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Viewpoint

Underwater Remote Skimming of Slow Sand Filters for Sustainable Water Production

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ABSTRACT: Slow sand filters (SSF) are a simple water treatment technology providing an important alternative to conventional drinking water treatment. SSF are extensive in terms of carbon cost and chemical use but require a large land area and are complex to operate, as periodic cleaning is required to prevent filter clogging. Therefore, redundant SSF beds are required to enable water production to occur during long cleaning downtimes. Underwater skimming (UWS) is a cleaning innovation where the foulant layer (containing sand and particles) is removed using a skimmer consisting of a shrouded blade mounted on a vehicle platform. Sand, particles, and biofilm are skimmed prior to *ex situ* washing of the recovered sand. In this Viewpoint, we posit that the introduction of an *in situ* underwater skimmer operated remotely can substantially help to offset the aforementioned challenge of downtime, with its associated loss of production, enabling the technology to operate more efficiently and remain a pertinent and advantageous process option within modern water treatment facilities or possibly resource constrained settings. Otherwise, this resilient biotechnological process could be replaced by chemical and energy-intensive processes which increase the entropy of water treatment more than SSF. The anticipated benefits and challenges of UWS of SSF are discussed.

Slow sand filters (SSF) are simple, inexpensive, robust, and extensive forms of water treatment using gravity filtration via a fine and uniform sand bed stacked on gravel within a vessel. SSF have helped reduce waterborne disease outbreaks for generations, for example, communities supplied by SSF (Altona, Germany) had reduced cholera incidence compared to upstream communities without SSF (Hamburg, Germany), as SSF consistently removes pathogens such as viruses, bacteria, and protozoa.[1] The efficacy of SSF is scale independent; is successfully utilized from single household to metropolitan water treatment scales; and is widely applied in countries such as the U.K., United States, Japan, Sweden, and The Netherlands. For instance, currently in the Greater London area of the U.K., about 80% of treated water volume is processed through SSFs. In contrast, use in developing countries at municipal scale is less prominent, possibly due to the perception of lack of flexibility and poor treatment performance, alongside competing land pressures in urban environments.

Water treatment using SSF results in algae, water microbiota, natural organic matter, and turbidity accumulating on the surface of the bed to form a microbial biofilm layer commonly referred to as the *Schmutzdecke* (muddy layer). The layer is crucial in the performance of the technology but must be periodically removed to avoid excessive head loss and/or reduced flow. SSF are usually the final stage of treatment deployed prior to chlorination (e.g., in the U.K., Sweden, or United States) or after ozone/UV-based disinfection processes (e.g., The Netherlands) to polish and improve biostability. In other applications, they are used as a pretreatment when deployed as bankside filtration as part of process trains for the

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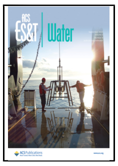

