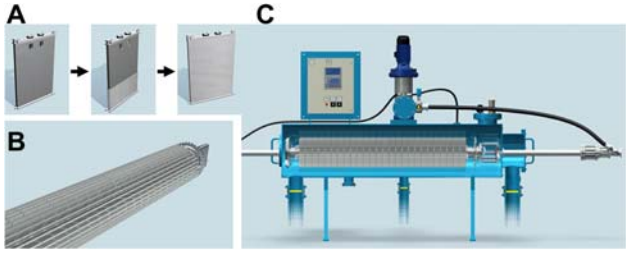

Fig. 2. Amiad Microfiber Filter. (A) Cassette element, (B) Cartridge, and (C) AMF assembly.

1″ PVC pipes with parallel ports. Each port accepts a press-fit plug holding a glass sample coupon with a surface area of 50 mm^2. The design of the plug was such that the surface of the coupon essentially becomes part of the channel wall. TEP, bacteria, and algae that flow with the water adhere to the glass coupon and ultimately establish a biofilm, which then may be removed for analysis. One Robbins device was installed upstream of the AMF (untreated water) and another in the filter outlet (filtered water); flow rates of 0.5 m^3/h and velocities of ~0.2 m/s were maintained throughout the experiments (Fig. 1).

2.4. TEP and chlorophyll

The concentrations of TEP and Chl were determined by the methods of Passow and Alldredge [19] and Holm-Hansen et al. [20], respectively.

2.5. Particle (>3 μm) counts, turbidity, and TSS

Particle counts were made using an AccuSizer particle counter (PSS). Turbidity (NTU) was measured with a 2100P HACH Turbidimeter. TSS (mg L^{-1}) were determined by Standard Methods [2540D] [21].

2.6. Determination of biofilm structure characteristics by confocal laser scanning microscopy (CLSM)

Biofilm structure parameters were determined by staining for bacterial cells (nucleic acids) with SYTO®9 (Invitrogen-Molecular Probes) and for the polysaccharides of EPS with Concanavalin A (Invitrogen-Molecular Probes) as outlined by Strathmann et al. [22]. The biofilm that developed on glass coupons in the Robbins Devices was washed three times with 0.1 M Tris–HCl and then drained without drying. After this initial wash, the biofilm samples were stained first with SYTO®9 (20 μl, 5 μM final concentration) and then with Concanavalin A (20 μl, 0.2 mg/mL final concentration). For each staining step, the biofilm samples were incubated for 25 min in the dark at room temperature. Following each staining step, the samples were washed three times with 0.1 M Tris–HCl and then drained. Finally, the samples were dried briefly and covered with an antifade.

CLSM was performed with Leica SP5 confocal microscope. For SYTO®9, excitation was determined at 488 nm and emission between 495 and 537 nm. Concanavalin A was determined at 561 nm with emission at 570–620 nm. For each sample, 15 fields of view were taken with a field size of 164 × 164 μm. Image analyses were performed by PHLIP as described by Eshed et al. [22].

2.7. Determination of biofilm characteristics by scanning electron microscopy (SEM)

Micro-photography and examination of each sample was carried out using a JEOL 840 SEM.

3. Results

3.1. Reduction of TEP, chlorophyll, particle (>3 μm) count, turbidity, and TSS by AMF filtration

Removal of TEP and other water quality parameters from the lake water by filtration through an Amiad AMF was tested in 24 experiments that were run from July 2010 to December 2011. Despite considerable variation, overall the filtration process was relatively efficient, removing on average 47(±21)% of TEP from the feedwater. The removal efficiency ranged from 6 to 75%. Some exceptionally low removal values (6, 9, and 16%) probably resulted from mechanical problems with the filter that occurred during the first experimental runs during July–August 2010. If these "aberrant" results were discounted, then the average filtration efficiency rose to 52(±17)%. In Fig. 3, we show the reduction in TEP levels in river water after AMF filtration at four different seasons.

