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Evaluating the impact of underwater skimming on slow sand filter performance and operation

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ABSTRACT

Conventional cleaning of slow sand filters (SSFs) requires the beds to be drained before a layer of media and the *Schmutzdecke* are removed, called 'dry skimming' (DS), which can result in significant downtime. An alternative is proposed whereby the filter is skimmed whilst still submerged, called 'underwater skimming' (UWS). Previous attempts to avoid draining the bed have led to concerns about the risks of UWS in terms of headloss development, particle penetration, and microbial water quality. In this study, pilot scale SSFs, cleaned by either DS or UWS, were operated concurrently, to compare and assess the potential risks of UWS in terms of filtrate quality, microbial removal, and recovery following skimming. While all filters exhibited effective turbidity removal (0.04–0.9 NTU turbidity from outlet), UWS filters had improved performance immediately after cleaning compared to DS in terms of recovery of filtrate microbial water quality. Specifically, total coliforms in the UWS filter outlets, in the first seven days post-skimming, ranged from 1 to 109 most probable number (MPN)/mL, compared to 1 to 1414 MPN/mL for DS filters. Both methods yielded satisfactory headloss recovery, indicative of limited particle penetration at depth, and effective cleaning. Exploring different sweetening flow rates during UWS revealed no observable differences in headloss, turbidity reduction, or microbial quality between the flow rates tested. *Schmutzdecke* microbial community was similar irrespective of cleaning method and was governed instead by seasonal changes and the ripening process. The improved microbial removal afforded by UWS provides a means of significantly improving water productivity and enabling options for much better utilisation of SSFs.

1. Introduction

Slow sand filtration is a low energy and chemical free treatment that removes a wide range of contaminants including inorganic particles, dissolved and particulate organic matter, algae, and pathogens from influent water through physical, chemical, and biological processes (Chan et al., 2018). An important part of slow sand filter (SSF) treatment occurs within surficial biofilm layers (*Schmutzdecke*), which provide a primary site for biological activity (Hijnen et al., 2007). The *Schmutzdecke* is reported to be essential for eliminating microbial contaminants, including coliforms (Burman and Lewin, 1961), other bacteria (Hijnen et al., 2004), viruses (Poynter and Slade, 1978), phages (Wang et al., 2014), and *Giardia* spp./*Cryptosporidium* spp. (Bellamy et al., 1985a). The unavoidable consequence of the function of the *Schmutzdecke* is an increasing headloss as particles accumulate and biofilm assembles, eventually clogging the filter (Graham and Collins, 2014). The subsurface filter bed supports filtration and biofilm, enhancing the overall efficiency, especially the capture of

Abbreviations: AOC, Assimilable Organic Carbon; BV, Bed Volume; DNA, Deoxyribonucleic Acid; DS, Dry Skimming; EPS, Extracellular Polymeric Substances; GAC, Granular Activated Carbon; HLR, Hydraulic Loading Rate; HPC, Heterotrophic Plate Count; LOD, Limit of Detection; MPN, Most Probable Number; NTU, Nephelometric Turbidity Units; PCoA, Principal Coordinates Analysis; rRNA, Ribosomal Ribonucleic Acid; SI, Supporting Information; SSF, Slow Sand Filter; TCC, Total Cell Count; TOC, Total Organic Carbon; UC, Uniformity Coefficient; UWS, Underwater Skimming; WTW, Water Treatment Works.

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difficult-to-filter small particles, such as viruses (Trikannad et al., 2023).

The rate and extent of SSF clogging depends on the source water quality, hydraulic loading rate, in bed growth and cleaning frequency. Conventional amelioration involves dry skimming (DS), where the filter is initially drained before the top 10–50 mm layer of the bed is removed. Once complete, the bed is refilled with water and the process restarted with the treated water run to waste until the required water quality is achieved. Cleaning of UK SSFs typically occurs every 1–3 months such that over a year the filter will be operation around 80–90% of the time (Hassard et al., 2022). A negative consequence of DS is that it may create environmental stress within the biofilms, changing nutrient availability, and disrupting the SSF microbial community by removing microbes at varying rates, analogous to sludge wasting in sequencing batch wastewater reactors (Ellis, 1985). Accordingly, minimizing drainage time and cleaning disruption is crucial to maintain the stability of the SSF ecosystem.

To address such concerns, underwater skimming (UWS) has been proposed (Hassard et al., 2022), which involves removing the *Schmutzdecke* and top sand layers, as achieved by DS, except with the filter fully submerged. UWS employs a skimmer, fitted with a shrouded horizontal auger moving along the surface of the bed that concurrently removes sand and *Schmutzdecke*, which are then pumped out of the filter as a slurry. The UWS process may involve either a complete pause of flow or a continuous 'Sweetening' flow regimen which is a small, continuous filtration flow maintained during skimming to support biofilm function), facilitating the steady provision of oxygen and nutrients to the filter during cleaning. UWS eliminates SSF drainage, minimizing 'stop-start' cycles and hence offers a less disruptive cleaning method, potentially increasing water production through semi- or fully continuous filter operation (Lloyd, 1996). In addition, UWS is hypothesised to preserve the microbial ecosystems leading to enhanced resilience (Hassard et al., 2022). In this context resilience is the ability of the SSF's microbial ecosystem to recover rapidly and maintain stable performance after operational disturbances, such as cleaning events.

The potential disadvantages of UWS and alternative cleaning methods, where the bed is left fully submerged, have been reported to be a reduction in filtrate quality and increased post-cleaning problems (Singer et al., 2017). These post-cleaning problems refer to operational challenges that can arise immediately after skimming, such as delayed ripening times for the filter, a temporary decline in microbial water quality, and prolonged periods before the filtrate meets compliance targets. Other reported issues include faster headloss development (Burman and Lewin, 1961), and deeper particle penetration (Huisman and Wood, 1974). For instance, a full-scale *in-situ* sand washing test indicated reduced filter run times, over months, attributed to rapid biofilm/algae growth and suboptimal cleaning, underscoring the need for further refinements in UWS applications for SSFs (Burman and Lewin, 1961). One such refinements is the ex-situ washing of the sand slurry produced from cleaning (as opposed to *in-situ* in the examples above).

In this study, an investigation into the impacts of UWS on water quality, filter performance and microbial community is presented with a real time side-by-side comparison with DS. Furthermore, a novel investigation of the previously unexplored impacts of varying sweetening flows on the performance of UWS is provided, offering new insights that could significantly enhance filter efficiency with regards to maintaining production through SSFs during and after cleaning.

Accordingly, this study assesses the potential risks associated with UWS in terms of impacts on filtrate quality, hydraulic performance and any associated shift in the microbial community or diversity using ten 0.54 m^2 pilot SSFs in a real-world, full-scale drinking water treatment works (WTW) setting for 15 months. It contrasts UWS with conventional DS comparing headloss development, recovery time to achieve microbial compliance, and performance post-multiple UWS cycles. The underpinning hypothesis is that UWS minimises SSF ecosystem disruption, quickens ripening, and lessens quality impacts, enhancing performance during the post-skim period through reduced breakthrough risk(s). In addition, it is suggested that the proposed benefits will occur without an associated increase in clogging in the lower layers of the SSF. This will be tested by comparing the post-skim headloss of UWS to DS, and whether the introduction of a sweetening flow through the filter during UWS promotes the improved benefits of UWS.

