

## Biological aspects of slow sand filtration: past, present and future

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### ABSTRACT

For over 200 years, slow sand filtration (SSF) has been an effective means of treating water for the control of microbiological contaminants in both small and large community water supplies. However, such systems lost popularity to rapid sand filters mainly due to smaller land requirements and less sensitivity to water quality variations. SSF is still a particularly attractive process because its operation does not require chemicals or electricity. It can achieve a high level of treatment, which is mainly attributed to naturally-occurring, biochemical processes in the filter. Several microbiologically-mediated purification mechanisms (e.g. predation, scavenging, adsorption and bio-oxidation) have been hypothesised or assumed to occur in the biofilm that forms in the filter but these have not yet been comprehensively verified. Thus, SSFs are operated as 'black boxes' and knowledge gaps pertaining to the underlying ecology and ecophysiology limit the design and optimisation of the technology. The objective of this review is to outline the biological aspects of SSF in the context of recent developments in molecular microbial ecology.

**Key words** | biofiltration, biological water treatment, microbial ecology, slow sand filter

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### INTRODUCTION

Slow sand filtration (SSF) or biological sand filtration is one of the earliest forms of engineered potable water treatment. Such systems date back to 1804 when John Gibb designed and built an experimental slow sand filter for his bleachery in Paisley, Scotland, and sold the surplus treated water to the public (Baker & Taras 1948). Robert Thorn further developed the mechanism, and then later James Simpson implemented the first public supply at the Chelsea Water Company, London, in 1829 (Baker & Taras 1948). This technology soon spread and was installed in major European cities (e.g. Paris, Hamburg, Amsterdam), where many such systems continue to operate. Yet, early in the 20th century, SSFs soon lost their popularity to rapid sand filters which, coupled with chemical coagulation, could operate on a smaller footprint and better tolerate greater variations in water quality.

It was not until the 1980s that a renewed interest in SSFs spawned mainly for small to medium community applications in both industrialised and developing countries.

This was mainly due to their simplicity, low chemical and energy requirements, and high level of water treatment. SSFs can provide an efficient single-stage treatment for raw waters within certain water quality limits of turbidity and other parameters (Table 1). Importantly, SSFs can remove a high proportion of pathogenic microorganisms in comparison to rapid sand filters, including protozoan oocysts, cercariae and schistosomes (Table 1). Despite its advantages, the fundamental biological mechanisms underpinning SSF operation remain poorly understood, which may have further limited the application and wider utilisation of this technology.

The increased concerns with the water industry's energy requirements within the backdrop of dwindling supplies of fossil fuels and increased awareness of carbon emissions and their impacts on climate change (Mo *et al.* 2010) may well prompt a renewed interest in slow (or biological) sand filtration. Historically, advances in SSF

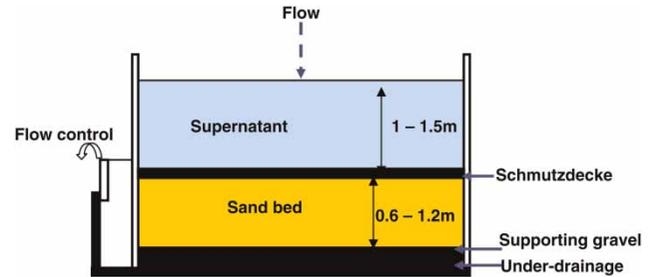
**Table 1** | SSF performance summary (Adapted from Gimbel & Collins 2006)

Water quality parameter	Removal capacity	Reference
AOC	14 to 40%	Lambert & Graham (1995)
BDOC	46 to 75%	Lambert & Graham (1995)
Cercaria	100%	Ellis & Wood (1985)
Cryptosporidium	>99.9%	Hijnen <i>et al.</i> (2007)
DOC	5 to 40%	Lambert & Graham (1995)
Enteric bacteria	90 to 99.9%	Hijnen <i>et al.</i> (2007)
Enteric viruses	99 to 99.99%	Poynter & Slade (1978)
Giardia cysts	99 to 99.99%	Bellamy <i>et al.</i> (1985)
Iron, manganese	30 to 90%	Ellis & Wood (1985)
Nitrate	95%	Aslan (2008)
Pesticides	0 to 100%	Lambert & Graham (1995)
TOC; COD	<15–25%	Haarhoff & Cleasby (1991)
True colour	25 to 40%	Ellis & Wood (1985); Smet & Vissher (1989)
Turbidity	<1 NTU	Smet & Vissher (1989)
Zoospores	>99%	Calvo-Bado <i>et al.</i> (2003)

have been associated with developments in microbiology. Notably, recent progress in environmental biotechnology (Rittman 2010), particularly in the field of microbial ecology, has provided a basis for a renaissance in engineered biological treatment processes from which SSF could benefit. The objective of this review is to outline progress in the characterisation of biological treatment in SSFs in view of recent developments in molecular microbial ecology.

