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Bacterial growth in batch-operated membrane filtration systems for drinking water treatment

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ABSTRACT

Membrane filtration treats drinking water by physical removal of bacteria and other particles present in the raw water. In order to study post-filtration contamination and growth, filtered river water and wastewater were used in a controlled laboratory-scale simulation of a batch-operated membrane filtration system. Bacterial batch growth was analyzed following intentional initial contamination with a river water microbial community. Batch growth in the permeate was measured with online flow cytometry at high intervals during 10 successive 24-hour operational cycles, simulating repeated daily use (filtration followed by stagnation). Two operational mechanisms influenced the growth characteristics: (1) initial selection of bacteria adapted to batch growth conditions, and (2) biofilm formation on the surfaces of the permeate containers. The first mechanism contributed towards a stable and reproducible growth behavior (lag phase of less than 4 h, maximum growth rates of 0.37–0.42 h^{-1} and final total cell counts of $1.5–1.8 \times 10^6$ cells mL^{-1}) throughout several consecutive operational cycles. When the feed water changed, the adapted bacterial communities grew rapidly and proportionally to the amount of substrate in the new water source. Biofilm development in the permeate containers resulted in a 20% reduction in the overall cell production during five operational days, suggesting this to be a potential novel strategy towards controlling biological stability in such systems.

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1. Introduction

Apart from removing pathogens, a primary goal of water treatment worldwide is to provide biologically stable drinking water. The major problems associated with biologically unstable drinking water are: corrosion, deterioration of taste and odor and proliferation of pathogens [31,2]. In order to minimize these effects most treatments aim at limiting microbial growth in the distribution systems by limiting the amount of nutrients available for growth. However, experience with both chlorinated and non-chlorinated drinking water systems in both developing and industrialized countries has convincingly shown that it is practically impossible to avoid bacterial growth in treated water [2,46,26,30,32,39,7,14].

Membrane filtration is a physical separation process that produces bacteria-free drinking water at appropriate filter cut-offs [32,11,14]. However, several studies have demonstrated that there are often bacteria present in the permeate of membrane filtration systems [40,18,11,32,34,59,12]. The causes of this microbial "contamination" of the permeate are ineffective membrane rejection [34,18,58,23] or post-filtration contamination [18,32,29]. Moreover, there is evidence that membrane filtration results in more favorable conditions for subsequent bacterial growth due to the elimination of competition and the passage of low molecular weight dissolved compounds (nutrients) in the permeate [18,37]. These arguments are further supported by evidence that filtration systems can drastically alter the bacterial composition in the water, whether it is after media filters [45] or after membrane filters [18,23].

There are several varieties of water treatment systems based on batch-operated membrane filtration and subsequent storage, especially for use in developing countries or disaster areas [42]. One of these systems is the so-called gravity-driven membrane (GDM) filtration, which uses gravity as the sole driving force for the ultrafiltration of surface water and which tolerates biofilm growth on the membranes [44]. GDM filtration is a particularly interesting model for studying post-filtration contamination and growth of bacteria due to fluctuating substrate concentrations and quality [8,6] and long stagnation times in the permeate containers. Moreover, these growth conditions are comparable to those in other small-scale batch-operated filtration systems, such as ceramic pot filtration [33]. It is important to understand microbial growth in such batch-operated filtration systems for a host of reasons: (1) they

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are mainly used in low income, developing countries where there are limited possibilities for expensive post-treatments; (2) it is assumed that membrane systems will be increasingly used in developing countries and emergency situations [42,33]; (3) areas of intended use often have variable source water, relatively warm temperatures and increased contamination risk [38]. Moreover, previous studies already observed post-filtration regrowth in the permeate of GDM filtration systems treating surface water [21], although this was not investigated in detail.

In the present study, a batch-operated membrane filtration system similar to a GDM filter was simulated under controlled laboratory-scale conditions with the purpose of characterizing post-filtration bacterial growth in detail (growth rates, total cell concentrations and community fingerprinting). The main questions were: (1) What happens in a membrane filtration system after filtration and during storage (stagnation) of the permeate with respect to bacterial growth? (2) What are the specific operational mechanisms (e.g., operational cycles, biofilm formation or rate of filtration) that influence growth in such systems and to what extent do they affect growth? (3) How are the growth characteristics changing with a change of the filtration conditions (e.g., different source water)? Proper characterization and understanding of bacterial growth in filter permeates would facilitate improved engineering approaches towards design and operation of systems delivering safe, aesthetically acceptable and biologically stable drinking water.