2. Materials and methods

2.1. Description and operation of pilot SSFs

The SSF pilot plant assembly included 10 no. ~0.54 m^2 rectangular filters, containing from the top downwards: a layer of sand (0.2–0.5 m, d_{10}=0.3 mm, uniformity coefficient UC=1.8), (of which the top 0.3 m was subject to successive skims), granular activated carbon (GAC, 0.1 m, d_{10}=0.6 mm, UC=1.9), sand (0.2 m), and gravel (0.1 m), resting on a metal plate containing 24 filter nozzles, with 36 no. 0.2 mm width slots acting as a filter false floor (Fig. 1). Each gravity-fed filter was manually controlled using outlet valves and flow meter. Each weekday headloss was measured and outlet flow rate was checked volumetrically and adjusted when required. Sampling from the inlet and filtrate occurred ~five days weekly, with water quality parameters measured either daily or weekly. The GAC layer was incorporated beneath the sand layer in the pilot filters to replicate a configuration commonly employed at full-scale UK WTW. Additionally, slight variations in the total filter media depth (ranging from 50–80 cm) arose due to practical operational constraints and periodic sand top-ups conducted across multiple filter runs. While this approach differs from conventional SSF designs reported in other studies (e.g. Trikannad et al., 2023) — many of which utilize sand-only media, the present setup remains representative. These differences are highlighted and discussed in the context of existing literature (e.g., to ensure the broader applicability and relevance of our findings).

2.2. Feed water characteristics and filter operation

The pilot plant influent came from a raw water reservoir, with a 30-day retention, fed from the River Thames. Average feed water quality included a total organic carbon (TOC) concentration of 3.6±0.2 mg/L, turbidity of 0.6±0.4 NTU, and pH of 8.1±0.2 (Supplementary Information SI, Table S1). The filters operated in air temperatures of -6 to 22 °C, and water temperatures of 3–16 °C (SI, Figure S1). More detailed characteristics of the inlet water quality are available in the supporting information (SI, Table S1). Initially backfilled with filtrate, the SSFs were started at a hydraulic loading rate (HLR) of 0.1 m/h, increasing by 0.1 m/h daily until reaching an operational rate of 0.3 m/h HLR. Typical SSF pre-treatment by roughing filtration was omitted for the duration of the experiment due to the low feed water turbidity (<1 NTU).

2.3. Headloss measurement and skimming procedures

Headloss was measured using piezometers attached to the plenum of each SSF, calculated as the difference between the supernatant surface and the water pressure in the plenum under the filter media and nozzle plate, with a maximum measurable headloss of 1350 mm. Before each measurement, the flowrate was set to the operational rate, and values were temperature-normalised to account for seasonal viscosity changes:

$$h_N = h_m . \frac{\mu_N}{\mu_m}$$

Where:

h_N	Normalised headloss (mm)
h_m	Measured headloss (mm) at time, t
μ_N	Dynamic viscosity (Pa.s) at normalising temperature of 20 °C
μ_m	Dynamic viscosity (Pa.s) at measured temperature at time, t

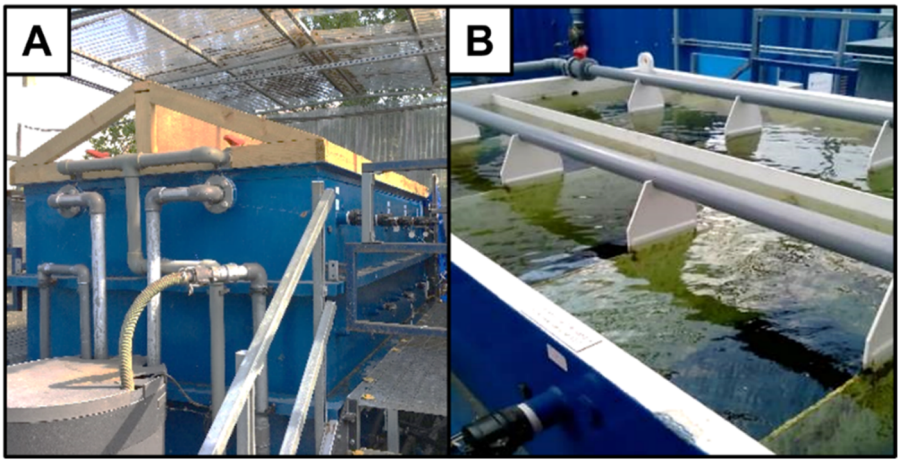

Fig. 1. SSF pilot plant assembly, showing: (A) an anterior view of feed pipes, overflows and transparent roof of the filtration tank and access platform; (B) 10 individual cells and central dividing wall, individual submerged filter dividing walls and parallel common feed pipes.

Skimming started when the maximum headloss was reached, for one or more of the filters, or at seasonally adjusted intervals (40 days in summer due to biological growth, 70 days in winter), whichever came first, which is standard practise for the water utility. The decision to skim all filters within days of each other (whether or not maximum headloss was reached for some), was to allow all filter runs to commence at similar times and under similar conditions. The two cleaning methods, UWS and DS, were compared. DS used a disinfected scraper and shovel, cleaned with 70% isopropanol and then final water, to manually remove a 40 mm surface layer from drained filters, confirmed by a laser measurement tool. UWS involved a specialized HDPE wet vacuum blade for submerged sand removal, operating at varying 'sweetening flows' (100, 67, 33% of operation flow), and zero flow, with DS as the control (SI, Table S3 for breakdown of skimming procedure and Method S2 for graphical representation of UWS device) and Fig. 2 for schematic of skimming procedure. During UWS, a surface layer of approximately 40 mm of sand is removed which is equivalent to the layer taken off in DS—but the process is carried out with the filter bed fully submerged, eliminating the need for filter drainage prior to cleaning. 'Sweetening flow' refers to a continuous and steady flow of water through the SSF that was maintained during UWS, and denoted as follows: 100% of the operational HLR (UWS-100), 67% (UWS-67) to 33% of the HLR (UWS-33). The "locked-in" filter (meaning no flow was applied during UWS skimming) was UWS-0. Post-skimming, SSFs returned to the operational HLR with 0.1 m/h increments every 24h. UWS-100 needed no increments, UWS-67 one increment, and UWS-33 and UWS-0 two increments each. The differences in increments were associated to differences in 'sweeting flow' versus operational flow rates. DS filters were restarted in the same manner as the initial setup, with backfilling and gradual filtration resumption using the daily 0.1 m/h increments. For DS filters, the flow direction is effectively reset: the bed is first drained, then refilled from the top, resuming downflow filtration once the filter is brought back online. In contrast, UWS filters remain submerged, and the flow direction is maintained as downflow throughout the cleaning. When sweetening flow is applied, it simply represents a reduced downflow rate sustained during the skimming process, ensuring continuous oxygen and nutrient supply to the microbial community while the top sand layer is removed.