## SSF OPERATION

Several mechanisms for the removal of particles, microorganisms and organic matter exist in SSFs. The raw water to be purified enters the supernatant (Figure 1) and moves through the sand bed due to gravity, which requires 3–12 h, depending on the applied filtration rate. As water percolates through the sand, organic material and microorganisms are removed by both mechanical (e.g. absorption, diffusion, screening and sedimentation) and biological processes (e.g. predation, natural death and metabolic breakdown; Huisman *et al.* 1974; Ellis & Wood 1985; Haarhoff & Cleasby 1991; Fogel *et al.* 1993;

**Figure 1** | Schematic representation of a slow sand filter, adapted from Huisman *et al.* (1974).

Lloyd 1996; Bahgat *et al.* 1999). Extensive work has been done to understand the mechanical processes (e.g. Huisman *et al.* 1974; Bellamy *et al.* 1985; Weber-Shirk & Dick 1997a, b); however, the same cannot be said for the biological processes.

## THE BLACK BOX OF SSF: BIOLOGICAL PURIFICATION MECHANISMS

Initially, the role of biological purification in SSFs was hypothetical and largely based on empirical observations (Baker & Taras 1948; Huisman *et al.* 1974). Since then, most SSF research and development has assumed that biological purification would occur and has focused on: (a) pre-treatment methods (particularly for application in developing countries); (b) process development, performance and modelling; and (c) ecological aspects/biological treatment. However, much of the attention corresponding to the ecological aspects of SSFs, has been based on hypothesising about the biological treatment in SSFs, considering them as 'black boxes'. Indeed, many studies attempting to characterise the purification mechanisms and the microbes involved were limited by the available techniques (Figure 2). Even recently, many of these investigations have also been limited by a focus on specific elements of the filter, such as the schmutzdecke (Figure 1; Campos *et al.* 2002; Rooklidge *et al.* 2005; Unger & Collins 2008), or on specific biological processes, such as denitrification (Aslan & Cakici 2007), predation (Weber-Shirk & Dick 1999) or pathogen removal (McConnell *et al.* 1984). A further limitation is that the majority of the research has been performed on laboratory-scale microcosms, with carefully

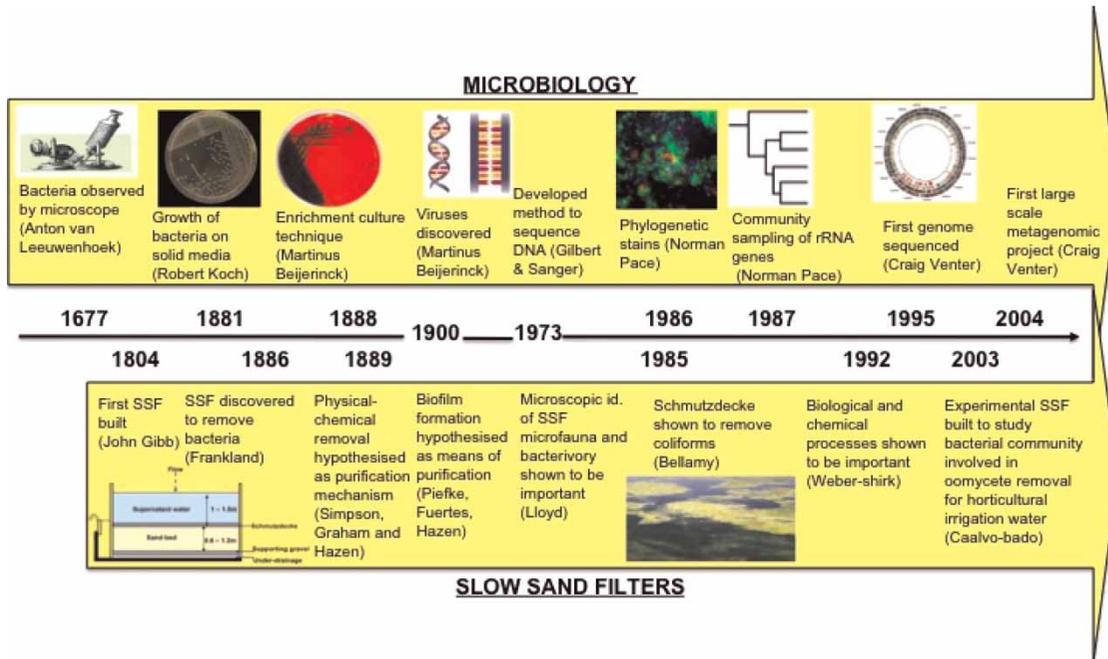


Figure 2 | Timeline of major events in the fields of Microbiology and SSF research.

controlled parameters, which may not fully represent the presumably complex and diverse microbial communities underpinning full-scale SSFs.

