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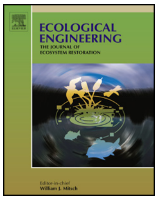

Removal of pathogen indicators from secondary effluent using slow sand filtration: Optimization approaches

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ABSTRACT

In many arid regions, the reuse of wastewater is an economic option for crop irrigation. To avoid health risks for consumers, pathogens must be eliminated prior to application. Slow sand filtration (SSF) represents an effective low-tech treatment technology for pathogen removal from water. To further improve the time-space yield of SSF, innovative filter configurations were investigated regarding the removal of the pathogen indicators *Escherichia coli*, enterococci, *Clostridium perfringens* spores, somatic and F-specific RNA coliphages as well as heterotrophic bacteria. A standard filter (***N***), a recirculating filter (***R***), a static cascade (***N+N***) and a rotating cascade (***C***) were tested at high and low hydraulic loading rates, two recirculation rates and two rotation frequencies. Results showed that only ***C*** and ***N+N*** concurrently complied with European standards for *E. coli* and enterococci, achieving mean log removal of 2.7-4.7 and 2.1-2.4, respectively. The best performance was reached by ***C*** with weekly rotation; ***N+N*** may be a promising, technically simpler alternative. The crucial role of biological removal mechanisms for *E. coli* and enterococci elimination was indicated by (i) the increased efficiency of the standard SSF ***N*** after 1½ years of operation and (ii) the positive impact of several *Schmutzdecke* layers. *C. perfringens* spore removal performance was good for all SSFs. Considerable sorption of spores was indicated by decreased efficiency in ***N*** and ***C*** at long operation times. Somatic coliphages were reduced to concentrations close to the detection limit, while F-specific RNA coliphage removal was ~1.1 log. Removal of heterotrophic bacteria was generally limited.

1. Introduction

In many arid regions of the world, the demand for irrigation water in agriculture periodically or permanently exceeds the available water resources (Pedrero et al., 2011). Water scarcity is aggravated by population growth, intensified agricultural practices, deterioration of soils and climate change leading to less precipitation (Rosegrant et al., 2009).

To mitigate this problem, the use of wastewater for irrigation is more and more widely applied with the added benefit of utilizing its considerable nutrient content (Pedrero et al., 2011; Norton-Brandão et al., 2013). The use of insufficiently treated or untreated wastewater is problematic, partly due to undesirable levels of salinity and heavy metals (Norton-Brandão et al., 2013) but mainly due to its pathogen load stemming from human and animal excreta. Pathogens may contaminate crops and pose health risks for agricultural workers, crop handlers and consumers (Schaefer et al., 2004). Thus, wastewater should be treated for pathogen removal in addition to primary treatment for removal of Chemical and Biological Oxygen Demand (COD/BOD), salt and metals, prior to reuse in agriculture. For unrestricted irrigation of human food crops intended for raw consumption, all relevant guidelines and regulations require coliform indicators (total/faecal/thermotolerant coliforms) to be below 10^3 Colony Forming Units (CFU)/100 ml (WHO 1989; ANZECC, 2000; US EPA 2004), while stricter European

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Abbreviations: BOD, Biological Oxygen Demand; CFU, Colony forming units; COD, Chemical Oxygen Demand; CWs, Constructed wetlands; DOC, Dissolved Organic Carbon; FC, faecal coliforms; HLR, hydraulic loading rate; HPC, Heterotrophic Plate Counts; HSSF, horizontal subsurface flow; MPN, Most Probable Number; PFU, Plaque Forming Units; PVC, polyvinyl chloride; R2A agar, reasonerís 2A agar; SCE, secondary clarifier effluent; SPS agar, sulfite polymyxin sulphadiazine agar; SSF, slow sand filtration/filter; TC, total coliforms; TN, total nitrogen; TOC, total organic carbon; WWTP, wastewater treatment plant.

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Table 1
Biological characteristics of the secondary clarifier effluent (SCE) used as the inflow water for the Slow Sand Filter (SSF) systems and of the outflow from the horizontal subsurface flow constructed wetlands (HSSF CWs) at the Langenreichenbach wastewater treatment facility.