Consistent with full-scale SSF practice, sand was not replaced during skimming. After five filter runs (Phase 1), all filters were drained (including the UWS filters), and sand levels were increased with cleaned sand (via a re-sand event), akin to full-scale SSF practices, to maintain a skimmable layer above the minimum 500 mm media depth (200 mm sand above 100 mm GAC above 200 mm sand). At this point, an

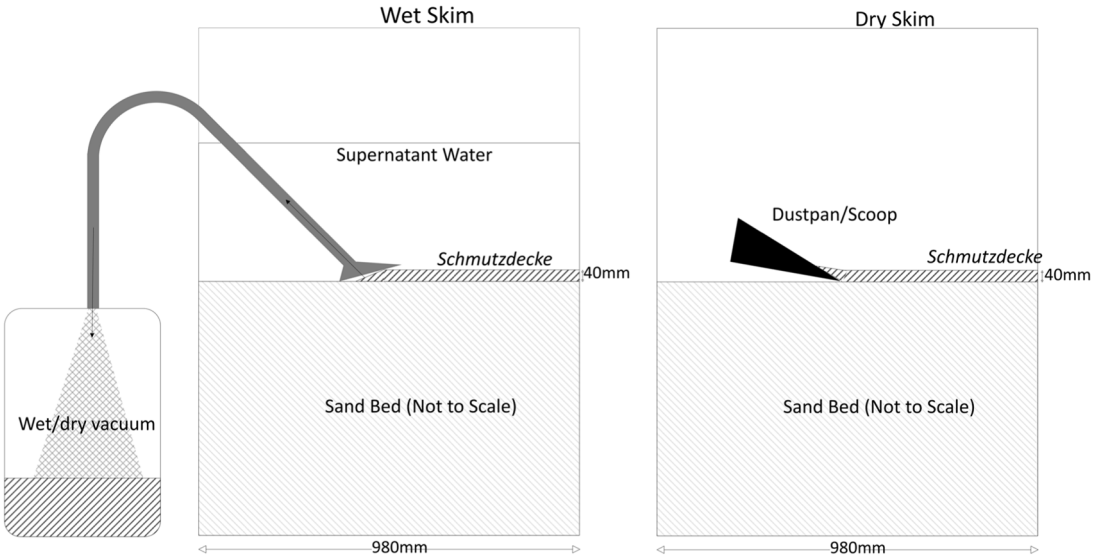

Fig. 2. – Schematic of skim approach using underwater skim (UWS – left) and conventional dry skim (DS – right).

additional DS methodology was included (Phase 2) that further increased the downtime from approximately 14 hours to about 28 hours) to better replicate conditions that are observed in full-scale SSFs. Consequently, the UWS-67 experiment was discontinued and an additional set of DS filters (labelled as DS-Ext) were introduced (See SI, Table S3).

2.4. Water sampling, analysis and biofilm analysis

Water samples (feed and filtrate) were aseptically obtained from the inlet to the filters (feed) and from the outlet of individual filters (filtrate) for microbial analysis and were collected daily during critical phases and weekly otherwise. Total coliforms and Escherichia coli were quantified using the were quantified via the Most Probable Number (MPN) method, using Colilert and Quanti-Tray approach, which involves serial dilution and selective media incubation to estimate bacterial concentrations (Standing Committee of Analysts, 2009). Heterotrophic Plate Count (HPC) was determined by plating on yeast extract agar with up to a 68-hour incubation at 22 °C (Standing Committee of Analysts, 2007). The *E. coli* results were consistently at measured at low levels or were non-detectable, and thus were omitted from subsequent analysis. Turbidity was determined daily with a TU5200 instrument (Hach, Loveland, Colorado, USA), and water temperature was monitored hourly (Metrinet M-node). Conductivity and pH were measured with a Hach HQ440d Multi-Parameter Meter (Hach, Loveland, Colorado, USA) using the intellical CDC401 and PHC101 probes, respectively. TOC was determined using an O.I. Analytical Carbon Analyser, Model 1030 (Xylem Inc., Washington, D.C., USA) and true colour was measured by spectrophotometry using a Cecil CE 2021 Spectrophotometer (Cecil Instrumentation Services Ltd., Cambridge, UK). Automated inline flow cytometry was undertaken using a BactoSense instrument (bNovate, Switzerland). This instrument features a built-in laser operating at a wavelength of 488 nm, a side scatter (SSC) detector, and two fluorescence detectors equipped with bandpass filters for green-light (FL1, 525/45 nm band pass) and red-light (FL2, 715 nm long pass) emissions (see SI, S1).

Over the first year of operation (March 2021-March 2022), small volume media samples from the top 25 mm of the individual beds were collected weekly while the beds were in operation. Sample collection entailed extracting 'cores' using single use modified sterilised syringes, with their nozzle and shoulder removed. This was then stored at -20 °C in sterile centrifuge tubes until ready for Deoxyribonucleic Acid (DNA) extraction. Detailed description of the DNA extraction process is provided in the SI (S2). Extracted DNA was analysed by Novogene (Cambridge, UK) for amplification of the 16S Ribosomal Ribonucleic Acid (rRNA) gene via the NovaSeq PE250 platform (Illumina Inc.). The raw sequence data obtained from the Illumina sequencing were processed via QIIME2 (version 2018.11) and its associated plugins (Bolyen et al., 2019). The sequence data were analysed using PRIMER v7/PERMANOVA+ software (Primer-e, UK). A detailed description of the sequencing and data analysis are provided in the SI (S2).

3. Results and discussion

3.1. Treatment performance

In this study, the filter maturation period was defined by filtrate coliform levels <50 MPN/100 mL. During the initial startup (Run 1), before any skimming was conducted, this period ranged from 1–17 days. Following re-sanding (Run 6), the maturation period was between 1–14 days, consistent with the performance of full-scale SSFs, with no difference between DS and UWS filters.

Comparison of the performance of the SSFs in terms of the physicochemical properties such as pH and conductivity (see SI, Table S2), and TOC and true colour (see SI, Figure S2), revealed no difference in treatment performance between the DS and UWS operations. This consistent performance held true for the experiments. Except from Run 6 onward, colour removal gradually declined, which may reflect the diminishing adsorption capacity of the GAC layer as its pores become saturated over prolonged usage. Additionally, skimming events at the approach to maximum headloss/run length could have enhanced the natural biological and physical removal mechanisms at the filter surface. It is not known which factor(s) contributed to the observed decrease in colour removal. Accordingly, the use of UWS offered no risk of treatment deterioration during the steady state phase of operation irrespective of the rate of sweetening flow. This was consistent with previous observations when using backwashing (Fernando Hymnô F.H. de Souza et al., 2021), and *in-situ* sand washing (Burman and Lewin, 1961), which found that filter performance remains unchanged once filters have matured, regardless of the cleaning method employed.

For the turbidity (Fig. 3), the feed water values ranged between 0.4 NTU (March-December 2021) and 1.1 NTU (January-April 2022), representing low values compared to previous studies that had higher inlet turbidity values (e.g., >30 NTU (Aydin, 1996)). All SSFs exhibited good turbidity removal, with filtrate turbidity values ranging from 0.04–0.7 NTU (UWS-100), 0.04–0.4 NTU (UWS-67), 0.04–0.4 NTU (UWS-33) and 0.04–0.9 NTU for the DS filters. Turbidity values exceeding the water company internal target of 0.3 NTU were very infrequent in any of the samples from the different filter skimming treatments, only occurring during the initial maturation phase at the start of the experiment (Run 1), and on three other occasions throughout the experimental period (0.39 NTU for UWS-0 Run 5, 0.33 NTU for DS-Ext Run 7 and 0.34 NTU for UWS-33 Run 8). These three occurrences of filtrate turbidity measurement >0.3 NTU were separate and did not suggest any pattern favouring DS over UWS. In addition, the level of sweetening flow did not affect filtrate turbidity. Furthermore, when comparing the DS filters, there was no substantial difference in the treatments with the extended downtimes.

