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Backwashing of granular media filters and membranes for water treatment: a review

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ABSTRACT

Filter backwashing is a supplemental part of a drinking water treatment (DWT) facility to wash the filter bed at regular intervals using water or air scour/water by fluidizing the filter bed. Deposited material induces clogging the filter pores and enhances head loss in the bed. Biofiltration has been extensively utilized to decrease organic matter and manage the occurrence of disinfection by-products within drinking water sources. Biological rapid sand filters are frequently utilized to eliminate ammonium from groundwater provinces with the purpose of meeting drinking water requirements. Biological activated carbon (BAC) filters need to be backwashed to wash and enhance the treatment capability by detaching both restrained materials and residual biomass. The reclamation of activated carbon-used backwash water (UBW) was managed by exercising an ultrafiltration (UF) procedure.

Key words: backwashing, biological activated carbon (BAC) filter, rapid sand filter (RSF), ultrafiltration, used backwash water

HIGHLIGHTS

- Microbial density in RSFs is great but changes spatially.
- Disinfectant-improved backwash is raised to remove attached biomass.
- BIEX filter discharged ammonia in a mild water state.
- AC blends were well stirred after water backwashing.
- UF membrane showed good practice to treat AC-UBW.

1. INTRODUCTION

Backwashing of granular rapid filters is gained by fluidizing the filter bed and is a more sensitive operation than the filtration process. For this reason, the hydrodynamic properties of the backwashing process and the detachment rate of accumulated material from the filter need to be accurately determined. The accumulated material clogs the filter pores and increases pressure loss in the filter media (Kawamura 1999). A backwashed filter typically functions as a liquid–solid (or water) fluidized bed, which is explained by the upward flow of fluid along the filter media at a sufficient velocity to keep the filter particles suspended. An excessive increase in the fluid velocity increases the bed expansion ratio, and the particles in the filter media behave randomly. The accumulated material in the filter media can be removed using the fluidization process. Furthermore, water washing combined with air scouring improves the performance of backwashed filters (Hewitt & Amirtharajah 1984; Turan 1986; Stevenson 1995; Akkoyunlu 2003).

A new fluidization backwash system using the air–water bubbly flow of different-sized air bubbles has been suggested for granular rapid filters. The backwash yield is nearly connected with the bubble wake movement. The effect of bubble wakes on backwashing yield was provided by dominating the fluidizing state, and the backwashing yield of the filter media obtained nearly 94% with the air–water bubbly flowing (Kuroda *et al.* 2020). A regular backwashing process was used in practice, and effluent turbidity was used as a measure for filtration termination. The backwash water volumes required, an interval of the filter-to-waste term, completion of the process, total filtrated water volume, and filtration time were specified, along with an estimated mean filtration velocity and filter performance (Slavik *et al.* 2013). The purpose of this report is to collect several research studies containing the advancement and assessment of backwashing processes in biological and non-

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biological granular rapid filters for water treatment processes and also in granular activated carbon (GAC)/ultrafiltration (UF) hybrid systems for the pretreatment selection to alleviate biofouling.

2. BACKWASHING STUDIES IN GRANULAR FILTERS AND PLANNING

Recurrent backwashing with water and air scour/water is the most effective procedure for granular rapid filters to expose the adsorption capability of GAC filters, and prohibit the secondary contamination of filter effluent until regeneration is necessary (Kim *et al.* 2014; Qi *et al.* 2019). Unlike the backwashing of sand filters, air and water backwashing are impracticable for GAC filters due to the low density of GAC particles (Dabrowski *et al.* 2008). Along with backwashing operation, bedding events may happen in the GAC bed with respect to particle size (Asif 2012). Granular filters start to expand while up-flow velocity of washing water is at the minimum fluidization condition. Nearly 30% bed expansion ratio is suitable for the water backwashing procedure while providing about 90% bed expansion ratio of GAC particles at once (Turan 1992; Asif 2001; Akkoyunlu 2003).

The filtration procedure is necessary in the drinking water treatment (DWT) process and is an essential step for particle removal. Sand or a composition of sand and anthracite as double layers is extensively used as media in the filter (Boller & Kavanaugh 1995). Besides, various materials can be utilized in order to enhance the performance of the filters such as charcoal (Sanyaolu 2010), GAC (Frank *et al.* 2015; Marais *et al.* 2018; Liu *et al.* 2020a, 2020b; Fundneider *et al.* 2021; Korotta-Gamage *et al.* 2021; Zielina & Dabrowski 2021), calcined flint (Tatari *et al.* 2017), fiber-ball (Gao *et al.* 2012), polystyrene (PS) granules (Schöntag & Sens 2015; Schöntag *et al.* 2015, 2017), and slag (Anjali *et al.* 2019).

Otherwise, as the pollutants (e.g., biopolymers) are efficaciously dissipated in biological activated carbon (BAC) filters (Cuthbertson *et al.* 2020), BAC as the pre-treatment for UF could effectively remove membrane fouling (Andrews *et al.* 2015; Xu *et al.* 2021). Thereby, the connection of BAC and UF is an encouraging treatment for providing safe drinking water and developing the sustainability of UF in DWT facilities. Chang *et al.* (2022) also estimated the long-term impact of BAC on method application and water quality in a full-scale DWT plant in connection with UF. Table 1 gives major studies about the backwashing of granular media filters with system scale.