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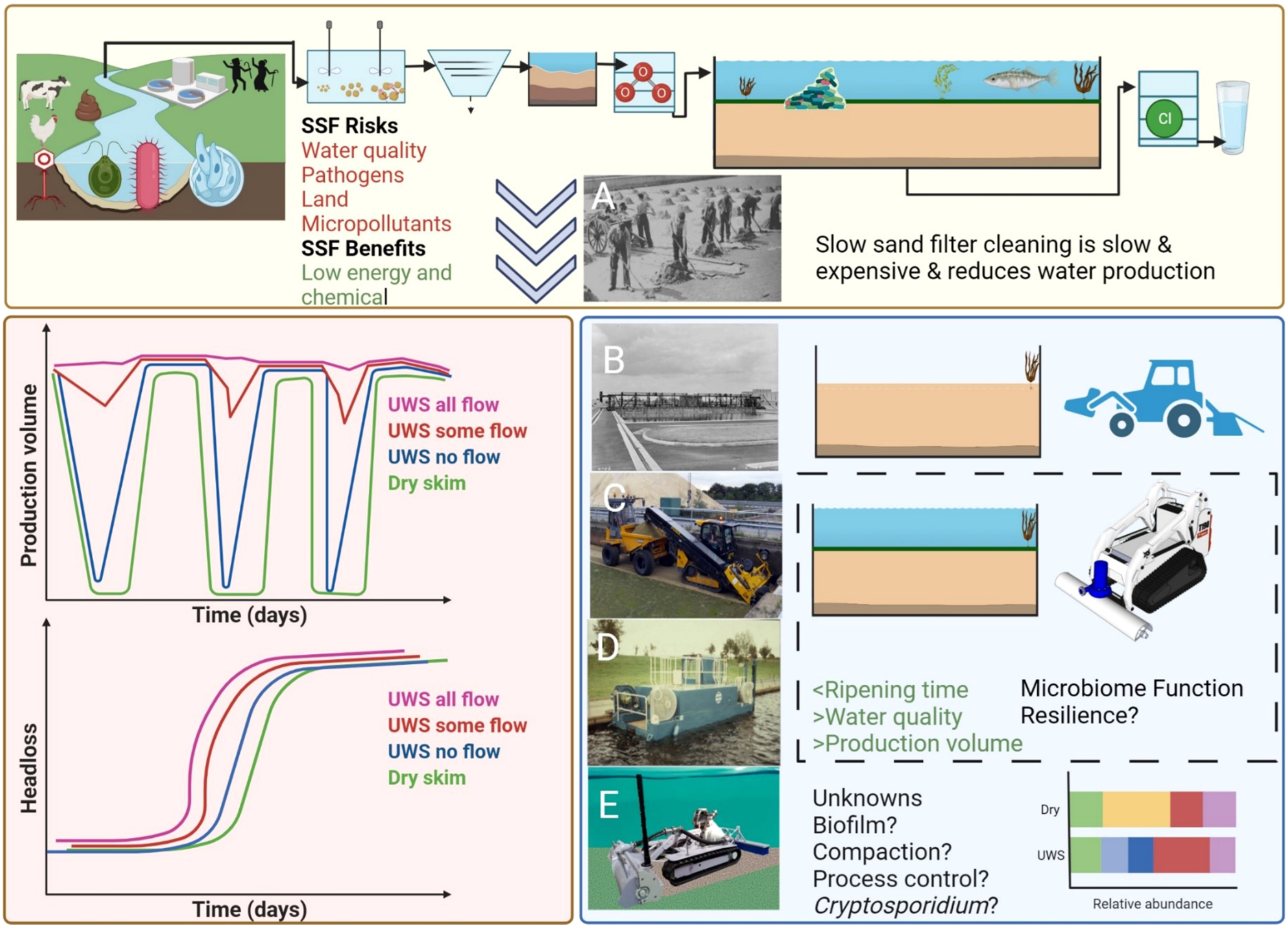

Figure 1. Underwater remote skimming of slow sand filters for sustainable water production. (A) Manual skimming; (B,C) mechanized cleaning using heavy machinery; (D) floating dredger; (E) underwater remote skimming vehicle.

generation of nonpotable reuse water from treated wastewater (e.g., United States, Israel). SSF are distinct from rapid gravity filters (RGF) but similar to biological granular activated carbon reactors (BAC) in that there is a significant biological component to the treatment. However, SSF operate at substantially lower hydraulic loading and greater contact times than RGF/BAC, which promotes an active and diverse microbiome with numerous reports of additional reactor functions such as pathogen and micropollutant reduction.[2,3] In addition, this produces biologically stable water, as biofilms within the bed use assimilable organics and their precursors during long contact times, which is thought to reduce microbial regrowth in drinking water distribution systems. Importantly, the utilization of biological treatment pathways enables SSF to operate with minimal energy or chemical inputs providing an important alternative to conventional water treatment plants.

The two main limitations of SSF are (i) pretreatments are often needed to address poor and variable inlet feedwater quality (especially high turbidity) as this results in unacceptable water quality, short filter run length, and additional cost; (ii) redundant beds are required due to long cleaning downtime requiring more land area. It is posited that climate change will adversely affect this by deteriorating feedwater quality, resulting in a need for increased land availability, and hence, we contend that without significant research to address this challenge, this resilient biotechnological process could be replaced by chemical and energy intensive processes which increase the entropy of water treatment more than SSF.

The operation and cleaning of SSF is a batch process which includes the steps of draining, skimming, refilling, run to waste, and operation to service. During skimming, the sand is not replaced, and therefore, infrequently, sand depth has to be amended by resanding events. Most maintenance of SSF, including media regeneration through sand washing, is undertaken onsite without the need for chemicals or substantial energy. Consequently, SSF can produce water for about 80% of the total cycle time with most of the downtime (70−90%) being associated with bed draining, sand cleaning, and backfilling. Historically, the cleaning of SSF has transitioned from using simple hand tools (Figure 1A) to modern day mechanized cleaning, using heavy machinery[4] (Figure 1B,C). Since innovations are required to help SSF become more productive, but the established maximum hydraulic loading of 0.5 m/h is considered the ceiling of the technology (most filters operate at 0.1−0.3 m/h), it is clear that the most effective improvements will be associated with cleaning. Therefore, we posit here that the introduction of *in situ* underwater skimming (UWS) can substantially help to offset the aforementioned challenge of downtime, with its associated loss of production, enabling the technology to operate more efficiently and remain a pertinent and advantageous process option within modern water treatment facilities.