Headloss development was characterised by three distinct phases: an initial gradual increase (slow rate), an intermediary phase with a more rapid increase, followed by a sharp ascent (fast rate), marking the transition from depth filtration to surface filtration and subsequent surface clogging (Fig. 4). These phases were determined based on the slope of the individual sections of the headloss development curves, where the slow rate was based on the curves where the slope was less than 10 mm/d, and the fast rate based on the curves where the slope was greater than 15 mm/d (further details in SI, Figure S4). The difference in headloss development between runs was greater than that observed between different skimming options within individual runs. In Run 2, the initial slow rates of headloss were 1.7 mm/day for DS and 1.5, 1.3, 1.4, and 1.4 mm/day for UWS-100, UWS-67, UWS-33, and UWS-0, respectively. By Run 5, no initial slow phase was observed, and all filters transitioned directly to a rapid rate of headloss. After re-sanding, headloss profiles again shifted, with UWS filters developing headloss more rapidly than DS. Statistical analysis of the slow-rate phase across runs (excluding Runs 1 and 6) showed no significant difference among treatments (Kruskal-Wallis: $H(80) = 10.6$, $p=0.385$). These runs were omitted because Run 1 was the initial startup and Run 6 followed a re-sand event. In contrast, the fast-rate phase showed a significant difference between DS and UWS (Kruskal-Wallis: $H(80) = 8.4$, $p=0.004$) (Fig. 5).

Here, 'ripening' refers to the post-cleaning period when the biofilm re-establishes optimal filtration conditions. UWS preserves partial flow, likely retaining portions of the biofilm and accelerating its re-establishment — potentially by flushing microorganisms from the *Schmutzdecke* downward and re-seeding the surface layer. Changes to the ripening pattern when deploying UWS has interesting implications for SSFs applied as a pre-distribution polishing treatment step (i.e., in the Netherlands) where ripening periods are extended but frequency of skim is much less. No significant difference in headloss development was observed with varying sweetening flow within individual runs (Kruskal-Wallis: $H(56)=6.8$, $p=0.341$). Similarly, when both slow and fast

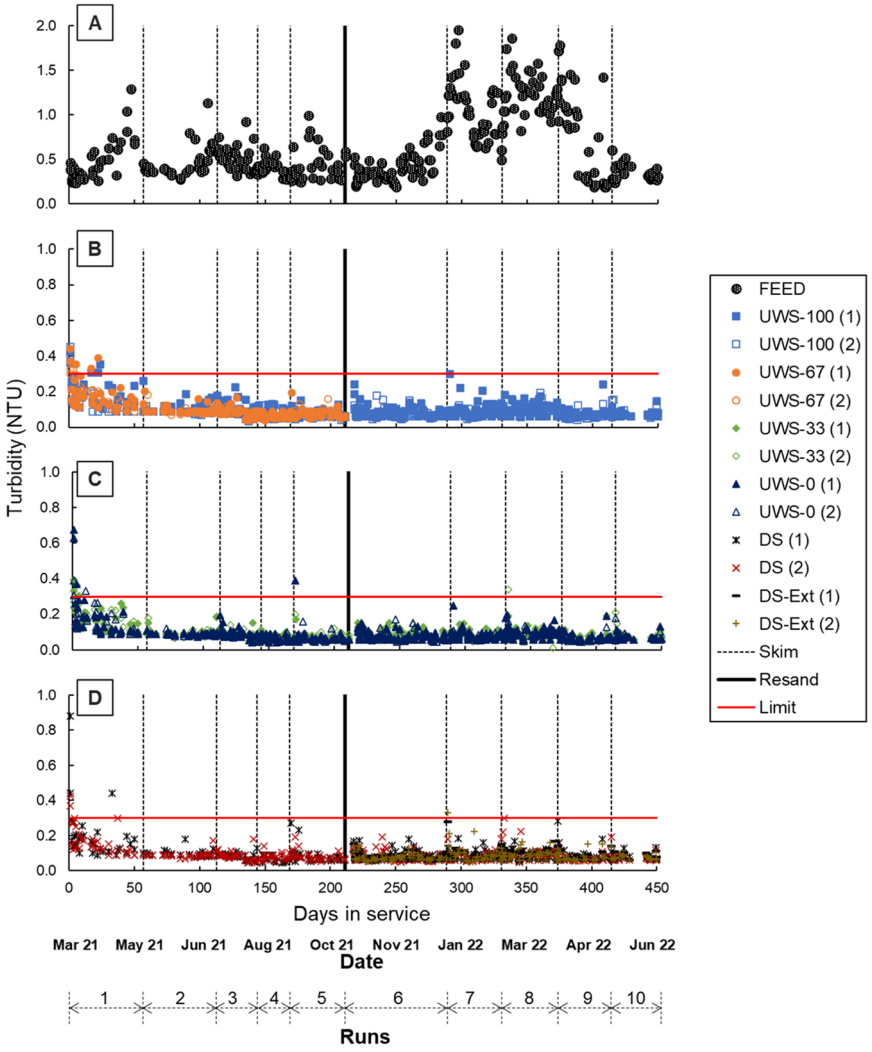

Fig. 3. Variation of turbidity from March 2021-June 2022 with skimming/re-sanding events. (A) feed water turbidity; (B) and (C) show UWS turbidity at operational loadings: UWS-100(1&2), UWS-67(1&2), UWS-33(1&2), UWS-0(1&2); (D) DS treatments: DS(1&2), DS-Ext(1&2). Operational target is <=0.3 NTU.

headloss phases were analysed together, extended downtime (DS-EXT) did not differ from DS (Kruskal-Wallis: H(24)=5.0, p=0.174). Nonetheless, while slow headloss was similar across treatments (Fig. 5), differences became more pronounced in the fast headloss phase. In this late phase, it is probable that as a denser *Schmutzdecke* formed, impacts of reduced downtime appeared to exacerbate surface clogging mechanisms or biofilm sloughing, leading to greater divergence in headloss profiles. This raises the prospects of operators can exploit the distinct slow/fast headloss phases to balance removal efficiency with acceptable headloss. By adjusting sweetening flow or downtime, they could delay or accelerate fast-phase clogging, thereby either enhancing particle retention (and tolerating higher headloss) or preserving throughput (and accepting slightly lower removal).

Both skimming methods recovered up to 90% headloss after cleaning but a higher initial headloss was observed as the runs continued, and this was similar for both DS and UWS filters. To illustrate this, the normalised starting headloss for the DS beds were 25±1, 52±3, 59±2, 30±2, 52 ±5, 71±7, 88±7, 109±13, 124±18 and 103±10 mm for runs 1 to 10 respectively. In comparison, the equivalent normalised starting headloss for the UWS-100 were 27±3, 56±12, 52±7, 46±13, 46±7, 81±10, 97 ±9, 90±6, 125±9 and 132±15 mm. Analysis of variance showed that there was no significant difference between the UWS and DS starting headloss values (ANOVA: $F(1, 18) = 0.063$, $p = 0.804$), or between the different sweetening flows (ANOVA: $F(3, 31) = 0.787$, $p = 0.510$). The increasing starting headloss with subsequent runs was not considered to be unusual or exceptional, as Mauclaire et al. (2004), noted extracellular polymeric substances (EPS) occupied up to 7% of top layer pore volume, and 3% sub-surface, thus preventing a return to clean bed conditions, underscoring the requirement to replace sand after prolonged treatment. This did not raise concerns about a disproportionate deep penetration of particles and accumulation at specific depths due to UWS, as the head recovery after skimming allowed the filters to operate at normal hydraulic loading rates, and sustained their performance for the entire duration of the subsequent filter run. It is also noteworthy that the starting headloss continued to increase even after the re-sanding activity. This was because, although the top sand layers (0–0.2 m) were replaced, the hydraulic conductivity of the entire bed (estimated using Darcy's law) was not restored to its initial conditions. For instance, during run 1, the hydraulic conductivity of the filters was 9.2±0.7 m/h (L = 0.8 m). By the start of the second run, this had dropped, to 4.4 m/h (L = 0.76 m), and after re-sanding in run 6, it was 3.2±0.4 m/h (L = 0.8 m). At this point, the lower part of the filter bed (0.2–0.8 m) was operating with reduced hydraulic conductivity; as such, a marginal increase in starting headloss is acceptable. In full-scale operations, this phenomenon is accepted as normal behaviour, and there is often a set limit on maximum starting headloss allowable. Overall, the results indicated that UWS provided a less disruptive cleaning process and did not pose additional risks compared to DS. In this context, 'less