3. PREDICTION OF FILTER EXPANSION DURING BACKWASHING

After a selected filter effluent quality is achieved, the filtration procedure is ended and the filter media is backwashed. The backwashed filter is categorized as a particulate fluidized bed in the fluidization literature. Particulate (or water) fluidized beds have insured increasing function in industrial treatments such as ion exchangers, bioreactors, and heat exchangers (Epstein 2002). In the water fluidized beds, the particles may be assumed to be uniformly scattered wherein the bed and the fluid forces on the suspending particles in the bed are in dynamic balance. The expansion of fluidized beds depends on various parameters, namely hydrodynamic forces, particle characteristics, and turbulent flow. Therefore, the Richardson–Zaki correlation is extensively used to determine bed expansion properties of particulate fluidized beds as follows (Turan 1992; Turan *et al.* 2003),

$$U = U_i \varepsilon^n \tag{1}$$

where U is the up-flow (or superficial) velocity, U_i is intercept velocity, ε is the fluidized bed porosity, and n is the expansion coefficient of particles in the fluidized bed. The expansion rate of the fluidized bed (E) can be described as follows,

$$E = \frac{(L - L_s)}{L} = \frac{(\varepsilon - \varepsilon_s)}{(1 - \varepsilon_s)} \tag{2}$$

where L_s and L are the height of the granular fixed bed and fluidized bed, respectively, and ε_s is the fixed bed porosity. Water qualities of the backwash influent and the backwash effluent can be defined in relation to the turbidity, and the detachment rate of accumulated substance (r_d) can be described by the ratio of the turbidity removal yield during the backwashing process to the effluent turbidity of the backwash water as (Turan & Eroglu 2001),

$$r_d = \frac{(T_e - T_o)}{T_e} \tag{3}$$

where T_o is the raw water turbidity and T_e is the effluent turbidity of the backwash water. The filtration technique exposes the

Table 1 | Backwashing of various granular filter systems

Study	System scale	Purpose of the studying	References
1	Pilot-scale	Various backwashing processes were conducted using a pilot facility for SMF and DMF.	Slavik *et al.* (2013)
2	Lab-scale	Attitudinal structuring of down-flow and up-flow rapid sand filtration compared to ripening.	Salkar & Tembhurkar (2016)
3	Full/pilot-scale	Filter having thin layer beds namely colored sand, anthracite, garnet and glass beads as tracers was utilized to measure particle displacement along backwashing.	Ramsay *et al.* (2021)
4	Lab-scale	Effect of various parameters of RSF on bed expansion along backwashing process.	de Souza *et al.* (2019)
5	Lab-scale	Impacts of recyclable UBW on the elimination of organic pesticides were analyzed in the simulated DWT.	Li *et al.* (2018)
6	Lab-scale	Impact of running states on the application of RSF and the effectual depth for turbidity removal along backwashing.	Hani *et al.* (2018)
7	Lab-scale	The biofiltration method was utilized to query various backwash methods on DOC elimination, backwash water use, and effluent turbidity.	Ikhlef & Basu (2017)
8	Pilot-scale	Effects of backwashing on biomass and biofilm development in BAC filtration procedure were examined.	Liao *et al.* (2015)
9	Batch/pilot/ full-scale	MnO_4^-–Fe(III) dosing enhanced As(III) elimination at groundwater treatment along the aeration-rapid sand filtration system and also enhanced the settlement ratio of backwash sediments.	Ahmad *et al.* (2018a)
10	Bench-scale	DBP concentrations and formation potential in UBW were researched and the potential influence of crude UBW recycling on treated water characteristics was estimated.	McCormick *et al.* (2010)
11	Pilot-scale	Recycle of combined UBW directly to DWT facilities was evaluated as a feasible procedure to improve pollutant elimination capability.	Chen *et al.* (2016)
12	Lab-scale	An enhanced expansion estimation model on the GAC filter backwashing was introduced.	Kramer *et al.* (2021b)
13	Full/pilot-scale	Longtime application of GAC-filters and their biological behavior was pursued.	Fundneider *et al.* (2021)
14	Pilot-scale	Execution of BIEX and GAC filters by DWT facility maintained by low DOC/high sulfate preliminary treatment water.	Liu *et al.* (2020a, 2020b)
15	Full-scale	BAC application within a hybrid full-scale DWT facility in integration by UF was investigated.	Chang *et al.* (2022)
16	Full-scale	RSFs was utilized for groundwater treatment by DWT facility and density and distribution of total bacteria and nitrifying unities was researched.	Tatari *et al.* (2017)
17	Lab-scale	Application of a BAC filter between backwashing was estimated based on DOC elimination by ensuing coagulation.	Korotta-Gamage *et al.* (2021)
18	Full/lab-scale	GAC filtration was compared with full-scale DWT and UF membrane processes in respect to NOM elimination.	Marais *et al.* (2018)
19	Lab-scale	Granulated blast furnace slag filter was used in DWT.	Anjali *et al.* (2019)
20	Lab-scale	Application of novel fiber-ball filtration was examined for treatment of high-turbidity surface water.	Gao *et al.* (2012)
21	Pilot-scale	Down-flow rapid filter was run using PS granule media.	Schöntag & Sens (2015); Schöntag *et al.* (2015, 2017)
22	Bench-scale	Progress of BAC biofilm diversity and variety structure with regard to backwashing procedure in various carbon filter drafts.	Qi *et al.* (2019)