UWS is a cleaning innovation where the *schmutzdecke* is removed using a shrouded blade to simultaneously skim *schmutzdecke* and capture particles, sand, and biofilm prior to *ex situ* washing of the recovered sand. This system is mounted on a free-floating (e.g., vessel) or bed-mounted (e.g., vehicle) platform, "crawling" along the media surface with a pipe to permit slurry transit to the surface. Through UWS, improvement to the cleaning processes of SSF could accrue from (i) reduced time spent draining and refilling the filter and scraping media; (ii) reduced ripening time expanding the window for safe operation; and therefore (iii) result in less pretreated water lost to supply and indirectly, cost, and energy benefits. The ability to carry out cleaning without draining the bed should reduce the downtime associated with draining and refilling the beds, thus increasing potential production output. Cleaning innovations such *in situ* sand washing[5] (Figure 1B), underwater sand rinsing,[6] and floating dredgers[7] (Figure 1D) enabled cleaning without drain down, but deterioration of filtrate water quality and operator safety concerns prevented widespread adoption and implementation of these technologies.

We moot that UWS could confer additional treatment benefits in terms of resilience of the process. Experience from 1 year of pilot scale UWS trials at Thames Water Utilities Limited (U.K. water utility) and through design of a remote operated vehicle (ROV), has shown that UWS provides an alternative strategy for the cleaning of SSF. This approach involves no drain down and has flexibility to include a continuous operation during the filter cleaning process, effectively decoupling operation from cleaning. Therefore, this effectively transitions SSF from a true batch process (analogous to traditional downflow RGF) to a semicontinuous process (analogous to continuous upflow depth filters). The UWS SSF process is not truly continuous, such as the activated sludge process, as periodic resanding would be required at about 18-month intervals. For example, with UWS, the SSF bed would remain wet and oxic, which reduces the risk of anaerobic conditions and desiccation negatively impacting the microbiome of SSF (compared with dry skimming of SSF). However, the degree to which this occurs with different configurations of the technology such as batch UWS (without flow) or semicontinuous UWS (with some flow or full flow) (Figure 1) remains unknown. Our best estimates suggest that UWS of SSF could result in a reduction to operational downtime by up to 88%, and filters skimmed in this way could remain in a biologically mature state, resulting in rapid or nonexistent ripening time. Currently UWS of large municipal scale filters is planned to use ROVs, but automation of this process is conceivable for the future. UWS of SSF will reduce the risk of human contact with key drinking water assets and possible contamination from plant via this contact or human error alleviating health and safety concerns to consumers and operators. Skilled operators will be needed for maintenance and operation of ROVs retaining jobs and livelihoods. Electrification of ROVs will also reduce the risk of fuel spills from plant heavy machinery currently used in dry skimming. The use of UWS could improve filter performance through operation in a continuous pseudosteady state of intermediate headloss, by avoiding traditional skimming at high headloss or when high densities of autochthonous filamentous algae have developed. We predict the UWS SSF will have a similar or more consistent pathogen reduction via combined screening and physical removal mechanisms,[8] and persistent enhanced biological removal within the subsurface layers of the SSF[9] which are better preserved by a less impactful and disruptive cleaning framework (from a biological perspective).

It is important to ensure that the core treatment function of SSF is retained, this being the production of high-quality filtrate water. There are a number of anticipated challenges to the widespread use of UWS. For example, during long-term operation, the UWS SSF will be more compacted and have reduced filter porosity as the bed would not be backfilled or desiccated. These operational processes are thought to remove particles and clean biofilm, respectively, as a consequence of drain down and refilling beds. This implies that head loss development will be more rapid in the UWS bed when compared with an equivalent conventionally cleaned SSF, resulting in marginally shorter filter run lengths in the beds utilizing UWS. Consequently, a more frequent cleaning regimen is needed which could impact the anticipated net production volume gains. Finally, during continuous operation mode, there is the prospect of particle penetration in newly skimmed sand area resulting in short-circuiting of nonskimmed *Schmutzdecke* which could be offset via a closed-loop recycle during cleaning.

In addition to the time and production benefits UWS could afford, UWS would also provide greater flexibility in time and resource management, providing possibilities for exploring alternative means of increasing productivity, such as increasing the hydraulic ceiling of SSF through continuous automated and precision skimming. Finally, UWS could enable intensification of SSF by skimming in confined spaces, raising the possibility for stacked SSF in urban areas. Future research is needed to optimize the process engineering and its impact on the microbiome and its function in SSF.

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Notes

The authors declare no competing financial interest.

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