Parameters	Units	Secondary clarifier effluent			HSSF CW effluent		
		Mean ± σ	Median	N	Mean ± σ	Median	N
Total Coliforms	CFU/100 ml	$5.8 \times 10^4 \pm 5.4 \times 10^4$	4.1×10^4	25	–	–	–
E. coli	CFU/100 ml	$8.9 \times 10^3 \pm 8.2 \times 10^3$	7.0×10^3	41	$3.0 \times 10^5 \pm 1.9 \times 10^5$[b]	–	42
Enterococci	CFU/100 ml	$2.1 \times 10^3 \pm 2.0 \times 10^3$	1.4×10^3	42	$2.0 \times 10^4 \pm 1.5 \times 10^4$	1.9×10^4	5
Heterotrophic bacteria	CFU/100 ml	$1.2 \times 10^6 \pm 2.1 \times 10^6$	5.5×10^5	39	$1.1 \times 10^7 \pm 1.5 \times 10^7$	4.3×10^6	3
Presumptive *Clostridium perfringens* spores[a]	CFU/100 ml	$8.1 \times 10^2 \pm 5.7 \times 10^2$	7.0×10^2	33	$1.0 \times 10^5 \pm 2.0 \times 10^5$	3.2×10^3	4
F-specific RNA coliphages	PFU/100 ml	$6.4 \times 10^1 \pm 2.8 \times 10^1$	4.9×10^1	3	–	–	–
Somatic coliphages	PFU/100 ml	$3.5 \times 10^3 \pm 3.1 \times 10^3$	2.2×10^3	14	$1.6 \times 10^5 \pm 1.4 \times 10^5$	1.1×10^5	5

[a] Spores of anaerobic Clostridia grown on SPS medium.
[b] Headley et al. (2013).

guidelines call for *E. coli* loads below 200 or 100 CFU/100 ml (DIN, 1999; Italian Decree, 2003; Spanish Royal Decree, 2007).

Constructed wetlands (CWs) represent a low-tech and effective treatment technology for removal of pathogens. However, reported effluent loads of total coliforms (TC), faecal coliforms (FC) and *E. coli* from secondary subsurface flow CWs (TC: 4×10^6, FC: 9×10^5, *E. coli*: 3×10^3–2×10^6 CFU/100 ml) and free water surface (FWS) CWs (TC: 3×10^5–4×10^6, FC: 2×10^4–4×10^4, *E. coli*: 2×10^6 CFU/100 ml) (Decamp and Warren, 2000; Masi et al., 2004; Vymazal, 2005; Ghermandi et al., 2007; García et al., 2013; Headley et al., 2013; Abou-Elela et al., 2014; Wu et al., 2016) are too high for a safe reuse even in restricted irrigation (US EPA, 2004; WHO, 2006; Ghermandi et al., 2007; Norton-Brandão et al., 2013). In order to provide irrigation water quality, CW effluents require further disinfection steps. It has been suggested to apply ozone (Miranda et al., 2014) or UV (Toscano et al., 2013) for CW effluent disinfection, but simple and low-cost post-treatment options would be preferable.

Continuous Slow Sand Filtration (SSF) is a low-tech process that has been used for pathogen and particle removal in drinking water purification for decades (Logsdon et al., 2002), and can also be implemented under restricted conditions with locally available materials. Water continuously percolates through a sand column utilizing the pressure of a permanent water head. On the filter surface, a biologically active compartment (*Schmutzdecke*, German for ‘dirt layer’) forms where most of the pathogen removal takes place (Langenbach et al., 2009; Pfannes et al., 2015). Pathogen retention is mainly due to straining and adsorption (Stevik et al., 2004), while pathogen inactivation is caused by abiotic and biotic mechanisms. Natural die-off such as starvation, predation by eukaryotic bacterivores (protozoa and heterotrophic nano-flagellates) and bacteria such as *Bdellovibrio* sp., as well as lysis induced by bacteriophages and algal-derived reactive oxygen species have been identified as contributing factors (Weber-Shirk and Dick, 1997, 1999; Stevik et al., 2004; Wand et al., 2007; Haig et al., 2015).