SMF, Single-media filter; DMF, Dual-media filter; RSF, Rapid sand filter; GAC, Granular activated carbon; BAC, Biological activated carbon; BIEX, Biological ion exchange; DWT, Drinking water treatment; UF, Ultrafiltration; NOM, natural organic matter; DBP, Disinfection by-product; UBW, Used backwash water; PS, Polystyrene granules; DOC, Dissolved oxygen concentration; NOM, Natural organic matter.

mechanisms managing the residue accumulation on the particle surfaces and filter pores and, thereby, the head loss remains in the granular media. Otherwise, the smaller particle accumulation tends to cause more head loss than the larger particle accumulation for the same deposited material. Deposit removal depends intensely on the water chemistry and collision effects between filter particles during backwashing (Abadzic & Ryan 2001). The efficiency of a backwashing operation depends on several physical parameters, namely the size and density of the filter particles, superficial (up-flow) velocity, bed porosity, and total residue accumulation. In fluidized bed systems, the drag force effective on one particle depends on the presence of other particles. Consequently, the head loss in the fluidized bed (H/L) is proportional to the buoyant weight of particles in the bed as defined in the following way (Trussell & Chang 1999),

$$\frac{H}{L} = \left(\frac{\rho_s}{\rho - 1}\right)(1 - \varepsilon) \tag{4}$$

In turbulent flows, the power generated topically because of turbulent fluctuations equates to the power dissipation caused by turbulent motions (Hinze 1975). The total power dissipation in a unit volume (P_v) can be described as

$$P_v = \phi_1 + \phi_2 = \mu(1 + C)\left(\frac{du}{dy}\right)^2 \tag{5}$$

where ϕ_1 is the power dissipation by time-mean motion, ϕ_2 is the power dissipations by time-mean motion and by turbulent motion, in a unit volume, respectively, u is the local velocity in the x direction, and C is a coefficient which demonstrates turbulence dissipation effects in the total power dissipation (Turan 1992; Turan *et al.* 2003). The velocity gradient and the hydrodynamic shear stress are significant parameters for providing optimum cleaning during backwashing of granular filters. Camp (1964) expressed the velocity gradient as a function of power dissipation at laminar flow (Equation (6a) and Turan (1992) also improved the velocity gradient for backwashing flow in filters at transitional flow as between laminar flow and turbulent flow (Equation (6b), respectively,

$$G = \frac{du}{dy} = \left(\frac{P_v}{\mu}\right)^{0.5} \tag{6a}$$

$$G = \frac{du}{dy} = \left(\frac{P_v}{\mu(1 + C)}\right)^{0.5} \tag{6b}$$

4. BACKWASHING PROCESS IN GRANULAR MEDIA FILTERS

4.1. Sand, anthracite, and GAC filters for water treatment

4.1.1. Rapid sand filters

Generally, the rapid sand filter (RSF) model was efficient in correctly characterizing the backwashing procedure, using it to attain superficial velocity by supplying significant bed expansions using various sand particle sizes and filter bed heights. Besides, the backwashing operation and operational parameters were estimated, namely filter media, up-flow velocity, the expansion rate of filter medium, backwash water volume, and effluent turbidity, as shown in Tables 2–5. The lab-scale rapid sand filtration system was operated to treat drinking water using five various particles with a mean diameter between 0.15 and 0.92 mm, while filter bed height varied between 5 and 13 cm (de Souza *et al.* 2019). Besides, backwash cleaning was also suggested by many researchers as an executional development for the practicability of slow sand filters in rural areas or small municipalities (de Souza *et al.* 2021). de Deus *et al.* (2020) estimated the influences of filter bed media, particle size, and filter bed height on head loss and minimum fluidization velocity in the filter bed expansion along the backwashing procedure. Silica sand was used in the filter bed, and three particle sizes were exercised, as shown in Table 2.

The detachment mechanisms of accumulated substance during RSF backwashing, as well as the hydrodynamic condition and energy dissipation in a backwashed filter, were studied (Turan & Eroglu 2001). The backwashing processes were carried out with expanded porosities between 0.60 and 0.80, while the up-flow velocity is between 47 and 146 m/h, respectively. The head loss in the backwashed bed was also discovered to be approximately 0.18 m. The effluent turbidity of the backwash water, T_e, varied between 2.0 and 7.2 NTU in relation to the varying total backwash water volume from 24.4 to 378 L and operation time from 4 to 20 min, respectively (Table 2). The backwashing procedures in RSFs at various expanded porosities

Table 2 | Operating conditions and performance range for sand, anthracite, fiber-ball, polystyrene and blast furnace slag filters