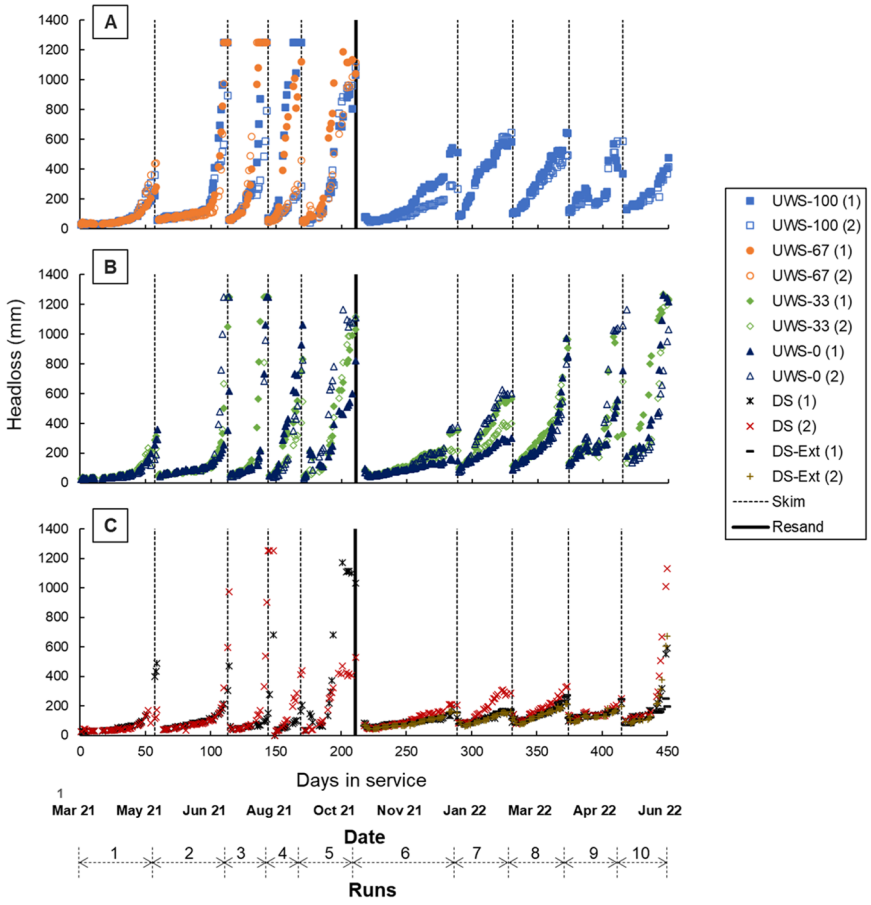

Fig. 4. Normalised headloss during pilot plant operation period (March 2021-June 2022) indicating timing of skimming and re-sanding activities. (A) UWS-100(1), UWS-100(2), UWS-67(1), UWS-67(2); (B) UWS-33(1), UWS-33(2), UWS-0(1), UWS-0(2); (C) DS(1), DS(2), DS-Ext(1), DS-Ext(2).

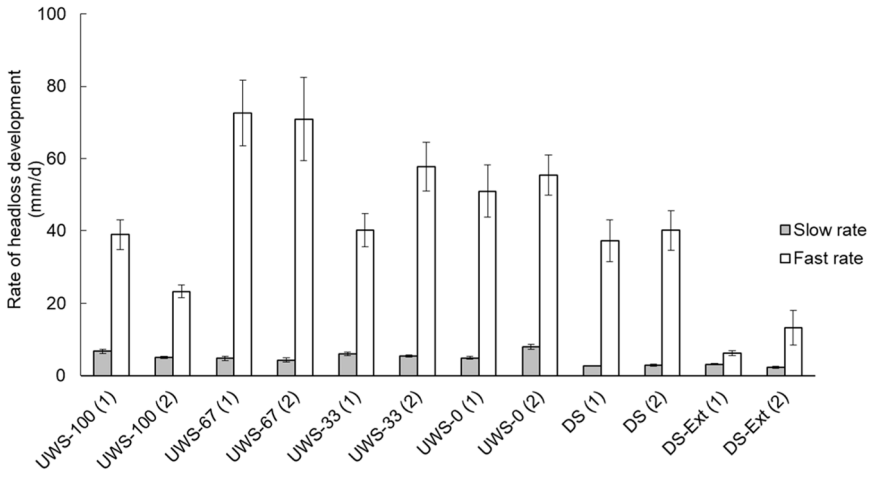

Fig. 5. Headloss development showing the slow rate and fast rate. Values are averages of all runs (excluding runs 1 and 6); error bars are σ.

disruptive' refers to the reduced microbial disturbances after skimming with UWS. Furthermore, the introduction of a sweetening flow did not exacerbate headloss development beyond that observed with DS.

3.2. *Influence of skimming on filtrate microbial quality*

Barring the maturation period at the initial start of the experiments (run 1) and after re-sanding (run 6), all UWS SSFs reduced the total coliform count to under 50 MPN/100mL, which is below the operational limit (defined by the water utility), with the exception of UWS-0 at the start of run 5 and UWS-67 at the end of run 5 (Fig. 6 B - C). These two exceedances were not of concern, as one occurred at the end of the filter run while the other was an unusual measure which was not replicated in the duplicate filter. For the DS filters on the other hand, there were a few more occurrences of exceedances (see runs 4 and 5 in Figure D) and these were mirrored in the replicates. After re-sanding there was more consistency and less coliform variability attributed to the combination of new sand being placed on top of seven-month mature sand. In general,