The AMF was considerably more effective in removing Chl than TEP from lake water (Fig. 4); the overall average removal in 24 experiments was 90 (±6)%. Although much of the Chl in the lake is associated with relatively large (>3 μm) algal and cyanobacterial species, picocyanobacteria, and picoeucaryotes (<2 μm) are present throughout the year and those were presumably the source of the Chl remaining in the filtered water.

In Table 1, we show the percentage removal by AMF of >3 μm particles, turbidity (as NTU), and TSS from Lake Kinneret feedwater. Microfiber filtration was highly effective in removing >3 μm particles and turbidity (generally ~90%) at all seasons during this

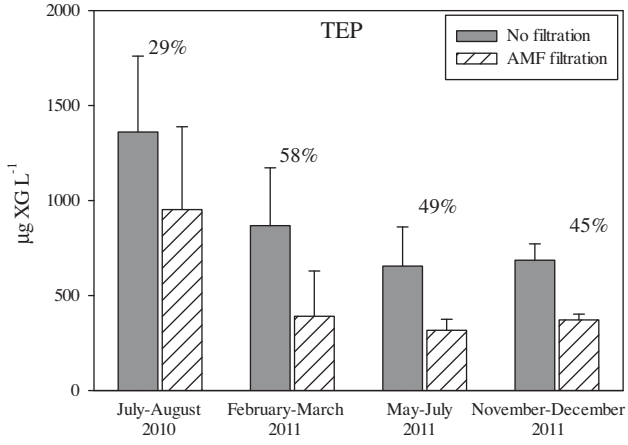

Fig. 3. TEP concentration expressed as Gum Xanthine equivalents ($\mu g GX\,L^{-1}$) in untreated water and AMF filtered water over the course of a year. Error bars indicate standard deviation. Percentages above bars indicate percent reduction of TEP for each sampling season.

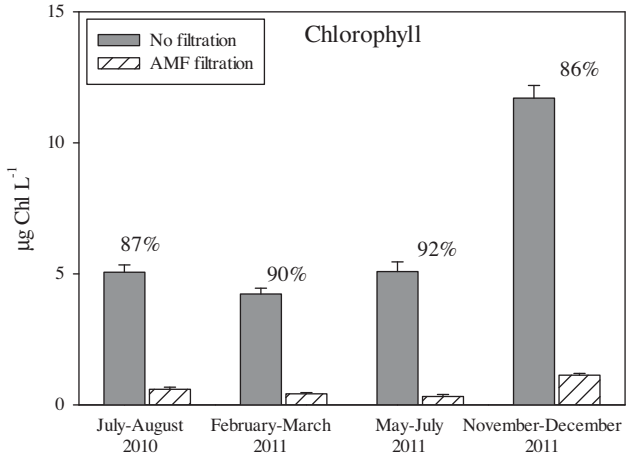

Fig. 4. Chl concentration in untreated water and AMF filtered water over the course of a year. Error bars indicate standard deviation. Percentages above bars indicate percent reduction of Chl for each sampling season.

trial. Somewhat lower filtration efficiency (59–77%) was observed for TSS removal.

3.2. Inhibition of biofilm development

The biofilm thickness and biomass as expressed in EPS and bacterial cell biovolume was evaluated using CLSM and SEM after 4 weeks of incubation. The thickness of biofilm formed after AMF filtration was significantly lower (*t*-test, $p < 0.005$) than in the unfiltered control during each season (Fig. 5(a)). The greatest reduction (82%) was observed in summer 2011. At other seasons, percentage reduction of biofilm thickness ranged from 35 to 78%. While the biofilm thickness in the control varied with season, the thickness of the biofilm formed after filtration was always less than 20 µm. In unfiltered water, the bulk of the biofilm was always composed of EPS. The greatest reduction in EPS biovolume (94%) was recorded in winter 2012 (*t*-test, $p < 0.005$) followed by summer 2011 (84%), see Fig. 5(B). In contrast, the reduction of bacterial cell biovolume was more apparent during summer (68 and 54% in 2010 and 2011, respectively) than in winter (Fig. 5(C)). SEM and CLSM imaging (Fig. 6) also emphasized the difference between biofilm formed in untreated water and AMF filtered water. In untreated water, most of the biofilm was composed of EPS (Fig. 6(A) and (C)) while the biofilm formed in filtered water consisted mainly of bacterial cells (Fig. 6(B) and (D)).