Media	d_{eq} (mm)	U (m/h)	E(%)	V_b(L)	T (NTU)	Reference
Sand	0.545	47/66/87/112/146	–	122/172/225/290/378	7.2/3.7/3.2/4.5/4.7	Turan & Eroglu (2001)
Sand	1.18/0.5	7.6/25.2	–	–	900/1,100	Naseer *et al.* (2011)
Sand	0.32–0.64	–	–	75.9–312.6	2.11–3.73	Elbana *et al.* (2012)
Clinoptilolite + sand	(0.3–0.85/0.85–4)/(0.12/0.37)	–	–	–	–	Abadzic & Ryan (2001)
Quartz sand (SMF)/Anthracite + quartz sand (DMF)	0.84/(1.4–2.5/0.71–1.25)	26.1/47	–/(26/10)	260–880/420–880	0.7/–	Slavik *et al.* (2013)
Sand	1.5	45.7	–	228.5×10^3	–	Zielina & Dabrowski (2021)
Sand/Charcoal	1.07/3.08	28	23/40	$12 \times 10^3/18 \times 10^3$	350/500	Sanyaolu (2010)
Silica sand G1/G2/G3	0.5–1.0/0.8–1.2/1.0–1.5	115/166/200	75	3.62/7.24/9.05 m^3/h	–	de Deus *et al.* (2020)
Sand	0.152/0.338/0.513/0.725/0.925	10.6/30.9/67/87.8/104	90/70/60/50/35	–	–	de Souza *et al.* (2019)
Sand	0.45	36–40	15–30	240	6,200	Adelman *et al.* (2012)
Sand/Anthracite + sand	(1.3–3.2)/1.6/1.0	–	–	–	–	Gude *et al.* (2016)
Calcined flint/Sand	1.5–2.0/(0.8–1.4/1.2)	–	–	$83 \times 10^3/(50\text{–}207) \times 10^3$	–	Tatari *et al.* (2017)
Sand	0.32–0.64	–	–	83×10^3	59.6–85.4%	Elbana *et al.* (2012)
Silica sand	1.3	–	–	75	80%	Ahmad *et al.* (2018a)
Sand	0.65	–	–	60	–	Kato *et al.* (2018)
Sand	–	–	–	–	250–460	Chen *et al.* (2016)
Sand	0.80–1.25	40	–	–	3	Kramer *et al.* (2021a)
Sand DFF/Sand UFF	0.5/0.8	5.1–9.6	–	8.9–16.8/11.5–21.6	8.2–12.5/8.5–13.5	Salkar & Tembhurkar (2016)
Sand	0.8–1.3/1.2–1.9	30/60	–	–	–	Ramsay *et al.* (2021)
Sand	0.7	53	20	75	–	Marais *et al.* (2018)
Sand	–	–	34	11.2–12.8	42.6–55.1	Li *et al.* (2018)
Sand-UBW	–	–	–	–	6.9 ± 0.2	Qian *et al.* (2020)
Sand	0.7–1.0	50	20	16×10^3	18	Hani *et al.* (2018)

Anthracite + sand	0.7–1.2/1.4–2.5	–	–	–	2	Telgmann *et al.* (2020)
Anthracite + sand	1.5–2.25/2–4	–	25	13	–	Janssen *et al.* (2010)
Anthracite + sand	–	–	–	$(110.6/60.5/190/285.9) \times 10^3$	$57.1 \pm 17.9/57.9 \pm 45.3/25.8 \pm 5.8/73.2 \pm 41.8$	McCormick *et al.* (2010)
Anthracite + sand	0.6 /1.2	–	–	–	–	Kuroda *et al.* (2020)
Anthracite + sand/Polystyrene granules	(0.4–2 /0.6–2)/(0.50–1.20)	66/(6.6–22.8)	40/(40–200)	–	360/140	Schöntag & Sens (2015); Schöntag *et al.* (2015, 2017)
Anthracite + sand	(2.0–4.0)/(1.5–2.25)	–	–	–	–	Janssen *et al.* (2010)
Fiber-ball	(20–30)/(0.015–0.02)	50	–	–	15	Gao *et al.* (2012)
Slag	0.29	11.9–15.2	40–50	48	–	Anjali *et al.* (2019)

Note: U: backwashing flow rate; d_{eq}: equivalent diameter; E (%): filter media expansion during backwashing; V_b: backwash water volume; T: maximum effluent turbidity during backwashing; SMF: single-media filter; DMF: dual-media filter; DFF: down-flow rapid sand filter, UFF: up-flow rapid sand filter.

Table 3 | Operating conditions and performance range for GAC and GAC/UF filters

Media	GAC origin	U (m/h)	E (%)	V_b (L)	T (NTU)	Reference
GAC	Chemviron Filtrasorb 100/200/400/TL820	38/37/30/21	–	(68/65/52/37) $\times 10^5$	–	Zielina & Dabrowski (2021)
GAC1/GAC2	AquaSorb 5,000 Jacobi, 12 × 30 mesh/Norit 1,240, 12 × 40 mesh	12/40	20/100	2,400	80/85/70%	Frank *et al.* (2015)
GAC1/GAC2/GAC3	Calgon Acticarbone® BGX, 0.5–0.7 mm/Nuchar® WV-B30, 0.8–1.1 mm/Jacobi PICABIOL-HP120, 1.2–1.4 mm	–	50	–	10	Liu *et al.* (2020b)
GAC	Sigma-Aldrich, USA, 2.4–4.6 mm	18	30	–	–	Korotta-Gamage *et al.* (2021)
GAC1/GAC2/GAC3	Hydraffin AR, fresh, Donau Carbon, (8 × 30 mesh, 0.60–2.36 mm)/(4 × 8 mesh, 2.36–4.75 mm)//(8 × 14 mesh, 1.4–2.36 mm)	–	–	–	2	Telgmann *et al.* (2020)
GAC	Norit HD4000, 10 × 40 mesh,1.16–1.29 mm/Calgon F300 8 × 30 mesh,1.16–1.29 mm	–	–	–	–	Corwin & Summers (2011)
GAC-UBW	–	–	–	–	8.1 ± 0.4	Qian *et al.* (2020)
GAC/UF	NORIT Vapure 612, 830P, 1.0 mm	29	25	13	–	Janssen *et al.* (2010)
GAC/UF	Chemviron Carbsorb 40, (0.43–1.7)/0.47	–/3.6×10^{-5} m/s	–	–	<0.1/2.8 ± 0.1	Monnot *et al.* (2016)
GAC/UF	–	–	–	117	46	Zhang *et al.* (2017)
GAC/UF	ASTM, 0.737–1.182 mm	32	20	75	–	Marais *et al.* (2018)
GAC/UF	Chemviron Carbon F400	–	–	18 m^3/h	–	Gibert *et al.* (2015)