In recent years, continuous SSF has gained increasing attention as a promising technology for disinfection of secondary effluent with the purpose of reuse (Adin, 2003; Christou et al., 2014). A wide range of removal efficiencies for TC (0.3–3.5 log units), FC (2-2.4 log-units), *E. coli* (1.9–4.1 log units) and enterococci (0.7-3.7) has been reported (Ellis, 1987; Farooq and Alyousef, 1993; Sadiq et al., 2003; Mälzer, 2005; Keraita et al., 2008; Langenbach et al., 2009, 2010; Bauer et al., 2011; Kader Yettefti et al., 2013), using various sand materials, filter designs and hydraulic loading rates (HLRs). Intermittent SSF, also known as Infiltration Percolation, is characterized by lower HLRs and pathogen indicator removal efficiencies (Young-Rojanschi and Madramootoo, 2014). Research conducted on recirculating SSF focused on intermittently loaded systems with recirculation tanks as specified by US EPA (1980), dealing with primary effluent or high strength wastewater (Gold et al., 1992; Healy et al., 2007). The use of SSFs with direct recirculation for tertiary treatment has not yet been reported.

Regarding continuous SSF, systematic approaches to optimize sand grain size distribution and operation mode (HLR, hydraulic head) for pathogen removal are scarce (Langenbach et al., 2009; Bauer et al., 2011; Kader Yettefti et al., 2013). Sand with an effective grain size d_{10} between 0.15 mm and 0.4 mm and a uniformity coefficient of $U < 5$ is recommended for drinking water purification with HLRs of 5–40 cm h^{-1} (Sánchez et al., 2006). Langenbach et al. (2009, 2010) have investigated removal of *E. coli* and enterococci using various sand grain size distributions and HLRs. Results indicate that a fine and uniform sand material with a high sand surface area achieves the best faecal indicator removal at HLRs of 5 and 10 cm h^{-1}.

For investigations on post-treatment of CW effluents, it is appropriate to consider horizontal subsurface flow (HSSF) CWs as the simplest technology (free water surface CWs were ruled out due to potential public health issues such as mosquitos). Taking into account reported secondary subsurface flow CW effluent qualities and SSF removal efficiencies for *E. coli*, post-treatment of CW effluent in SSFs can potentially produce *E. coli* outflow concentrations between zero and 10^4 CFU/100 ml. Thus, although optimally performing system combinations may be able to reduce *E. coli* loads to values falling below the limits defined in European irrigation water standards, many CW-SSF system combinations will not reach the specified goals (DIN, 1999; Italian Decree, 2003; Spanish Royal Decree, 2007). For the potential employment of SSF in hybrid CW-SSF units treating wastewater for safe reuse in irrigation, a further SSF performance optimization is needed in order to guarantee the compliance of effluents with established limits.

Thus, the goal of the present study was to compare the pathogen indicator removal efficiency of four different SSF designs: standard, recirculating, a static series of two SSFs, and a rotating cascade. The underlying aim was to improve SSF performance by an enhanced use of the biologically active *Schmutzdecke* layer(s) by (i) increasing the contact time between the wastewater and the active layer via partial recirculation of the effluent, or by (ii) formation of several active layers when operating multiple SSFs either in a static series or as a rotating cascade. By periodically rotating the wastewater recipient order in a SSF cascade, the formation of several *Schmutzdecke* layers could be promoted, each receiving high loads of organic carbon, nutrients and microbial matter in turn. So far, investigations on SSF cascades have very rarely been reported (e.g. Kadewa et al., 2010); to the best of the authors’ knowledge, no results have been published concerning pathogen removal in (rotating) SSF cascades.

Removal of indicators for wastewater pathogen groups relevant for irrigation water quality was investigated: aerobic bacterial load (Heterotrophic Plate Counts, HPC) and faecal bacterial indicators (*E. coli* and the more stress-resistant enterococci); pathogenic protozoa forming (oo)cysts such as *Cryptosporidium parvum* and *Giardia lamblia* (represented by *Clostridium perfringens* spores with similar characteristics regarding treatment: long-term survival, high resistance to disinfection, removal predominantly by fil-