4. Discussion

4.1. AMF filtration efficiency

In several studies TEP concentrations in feedwater have been correlated with biofilm clogging of filtration membranes [7,23,24]. Therefore, the removal of TEP from feedwater reaching filtration membranes and other sensitive surfaces is now recognized as an effective means of inhibiting biofilm development. However, some studies have shown that current pretreatment technologies are not very efficient at lowering TEP concentrations in feedwater [25], most likely

Table 1
Percentage (%) removal of particles (>3 µm), turbidity (NTU), and TSS ($mg\,L^{-1}$) from Lake Kinneret feedwater by AMF Filtration

	Particles	SD	Turbidity	SD	TSS	SD
July–August 2010	95.7	2.2	93.3	3.0	70.2	10.4
February–March 2011	93.7	1.7	88.7	9.0	58.9	24.3
May–July 2011	97.2	2.0	93.3	3.1	76.8	14.1
November–December 2011	86.3	4.4	80.6	5.4	63.8	21.6

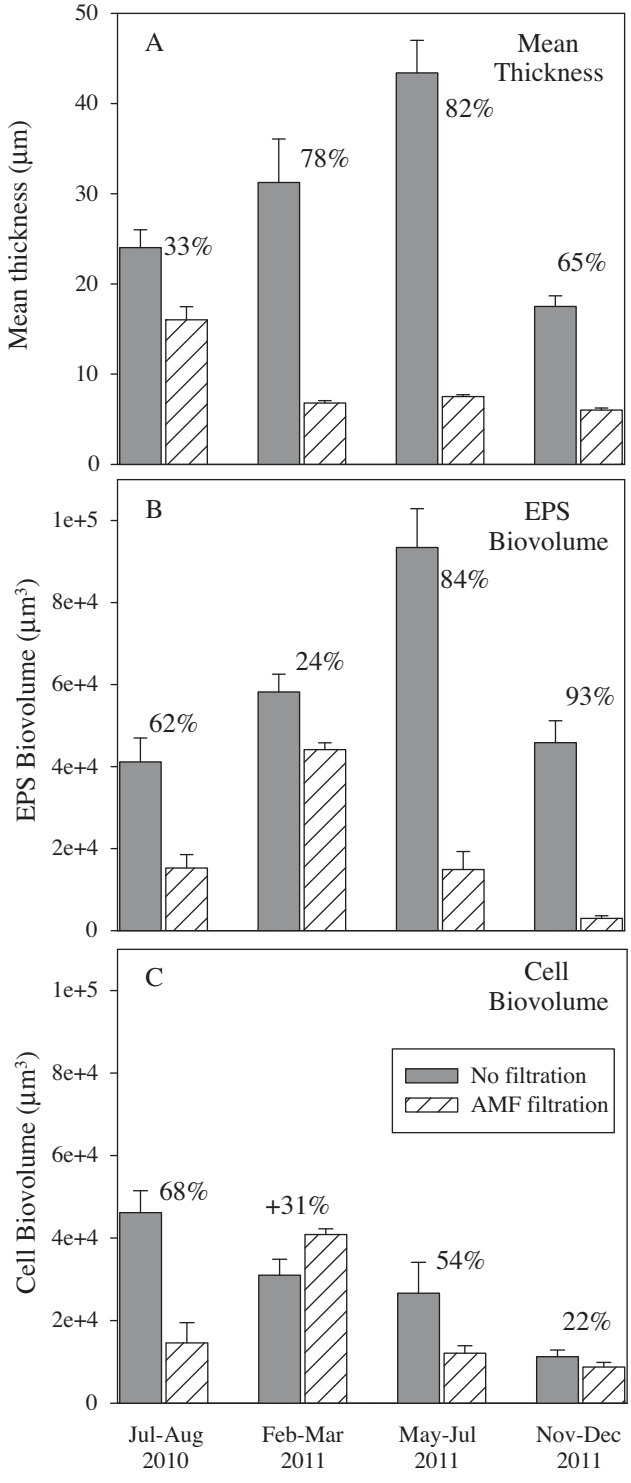

Fig. 5. Biofilm thickness (A), EPS biovolume (B), and cell biovolume (C) after four weeks of incubation in untreated water and AMF filtered water over the course of a year. Error bars indicate standard error of 15 fields of view for each sample. Percentages above bars indicate percent reduction of each parameter (excluding cell biovolume in February–March 2011 where an increase was observed).

because of the amorphous, deformable, microgel nature of these particles [10,26]. For example, Bar Zeev et al. [17] found that although pretreatment at an operational desalination plant lowered the levels of water quality parameters such as Chl and SDI by ~90% relative to input, TEP concentrations were only decreased by ~30% upstream of the RO membranes. The efficiency of a rapid sand filter in removing TEP at another desalination plant varied from ~20 to 60% [4].