Table 4 | Operating conditions and performance range for biological rapid sand filters

Media	d_{eq} (mm)	U (m/h)	E (%)	V_b (L)	T (NTU)	Reference
Sand	0.3–1.0					Chuang *et al.* (2011)
Quartz sand	0.7–1.25	35	20			Bruins *et al.* (2015)
Sand/Anthracite + sand	0.20/ (0.90/0.20)	–	20–30	–	–	Xu *et al.* (2020)
Anthracite + sand	0.85/0.50	–	30–50	–	–	McKie *et al.* (2020)
Quartz sand	0.8–1.4	30	–	259.2×10^3	–	Wagner *et al.* (2016)
Quartz sand	5–14	14–57	–	200.5×10^3	–	Lopato *et al.* (2013)
Sand	0.5–1/1–3	–	–	–	–	Bar-Zeev *et al.* (2012)

using 0.5- and 1.18-mm sand particles were studied (Naseer *et al.* 2011) and it was found that the effluent turbidity and detachment amount of accumulated material declined with increasing backwashing duration and total backwash water volume.

The multilayer installation of stacked RSFs in a lab-scale system was filtered at 5–7 m/h per layer and backwashed at 36–40 m/h with a comparable total flow rate (Adelman *et al.* 2012). The foulants were rinsed out on a short cycle, generating concentrated effluent water at about a turbidity of 6,200 NTU, while 94% of the solids accumulated in the filter bed and backwash time was nearly 5 min (Table 2). The application of a dual media filter (DMF) within charcoal with regard to a traditional RSF using the same kaolin solution in synthetic raw water was studied (Sanyaolu 2010). The DMF achieved a turbidity removal of 1.4 times more than that of the traditional RSF. In the first 5 min of backwashing, nearly 86% of the deposited substance in both RSF and DMF was detached by air and water scouring. The DMF showed a higher expansion rate of 40% compared to the RSF.

RSF in DWT was applied by Hani *et al.* (2018) and the filtration bed had sand particles of size 0.7–1.0 mm and filter depth of 80–140 cm while the filtration rate changed between 4 and 8 m/h. The synthetic raw water was produced in various turbidity stages between 10 and 30 NTU and aluminum sulfate (alum) was utilized as a coagulant in various concentrations between 20 and 40 mg/L, while the variation of application contexts, namely filter depth and rate, alum dose and influent turbidity, showed a remarkable effect on the filtration treatment performance. In another study, Kramer *et al.* (2021a) showed that upstream in a granular sand filtration under the backwashing process causes the filter media (Figure 1) to collapse much unclearly and expressed the succeeding manner using optimization of the extended terminal sub-fluidization wash (ETSW) backwashing process, while turbidity and peaks in the number of particles are dropped with a favorable impact on water quality.

A combination of recycling used backwash water (UBW) and DWT facility is regarded to be an appropriate method to improve decontamination. The genotoxicity of water samples from two pilot-scale DWT facilities, namely a recycling of combined UBW and a traditional procedure, was estimated (Chen *et al.* 2016). The DWT facility waste residuals were collected in the grid flocculation tank and RSF of the recycling procedure every 24 h, and then the waste residuals were discharged to the sludge storage tank and filter backwash water tank, respectively. The total organic carbon (TOC), dissolved organic carbon (DOC), and trihalomethane formation potential (THMFP) of the recycled backwash water procedures were found to be lower than those of the traditional procedure. The impacts of UBW recycling on pesticide elimination in traditional tap water treatment, including coagulation, flocculation, sedimentation, and filtration procedures, were also researched (Li *et al.* 2018). The results indicate that the pesticides that were adsorbed onto the floc surfaces during coagulation and afterward treated by the RSF would not be sent into the water medium during the backwashing procedure.

Filter ripening is a progressive improvement of filter media loading and enlargement of catchment efficiency, along the beginning phase of rapid filtration. The time duration when an affluent of contaminated water is transferred along a filter and subsequently backwashed is called filter ripening. Extended terminal sub-fluidized wash (ETSW), including cationic polymers within wash water, was examined to enhance ripening procedures (Salkar & Tembhurkar 2016). It was obtained efficiently by decreasing the initial degradation of treated water by down-flow and up-flow sand filters (DFF and UFF). Besides, the ETSW including polymer within wash water caused a remarkable rise in head loss through ripening for the DFF, and this increment in head loss following polymer-amended ETSW was found to be less for the UFF. Elbana *et al.* (2012) studied to establish the filter ripening cycle, namely the duration after the backwashing procedure when the filtration effluent arrives with the least quality and the influence of filter backwashing on filtration capacity. Based on the sand's