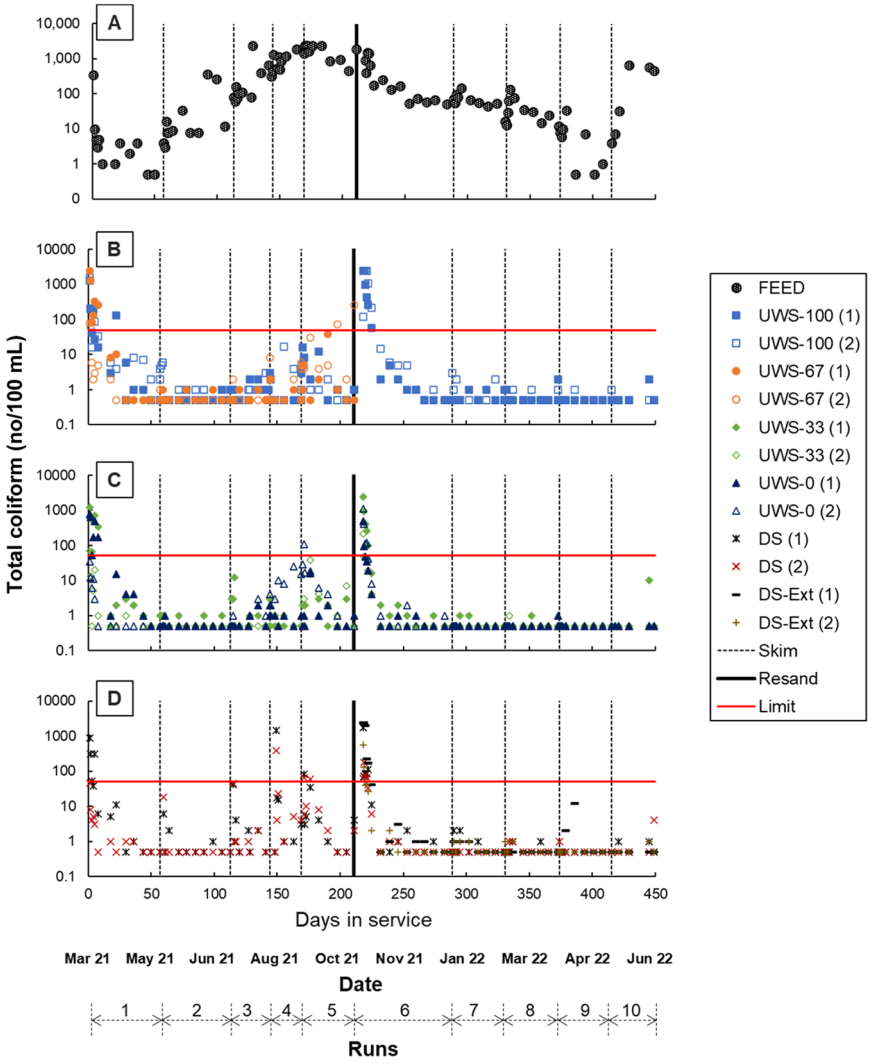

Fig. 6. Total coliform in feed and filtrate (March 2021-June 2022), noting skimming/re-sanding events. (A) feed water coliforms. (B) and (C) coliforms in UWS treatments: UWS-100(1&2), UWS-67(1&2), UWS-33(1&2), UWS-0(1&2). (D) coliforms in DS treatments: DS(1&2), DS-Ext(1&2). Acceptability threshold is 50 MPN/100mL. Values below detection marked at 1 MPN/200mL as half LOD.

DS SSFs showed a greater frequency for high coliform (Fig. 6) and HPC (Fig. 7) levels immediately post-skimming compared to UWS SSFs. Analysis of the filtrate coliform and HPC in the 7 days following a skimming event showed that there was a significant difference between the UWS and DS SSFs (Kruskal-Wallis for coliform: $H(1) = 6.1$, $p=0.014$; for HPC: $H(1) = 45.1$, $p=0.001$), with the UWS filters having on average a count of 2 MPN/100 mL (ranging from 1–109 MPN/mL) for coliforms as opposed to 25 MPN/100 mL (1–1414 MPN/mL) for DS filters. This shows that UWS filters may be returned to service faster, and potentially eliminating the need for a downtime in cases where UWS is accompanied by sweetening flow. One explanation for this is that UWS preserves some of the microbial community and maintains stable conditions during the cleaning process, unlike DS, which involves draining the bed and exposing the biofilm to abrupt changes (temperature, light moisture etc). By avoiding large-scale microbial detachment and shifts in environmental conditions, UWS reduces particle and bacteria release into the filtrate immediately after skimming, resulting in more stable and improved post-cleaning microbial water quality.

To further illustrate this, for run 8, HPC levels post skimming for the DS filters ranged from 300–2700 no/mL, while just before skimming HPC levels were between 10–11 no/mL. In contrast, the range of HPC levels for the UWS filters pre- and post-skimming were 1–9 no/mL and 3–12 no/mL respectively. The increase in HPC levels in the DS filters post-skimming may be attributed to bacteria released following the period where the bed was drained down. It is suggested that when the filter is drained (as occurs during DS), the temporary loss of water disrupts the microbial biofilm and causes cells to detach into the sand pore spaces. Upon refilling and resuming flow, these previously detached bacteria are not retained by the filter, resulting in a transient increase in HPC counts observed immediately after the flow resumes. This deterioration in filtrate quality following DS is well understood. For instance, experiments by Bellamy et al., (1985b) showed that following filter cleaning (using DS), filtrate tincreased from 4000 MPN/100 mL to 28, 000 MPN/ 100 mL when operating at 0.4 m/h. Other cleaning methods such as backwashing showed similar performance when compared with DS, with a 1.3 log reduction recorded by backwashing and 1.5 log reduction by DS (F.H. de Souza et al., 2021). The log removal efficiencies of HPC and total coliform bacteria in SSFs typically range from 0 to 3 before and after skimming. Immediately after skimming, removal efficiency declines, most noticeably in the first 18–36 hours—due to temporary biofilm (*Schmutzdecke*) disruption and detachment. As the biofilm regenerates, removal rates return to baseline levels, reflecting the normal regenerative behaviour of SSF biofilm communities. While the DS observation holds true, the findings in this paper support the hypothesis that the more considerate UWS method promotes fewer bacteria in the filtrate compared to the DS. Therefore in summary,

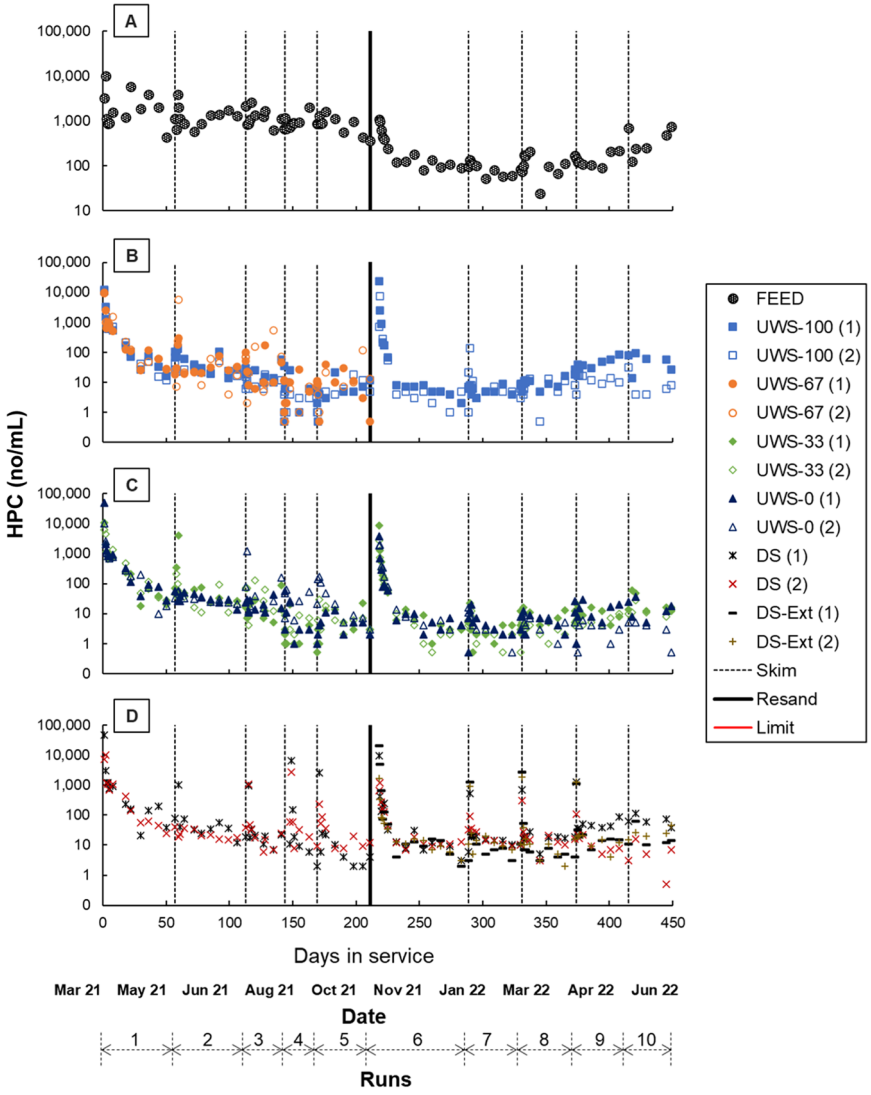

Fig. 7. HPC in SSF pilot feed and filtrate (March 2021-June 2022), with skimming/re-sanding times. (A) Feed; (B) UWS-100(1&2), UWS-67(1&2); (C) UWS-33(1&2), UWS-0(1&2); (D) DS(1&2), DS-Ext(1&2). Non-detections were 0.5 MPN/100mL as half LOD.