More acutely, most of the previous research was limited to the microbes (and their associated processes) that could be cultured using traditional microbiological techniques. The role of uncultivable (or ‘yet-to-be-cultured’) microbes, which comprise the majority of environmental biomes (Rappe & Giovannoni 2003) (including SSFs), has yet to be determined. Apart from one study (Calvo-Bado *et al.* 2003), the microflora of SSFs have not been studied and the roles of individual microbe in purification have not been determined. Despite recent developments, and the availability of new tools in molecular microbial ecology, information on the biological aspects of SSFs is sparse (Figure 2).

## APPLICATION OF MODERN MICROBIAL ECOLOGY TO SSF RESEARCH

The biology of most naturally-occurring microbial communities, including those found in SSFs, is complex. This complexity is due to the fact that microorganisms are

rarely found alone, but thrive in diverse biofilm communities, which collectively process the range of chemicals and nutrients entering the system. A biofilm is an aggregation of microorganisms (e.g. bacteria, diatoms, fungi, algae and protozoa) that is either self-immobilised (e.g. anaerobic sludge granules in wastewater treatment) or attached to a solid surface (e.g. dental plaque), and is enclosed by a matrix of extracellular polymeric substances. Biofilms facilitate various syntrophic relationships between different microbes allowing their synergistic survival, but further complicating the interrelatedness and interdependency between different species and trophic groups. Two main aims underpin modern microbial ecology: (i) unraveling diversity and identifying the ‘uncultivated majority’ (Kuypers 2007) and (ii) linking identity with activity. Both of those aims are integral to understanding SSFs.

In the late 1980s, genomic tools, including the polymerase chain reaction, revolutionised microbial ecology by enabling retrieval of genetic information directly from microbial individuals and entire microbial communities using the 16S ribosomal RNA gene. Several years later, developments in obtaining and working with messenger RNA have revolutionised the detection of functional genes – and their

expression – and underpin the field of transcriptomics. Techniques, such as microautoradiography – coupled with fluorescent *in-situ* hybridisation – or stable-isotope probing, enable the link between taxonomy and function by pairing genomics with substrate-labeling experiments. Practical applications of these techniques, to water and wastewater treatment, were recently discussed by Rittmann (2010). Additionally, advancements in proteomics and metabolomics continue to overhaul our understanding of how environmental biomes function.

The emergence of next-generation sequencing technologies, as the cost of sequencing decreases by orders of magnitude, has made microbial metagenomics more accessible. Unlike conventional microbial genomic sequencing, metagenomics attempts to determine directly the whole collection of genes in an entire environmental sample, including the estimated 99.9% of prokaryotes, which were thus far unculturable (Amann *et al.* 1995; Rappe & Giovannoni 2003), and to determine the biochemical activities and complex interactions. More importantly, metagenomics allows scientists to glimpse into fully functional, microbial communities, allowing observations of how individuals interact by exchanging nutrients, metabolites and signaling molecules (Wooley *et al.* 2010). The metagenomic approach includes both functional and sequence-based analyses of DNA extracted directly from the environment. Extensive studies have been performed on mammalian microbiomes, specifically the mucosal and epidermal surfaces (Turnbaugh *et al.* 2007; Grice *et al.* 2008; Zhu *et al.* 2010); however, scientists are only now beginning to explore the natural and engineered world.

From the perspective of SSFs, the deployment of new molecular techniques alongside traditional microbiological methods place scientists and engineers at a juncture, which will allow them to answer many questions relating to SSF ecology, such as:

1. Which microbes comprise the SSF community, and what are their functions?
2. Is community composition related to SSF performance?
3. How do the microbial communities react to perturbations, and can the response be replicated and predicted?

Close cooperation between scientists and engineers will support new insights into the functional ecology of SSFs,

and can result in a comprehensive framework for rational design and optimisation of new SSF technologies for water purification.

## SUMMARY

Access to safe drinking water is a basic human right (United Nations General Assembly 2010) and an important factor contributing to morbidity and mortality in developing countries. Additionally, energy-efficient water treatment technologies, which meet stringent drinking water standards, are urgently required due to the dissipation of fossil fuels and the rising costs of energy. SSFs have been used for hundreds of years to provide a safe and reliable source of potable drinking water. However, due to a lack of knowledge pertaining to the treatment mechanisms – specifically the biological processes involved – SSF design and operation has not yet been optimised. To date, SSF studies have focused on characterising and validating the biologically mediated purification mechanisms, by using carefully controlled, laboratory conditions, and conventional plating and isolation techniques, thus ignoring the uncultivable majority. Today, molecular microbiological techniques are available which, when used alongside conventional microbiological tools, will allow scientists to understand the ecology of SSF systems. This will, in-turn, promote optimisation of SSF design and operation.

## ACKNOWLEDGEMENTS

Sarah Haig is supported by a Lord Kelvin/Adam Smith Research scholarship from the University of Glasgow. Referees at the 2011 UK IWA YWP Conference are thanked for awarding Best Poster Presentation.

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First received 26 May 2011; accepted in revised form 28 July 2011