2. Experimental

2.1. Water samples and pre-treatment

Two types of water samples were used: the primary source water was river water (Chriesbach stream, Dübendorf, Switzerland) and the secondary source was wastewater treatment effluent (Eawag wastewater treatment plant, Dübendorf, Switzerland), with dissolved organic carbon (DOC) contents of 1.6 ± 0.5 mg L^{-1} and 3.8 ± 0.7 mg L^{-1}, respectively. Both water samples were collected at the same day, then filtered (capillary dialyzer FX80 with 20 kDA cut-off, Fresenius Medical Care, Germany) and finally pasteurized (30 min at 60 °C). The purpose was to simulate the cell-free permeate of a membrane filter in large enough quantities to store and thus to use the exact same batch of water for the entire experimental period. These pre-treated water samples were stored at 4 °C until use.

2.2. Experimental set-up

2.2.1. Overview of experimental set-up

All the experiments, variations, related figures and relevant discussion sections are summarized in Table 1.

2.2.2. Experiment 1: simulation of a batch-operated membrane filtration system without biofilm development

An experimental set-up was constructed to simulate a batch-operated membrane filtration system under controlled conditions of temperature, substrate, flow rates and stagnation times (see Fig. S1). At the start of the experiment, the pre-filtered river water (described above) was warmed to 30 °C and then delivered slowly (dripping during 5 h) with a peristaltic pump (Ismatec® IPC-8, IDEX Health & Science GmbH, Germany), with a constant flow rate of 20 mL h^{-1}, into containers (100 mL Schott bottles) also incubated at 30 °C. For the first contamination, the permeate containers were inoculated at the start of the experiment with 2.5 mL (= 2.5% of final volume) of untreated river water containing approximately 10^6 cells mL^{-1}. The filtration rate and time were representative values for household GDM filtration systems [43]. After this slow addition, a stagnation period of 18 h occurred, simulating a period in which the filtered water is not used or only partially consumed. The combination of 5 h dripping and 18 h stagnation was considered as one operational cycle after which the entire process was repeated. At the start of each consecutive cycle, the permeate container was replaced with a sterile one and 2.5% (= 2.5 mL) of the permeate from the previous cycle was transferred to the new container, in order to simulate water remaining in the permeate tank between filtration events (see Fig. S1). Planktonic microbial cell concentrations were analyzed with online FCM (see below in 2.3.1). All the tubing materials used were made of carbon-free material (Pharmed® BPT, IDEX Health & Science GmbH, Germany) in order to limit external carbon contamination. This experiment was conducted for eight consecutive days (corresponding to eight operational cycles) in quadruplicate for the first day/cycle, and in duplicate thereafter. Samples from the duplicates were measured sequentially at 30 min intervals (meaning 60 min intervals per reactor).

2.2.3. Experiment 2: influence of biofilm development in the permeate containers

For the first experiment above, new sterile permeate containers were used daily. For the second experiment, the original containers were used throughout and biofilms were therefore allowed to develop on the surfaces of the permeate containers. The purpose was to analyze the differences in the growth behavior with and without the presence of a biofilm. Experiment 2 was done in duplicate for five consecutive days concurrent with cycles 2–6 of Experiment 1 (above), using the same experimental set-up and the same feed water. After each operational cycle, the water was drained completely and only the biofilm remained. The bacterial concentration in the biofilms was measured in the permeate containers at the end of the experiment, as well as in the permeate containers from Experiment 1 that were replaced on a daily basis (Section 2.4 below).

Table 1
Experimental summary.

Nr.	Description	Cycle[a]	Source water (flow rates)	Microbial contaminant	Section	Fig.
1	Simulation of a membrane batch filtration system without biofilm formation	1–8	River water (20 mL h^{-1})	River water	3.1 3.2.1	Fig. 1 Fig. 2
2	Influence of biofilm development in the permeate containers	2–6	River water (20 mL h^{-1})	River water	3.2.2	Fig. 3
3	Effect of different filtration flow rates	7, 8	River water (0, 10 & 20 mL h^{-1})	River water	3.2.3	Fig. 4
4a	Change of feed water	9, 10	Wastewater effluent (20 mL h^{-1})	River water	3.3	Fig. 5
4b	New contaminant added	9, 10	Wastewater effluent (20 mL h^{-1})	Wastewater effluent	3.3	Fig. 5

[a] Refer to the cycles in which the experiment was performed. One operational cycle comprised a filling step (5 or 10 h) and a stagnation step (18 or 13 h).

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