despite turbidity and headloss remained similar, UWS significantly lowered post-skimming HPC and coliform spikes compared to DS, indicating more stable microbial quality and quicker recovery

To provide further analysis of UWS performance, flow cytometry was used to directly measure the microbial water quality before and after skimming. Flow cytometry results showed that UWS filters maintained more stable post-skimming microbial quality, indicated by a lower average total cell count of 2.0×10^5 cells/mL in the first 24 hours compared to 2.8×10^5 cells/mL for DS filters. This difference was statistically significant (Kruskal Wallis: $H\ (1) = 35.6$, $p = 0.001$). Furthermore, UWS exhibited a steadier microbial profile after skimming, with a deviation of 0.3×10^5 cells/mL, compared to 0.5×10^5 cells/mL for DS (Fig. 8). This indicates that UWS can facilitate a quicker return to consistent microbial water quality, potentially shortening the 'ripening' period and enhancing overall SSF productivity. The rapid stabilization may stem from preserving portions of the biofilm and maintaining steady conditions during cleaning, allowing microbial communities to recover more efficiently. Because only one flow cytometer was available, UWS and DS measurements were taken sequentially rather than simultaneously. Nonetheless, the influent water quality and operational conditions remained stable during the sampling period, minimizing effects of temporal variability. While we acknowledge this as a limitation, the stable conditions ensure the observed differences are suitable. Further work is needed to replicate this observation.

3.3. *Influence of skimming regime on SSF microbial community*

Analysis of the interplay between SSF operation and its biological and physicochemical phenomena has been hindered previously by sparse routine sampling (Graham and Collins, 2014) typically occurring only near the end of a SSF run, and/or recording peak headloss (Chen et al., 2021). This study used 16S rRNA gene amplicon sequencing consistently throughout the SSF operation to explore the SSF microbiology, assessing UWS's impact on the SSF microbial community, based on sampling of the *Schmutzdecke* (Bai et al., 2013). Genus-level beta--diversity was visualized using Principal Coordinates Analysis (PCoA) in Fig. 9.

The Shannon diversity index provides a measure of both the richness (number of distinct taxa) and evenness (relative abundance distribution) within the microbial community. By examining changes in this index, we can determine if operational conditions, such as skimming methods, influence the complexity and stability of the microbial assemblages in the filter. The Shannon diversity index averaged 5.73 ± 0.14 in all SSFs demonstrating no impact of UWS versus DS, or the level of sweetening flow used (Fig. 9 A). Diversity here was stable across a year, with slight

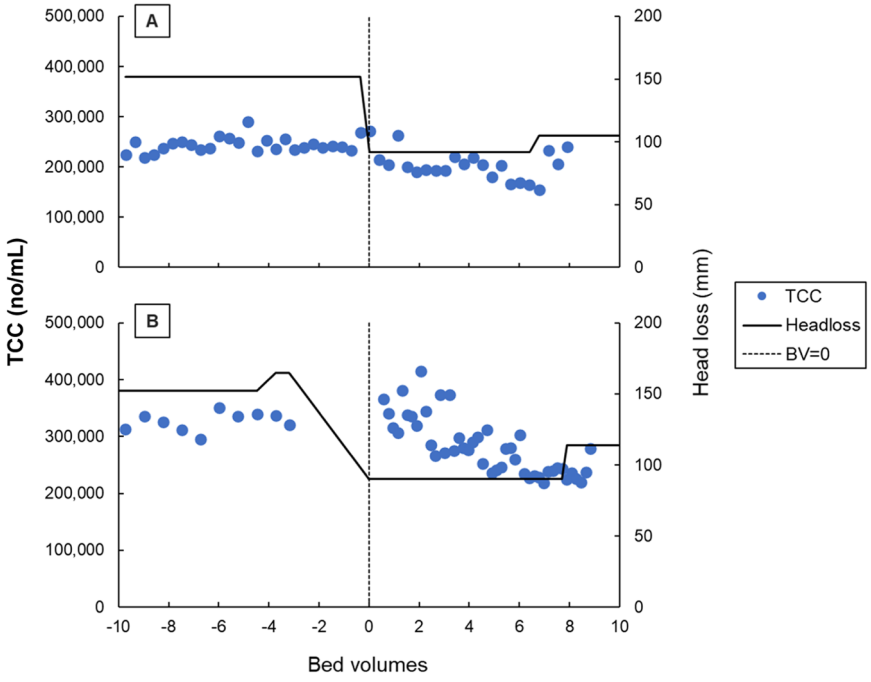

Fig. 8. Filtrate total cell count (TCC) and headloss development, focusing on the skimming window, for (A) UWS-0, and (B) DS. (BV=0 represents the time when a new filter run began when flow was restored after skimming. At the point of skimming the operational headloss was zero).

rises per run and reductions post-cleaning (Fig. 9 A). This disproved the hypothesis that flow maintenance and UWS would foster more diverse microbial communities and agreed with previous studies showing minimal biological changes from variations in SSF operation (Campos et al., 2002; Lautenschlager et al., 2014).

While genus-level beta-diversity in SSFs varied across runs, these fluctuations cannot be attributed solely to temperature. Seasonal influences on influent water quality (e.g., nutrient availability, organic content, and microbial load), in combination with operational factors like skimming and re-sanding, likely interact to shape the microbial community composition over time. Consequently, each run encompasses a distinct combination of environmental conditions and filter states, with temperature representing only one of many interrelated drivers of microbial assemblage changes (Fig. 9 B,C). These shifts in community composition did not translate into reductions in microbial removal efficiency. Even within the relatively low influent bacterial concentrations and detection limits of our methods, total coliform log removal remained >2 across temperatures ranging from 2–18 °C (Figure S3). While previous studies have postulated that higher temperatures might enhance pathogen removal (Anderson et al., 2009; Jabur, 2006), the observed stability in our filters should be interpreted within the narrow range of removals possible due to the low inlet bacterial concentrations. The filtrate continued to meet operational microbial quality guidelines (e.g., total coliforms <50 MPN/100 mL), mirroring long-term observations of stable *Giardia* removal in similar systems (Bellamy et al., 1985b).This observation indicates that while removal mechanisms remain stable across seasonal shifts, attributing them solely to physical or biological processes is challenging. It is possible that both factors contribute, and that mature SSFs are resilient enough to maintain effective removal under typical environmental temperature fluctuations (Arnold et al., 2016). However, further investigation is needed to disentangle the relative roles of these processes. The advantage of UWS over DS was pronounced immediately post-skimming, as clearly evidenced in the diminished HPC breakthrough and flow cytometry. However, since skimming disruptions constitute merely 3.5% of the filter's lifespan, the overall impact on microbial community seems minimal.