In this study, the results of the experimental series in which AMF filtered lake water was compared to untreated lake water indicated an average TEP removal efficiency of >45% (in 24 experiments, 47 ± 21%). Therefore, the AMF operated at an overall mean efficiency which is relatively high in comparison to other pretreatment technologies that have been examined and indeed significantly lowered the amounts of biofilm that developed on the Robbins coupons. Nevertheless, considerable amounts of TEP, or more likely colloidal precursors of TEP [23], remained in the AMF filtrate.

Microfiber filtration was very effective in lowering the feedwater levels of other factors that affect biofouling; Chl (Fig. 4), particles, turbidity, and TSS (Table 1). Because Chl, an easily monitored proxy for planktonic algae and cyanobacteria, can be a significant factor in causing fouling as it was important to check the performance of the AMF in respect to this parameter. Although most algae and cyanobacteria in natural waters are >3 μm there are often considerable populations of nanophytoplankton (<2 μm) present; these probably accounted for the Chl fraction that passed through the AMF in the experiments. Frequently Chl is also major contributor to turbidity in natural waters. In the case of Lake Kinneret water, algae and cyanobacteria were the major source of turbidity and also of the >2 μm particles measured in the particle counter. Therefore, it is not surprising that the filtration efficiency of the AMF was similar for Chl, particles, and turbidity in these experiments.

Although very high AMF filtration efficiencies were observed for removal of >3 μm particles and turbidity, lower efficiencies were found for TSS (Table 1). This was not surprising because of the very high proportion of small sized (<3 μm) particulate matter generally present in Lake Kinneret water [27]. Note, however, that the efficiencies for TSS removal were higher than those for TEP.

4.2. Inhibition of biofouling development

The results shown in Figs. 5 and 6 clearly indicate the marked impact of microfiber filtration of Lake Kinneret water on the development of biofilm on glass