Table 5 | Operating conditions and performance range for BAC and BAC/UF filters

Media	**GAC origin**	***U* (m/h)**	***E* (%)**	**V_b (L)**	***T* (NTU)**	**Reference**
BAC	Coal-based GAC, 1.0 mm	14.41	–	173	–	Lohwacharin *et al.* (2015)
BAC	–	8 L/(m^2s)	–	2,400 L/m^2	90%	Liao *et al.* (2015)
BAC/sand	GAC, PJ-08, 1.0/1.0 mm	–	20–30	–	–	Liu *et al.* (2012)
BAC	Cylindrical BAC grains, 1.0 × 3.0 mm	42 L/(m^2s	30	–	–	Liu *et al.* (2016)
O_3-BAC	Coal-based GAC, (8 × 30 mesh)/(12 × 40 mesh)	(20–30)/(10–20)	30	26.2	–	Liu *et al.* (2020a)
BAC/BIEX	Jacobi PICABIOL-2, 1.2–1.4 mm/Purolite® A860, IEX, 0.3–1.2 mm	–	50	–	10	Liu *et al.* (2020b)
BAC	Sigma-Aldrich, USA,2.4–4.6 mm	18	30	–	–	Korotta-Gamage *et al.* (2021)
BAC	Made of blind coal, 0.4–0.65 mm	8 L/(m^2s)	–	5,760 L/m^2	0.36 ± 0.26	Qi *et al.* (2019)
BAC	Calgon F400, USA	24	–	–	0.06 ± 0.01	Kim *et al.* (2014)
BAC	0.72	–	20–30	–	–	Xu *et al.* (2020)
BAC	Calgon Filtrasorb 400	17	14	220	–	Hess & Morgenroth (2021)
BAC	Calgon Filtrasorb 300	–	30–50	–	–	McKie *et al.* (2020)
(BAC/sand)/(BAC/anthracite/sand)	(1.2/0.65 mm)/(1.2/1.16/0.65 mm)	18.5–54.7	30	–	–	de Vera *et al.* (2019)
BAC/sand	0.5/0.7 mm	12–37	10–40	16.4–32.8	600–2,400	Ikhlef & Basu (2017)
BAC	1.7–4.25 mm	–	–	–	50.58%	Tan *et al.* (2017)
BAC	–	–	–	$2,430 \times 10^3$	–	Niu *et al.* (2018)
BAC	Nine various GAC samples, 0.53–9.36 mm	36–108	–	–	–	Kramer *et al.* (2021b)
BAC/(BAC/sand)	Epibon A 8 × 30 mesh, 0.6–2.5 mm/(0.6–2.5/0.7–1.1 mm)	–	–	–	–	Altmann *et al.* (2016)
BAC/UF	NORIT Vapure 612, 1.7–3.35 mm	–	–	–	–	Janssen *et al.* (2010)
(BACS1/UF)/(BACS2-S6/UF)	–	4/20	10/30	–	–	Fundneider *et al.* (2021)
BAC/UF	Coal based GAC 8 × 30 mesh, 0.99 mm	31	–	334.8×10^3	–	Chang *et al.* (2022)
BAC/UF	Calgon carbon, PA, US	3.0 L/min	–	45	–	Mohammed *et al.* (2021)