While the major removal of pathogens is attributed to the *Schmutzdecke* and top sand layers of the bed (Chen et al., 2021), significant removal occurs following cleaning, consistent with Trikannad et al. (2023) theory of extensive subsurface biofilm activity. More specifically, the minimal differences in performance between DS and UWS, even with frequent top layer removal and incomplete ripening, suggest that deeper subsurface biofilms and the GAC layer may play a more important role in maintaining filtration efficacy, warranting further investigation into their contributions. In conjunction with the consistency of treatment performance by UWS in this study, it is suggested there is a need to reassess the role of the *Schmutzdecke* in conjunction with the lower sand levels to provide a more holistic view of SSFs throughout their depth. Support for this is provided by Oh et al., (2018) who found that biofilms below the *Schmutzdecke* matured quicker than expected, which was also supported by the study of Bai et al. (2013), where a rapid two-day development was observed. Further, Chan et al. (2018) emphasized the sand bed's superior organic matter degradation compared to the *Schmutzdecke*, reinforcing the high removal efficiencies seen in UWS filters post-*Schmutzdecke* removal in this study, and suggesting extensive biological activity across the filter's depth. Further, measurement of the respiration rate of the biofilm on the sand as a function of depth revealed activity throughout (Elemo et al., 2024).

3.4. Context of the UWS for SSF

In this study, the pilot SSFs were operated under conditions representative of typical UK practice, where SSFs are generally employed as a bulk turbidity and organic treatment step. These filters were configured outdoors with a partial enclosure, mirroring full-scale conditions encountered in UK treatment works. Such an arrangement contrasts with practices in some other countries, such as the Netherlands and Sweden, where SSFs may be implemented at different points within the treatment process, or under indoor and controlled lighting conditions or as a polishing step prior to distribution. Recognizing these international variations is important, as different placement in the treatment flowsheet, environmental conditions, and operational targets can influence both filter design and performance benchmarks. Situating this

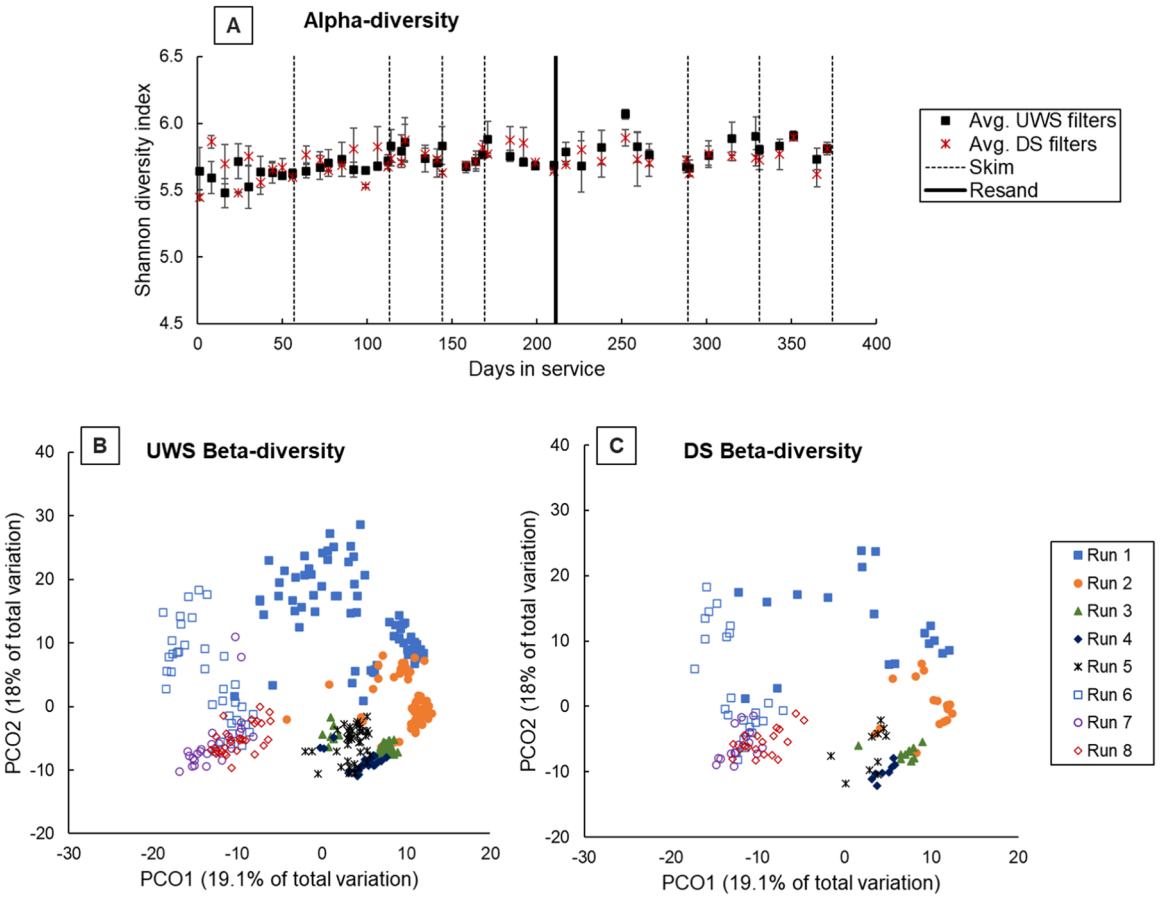

Fig. 9. Microbial community of SSF *Schmutzdecke*. (A) Microbial diversity measured by Genus Shannon Diversity Index (H') from samples taken during pilot plant SSF operation displayed as average of UWS filters and DS filters, with error bars representing the σ. (B-C) PCoA plot (beta-diversity) at genus level of bacterial community 16S rRNA gene amplicons for UWS (B) filters and DS filters (C). All samples were analysed together; however, to illustrate potential differences, results for UWS (B) and DS (C) filters are displayed separately. Each data point represents a single sample taken from the top 25 mm of the filter media. Deeper layers were not sampled.

investigation within the UK context ensures that the findings relating to UWS—are relevant to utilities and operators employing SSFs. Slight changes may be applied to adapt to differences in other regions.

4. Conclusion

The UWS preserved filtrate quality, accelerated post-cleaning recovery, and performed comparably to or better than conventional DS in terms of microbial and turbidity removal. Performance was unaffected by varying sweetening flows, suggesting UWS can maintain continuous operation with minimal downtime. The rapid headloss recovery in UWS filters suggests that particles did not penetrate deeply into the filter bed, helping maintain the integrity of the biofilm layers that drive microbial removal. Sustainable biological performance occurred by which we refer to the consistently low microbial counts such as reduced HPC and coliform levels—and the minimal post-skimming variability in filtrate quality. In other words, UWS filters quickly re-established stable conditions, ensuring reliable microbial removal after cleaning events due maintenance approach which reduces the disturbance from cleaning to the process. Overall, UWS offers a practical means to enhance the efficiency, consistency, and productivity of slow sand filtration systems. Trials of UWS at increased scale of SSF are required.

CRediT authorship contribution statement

Tolulope Elemo: Writing – original draft, Methodology, Investigation, Formal analysis. **Michael Chipps:** Writing – review & editing, Supervision, Project administration, Conceptualization. **Nigel Graham:** Writing – review & editing, Supervision, Investigation. **Andrew Turner:** Writing – review & editing, Supervision. **Sophie Bretagne:** Methodology, Formal analysis. **Bruce Jefferson:** Writing – review & editing. **Francis Hassard:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data is available at 10.6084/m9.figshare.26519746.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.watres.2025.123234.

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