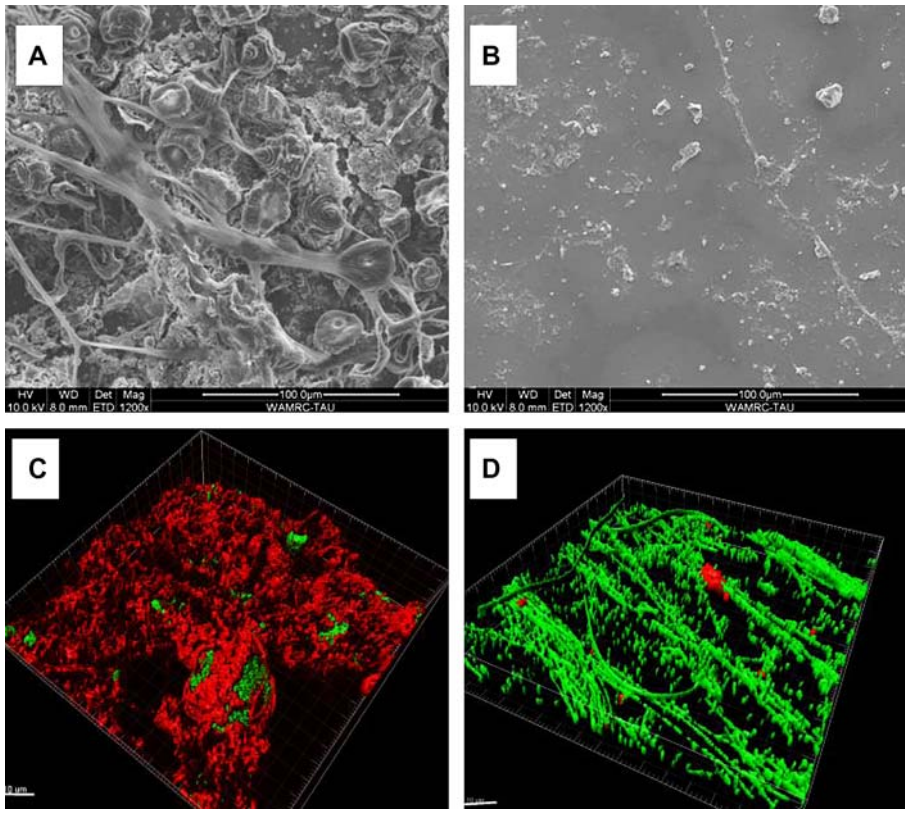

Fig. 6. SEM (A and B) and CLSM (C and D) imaging of a four weeks old biofilm formed in untreated (A and C) and AMF filtered (B and D) water. In the CLSM images, the red color indicates the EPS (by concanavalin A) and the green color indicates the bacteria (by SYTO9). CLSM images were processed for visualization with IMARIS.

surfaces in Robbins coupons as measured by CLSM and SEM. While the thickness of biofilm that developed in untreated feedwater varied with time of year, the thickness of biofilm formed in AMF filtered water was consistently low. We note that the EPS component of the biofilm developing in filtered feedwater was strongly inhibited in comparison with that in untreated water while the bacterial cell components were inhibited during summer only (Fig. 5). This finding is consistent with the idea that the levels of TEP in feedwater strongly influence biofilm development and clogging rate of membranes. We note that TEP have been characterized as a form of "planktonic EPS" [7] (see below).

5. Conclusions

Biofilm fouling of filtration membranes in desalination and wastewater facilities is a major problem [1,2]. Pretreatment of feedwater by self-cleaning filters can be a cost-effective approach to controlling biofilm development on sensitive surfaces. The present study indicates the high potential of an AMF to remove a variety of factors implicated in biofilm formation (TEP, Chl, particles, turbidity, and TSS) from a lake water source. We observed that the biofilm that formed in filtered water showed marked inhibition in comparison with biofilm that developed in untreated water.

We emphasize that the results presented in this study were obtained with only a single source of feedwater. Of course, the quality of this feedwater varied considerably in these experiments that were carried out over the course of two years. For example, the levels of Chl and turbidity in Lake Kinneret water ranged from 1.2 to 20.4 μg Chl l^{-1} and 1.98 to 16.1 NTU, respectively. It would be desirable to run similar experiments with different feedwater sources, especially seawater, in view of the potential of this filter technology as a pretreatment for desalination.

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