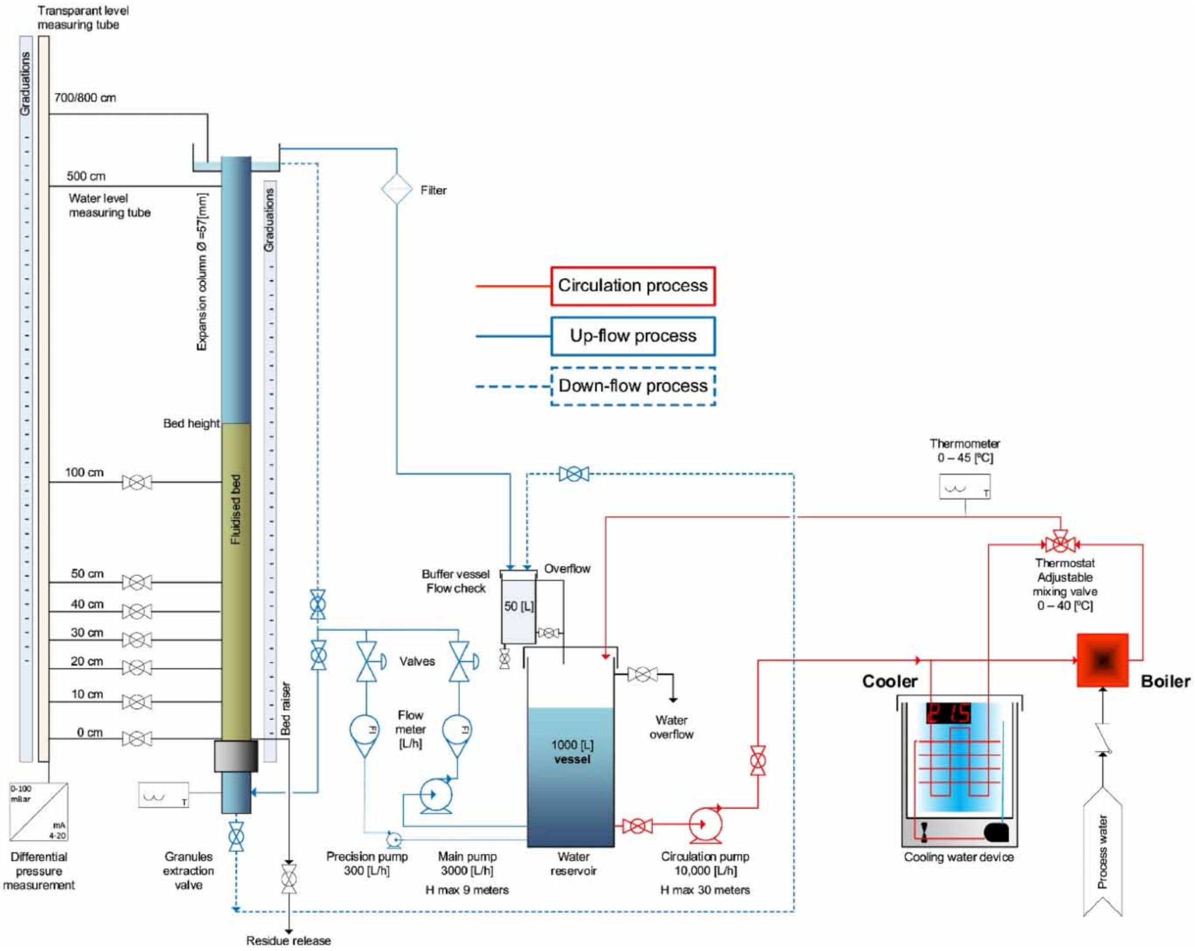

Figure 1 | Schematic of filtration and expansion processes for a locally produced drinking water system (Kramer *et al.* 2021a).

efficient size, the RSF's acquired turbidity declines in the range of 59.6 and 85.4% and dissolved oxygen increases in the range of 4.5 and 15.7%. During the operation, the filter ripening cycle took 15 min.

4.1.2. Anthracite and sand filters

Disinfection by-product (DBP) concentrations and the potential effect of UBW recycling on water quality in DWT facilities were analyzed (McCormick *et al.* 2010). All four traditional DWT facilities consisted of either sedimentation (SED) or dissolved air flotation (DAF) clarification pursued by dual-media filters composed of anthracite and sand particles. During studies, mass balance computations showed that UBW recycle application by mixing 10% UBW with untreated water previous to coagulation did not affect DBP concentrations added to the rapid mixing level of a DWT facility. The direct filtration performance in a pilot scale water treatment plant was composed of two filter columns having a diameter of 0.3 m, which were operated as single-media (quartz sand layer) and dual-media (quartz sand and anthracite layers) filtration (Slavik *et al.* 2013). It was indicated that the backwashing procedure not only influences effluent turbidity along with filter ageing, but also the time of the filter-to-waste and the filtration cycles.

Several grain movement phenomena were monitored in the pilot-scale filter using colored sand, glass beads, anthracite and garnet particles along the three-step backwash process (Ramsay *et al.* 2021). Statistical moments were exercised to determine the draft distributions resulting from replacement along the backwashing process. Results indicated that important particle replacement happens during backwashing including air scouring, air-and-water washing, and sub-fluidization water-only washing and replacement were found to be substantially independent of particle size, density, and shape. In another study, solids present in the filter backwash water were gathered, treated, and calcined at 800 °C to procure calcined filter backwash solid materials (CFBS) and researched for their possible application as subsidiary cementitious substances in the construction industry (Ahmad *et al.* 2018b).

An original fluidization backwashing procedure using an air–water bubbly flux with air bubbles of different sizes was proposed for granular media filters (Kuroda *et al.* 2020). The filter bed consisted of silica sand grain with a mean size of 0.6 mm and anthracite grain with a mean size of 1.2 mm while the specified bed height is about 400–600 mm (Table 2). The effect of the bubble wakes on the backwashing yield is provided by releasing and managing the fluidizing situation, which is readily defined visually, and the backwashing yield of the filter media is obtained at about 94% by optimizing the air bubble size in the air–water bubbly flux.

4.1.3. GAC and sand filters

GAC filtration is an essential unit procedure in a DWT facility, and GAC filtration is composed of two sequential phases: adsorption and filtration, catching the pollutants from the water in conjunction with a backwash process that removes the pollutants from the system. An annual saving of 71,045 m^3 of water was utilized during the backwashing procedure at the sand filters in a full-scale DWT facility with a mean capacity of 25,000 m^3/d (Zielina & Dabrowski 2021). The total water savings during the backwashing of GAC filters varied monthly from 3,800 to 6,800 m^3, related to filter bed material (Table 3). Frank *et al.* (2015) used GAC filters for the elimination of organic micropollutants (OMPs) from wastewater treatment facility effluents, and filter backwashing was approved by bed expansions of 20 and 100% with backwashing flow rates of 12 and 40 m/h, respectively (Table 3).

Qian *et al.* (2020) researched to qualify and quantify haloacetonitrile (HAN) and haloacetamide (HAM) precursors in UBW and sedimentation sludge water (SSW) recycled water from two DWT facilities. Both facilities utilize RSFs and produce sand-UBW. Potential treatment procedures are employed to decrease the DBP effect from UBW and SSW recycling (Qian *et al.* 2021). Besides, another facility (DWTP-B) acquires a GAC filter and produces carbon-UBW. Water including free chlorine is utilized to backwash the rapid sand and GAC filters. As a result, in the UBW mode, HANs react with organic material in the filters prior to backwashing.

Corwin & Summers (2011) investigated the empirical examination and structure of organic pollutant adsorption and desorption at environmental impact limits after discontinuous loadings and during backwash cycles. The rapid small-scale column test (RSSCT) and the surface diffusion model (PSDM) were exercised to work desorption procured by the reversal concentration gradient. Mixing in the GAC filter bed to compare the backwashing procedure did not seem to cause an early breakthrough. The simultaneous removal of total phosphorus (TP) and chosen micropollutants was researched (Telgmann *et al.* 2020). First, the target phosphorus threshold of 0.2 mg/L TP during the filtration process was obtained in a sand-anthracite filter with a flow rate of 16 m/h. Next, the filter beds were moved by three GAC filters, and in all filter beds, significant variations were attained. The backwash process could be initiated automatically based on pressure decline and effluent turbidity.

4.1.4. Fiber-ball, PS, and blast furnace slag filters

Several instruments are exercised to develop the operation of granular filters, increasing the filter run and decreasing the backwash velocity with the use of multilayer filters and various filter materials. Application of the new fiber-ball filter was studied for the treatment of excessively turbid surface water during deep bed filtration, and the results of clean-bed filtration indicated that the fiber-ball filters had excellent potential for the elimination of turbidity materials (Gao *et al.* 2012).

A new granular filter using PS particles was developed whose effective size was 0.68 mm, sphericity was 0.96, and density was 1,046 kg/m^3 (Schöntag & Sens 2015; Schöntag *et al.* 2015, 2017). The following two speeds were used for the PS filter: 6.6 and 22.8 m/h (0.11–0.38 m/min) for expansions of 40 and 200%, respectively (Table 2). It was found that the PS filter running time was 1.65 times lower than that of the sand and anthracite filters. The PS granule had a lower head loss during backwashing, while the average backwashing velocity was three times lower, and the time necessary for an effective cleaning was 3.3 times higher, regarding the optimum time.

The application of granulated blast furnace slag as an industrial by-product from ferrous industries for the treatment of potable water was examined (Anjali *et al.* 2019). A lab-scale filter having a column diameter of 9 cm and iron slag media of 40 cm on a gravel bed was constructed to remove influent having turbidity of 28.26 NTU, total suspended solids of 128.85 mg/L, and color of 177.05 PCU at a filtration rate of 0.32 $m^3/(m^2h)$. The highest head loss for continuous running without backwashing was about 75 mm. Intermittent backwashing assisted in enhancing the quality of the filtered drinking water for several filtration rates. With the exception of sulfate and nitrate, increasing the filtration rate to 1.28 $m^3/(m^2h)$ had no effect on the quality of the treated water.

4.2. Sand, anthracite, and GAC filters for groundwater treatment

4.2.1. Rapid sand filters

RSFs are greatly utilized in groundwater treatment to eliminate complexes such as NH_4^+, Fe^{2+}, and Mn^{2+} that are below drinking water quality norms. Elimination happens with a combination of physico-chemical and biochemical facilities. Tatari *et al.* (2017) researched substantial spatial changes in the distribution of total bacteria and nitrifying guilds such as ammonia oxidizing bacteria (AOB), ammonia oxidizing archaea (AOA), itrobacter, and nitrospira in the RSFs for groundwater treatment. The backwashing process was applied for pre- and post-filters at regular times with air and water scouring. The backwashing method is significant to govern the interference of the filter media, consequently hindering or enabling continuous bedding in the filter. A MnO_4–Fe(III) dosing method was investigated to improve As(III) removal at groundwater treatment plants that typically use aeration and deep sand filtration to obtain treated drinking water (Ahmad *et al.* 2018a). The surface area of the filter, filter bed height, sand particle size, and filter velocity are 27 m^2, 1.8 m, 1.3 mm, and 4.6 m/h, respectively. MnO_4–Fe(III) dosing increased the precipitation rate of backwash solids, which was attributed to increased Mn concentration in the backwash deposit rather than differences in the molecular-scale nature of the Fe-precipitates that are generated during treatment.

To determine the maximum nitrification values and safe running conditions of RSFs, a pilot-scale RSF was utilized to test short-run increased ammonium loadings and to regulate by changing influent ammonium loadings or hydraulic loading rates (Lee *et al.* 2014). The tracer studies were managed for 17 days after backwashing the filter media and revealed low blending as well as no monitored channeling or short circuiting in the filter media (Figure 2(a)). Ammonium and iron removals were coherent in both the pilot and the full-scale filters. The impact of copper dosing on nitrification in various biological RSFs for groundwater treatment was researched (Wagner *et al.* 2016). Two lab-scale sand filters were constructed with quartz sand media of 30 cm depth and particle diameters of 0.8–1.4 mm and filter effluent water was utilized as an influent substrate, rich with ammonium. In one of the filter columns, additional trace metals were appended. Copper dosing shifted ammonium and nitrite oxidation upwards in the filters (Figure 2(b)). During operation, the total treated water flow was 190 m^3 /h, with six single-stage biological RSFs filtering 32 m^3 /h each. Subsequent to the treatment of 2,500 m^3 of water per filter, filters are backwashed for 6 min with air scour, followed by a water backwash at a velocity of 30 m/h (Table 4).

The ripening conditions of manganese removal filters and the formation of manganese oxide called Birnessite on virgin sand particles were initiated biologically or physico-chemically (Bruins *et al.* 2015). The ripening conditions of a virgin filter bed in a pilot filter system supported by pre-treated manganese including groundwater were employed for 600 days. After nearly every 2 weeks of consistent running, the backwashing process was carried out using only water at a backwash rate of 35 m/h and a filter bed expansion of nearly 20% (Table 4). Solids accumulated from filter backwash water throughout the entire ripening period indicated a biological source.

Tests were performed to determine ammonium removal kinetics in a working, biologically active RSF at an anaerobic groundwater treatment facility (Lopato *et al.* 2013). A full-scale RSF had a filter velocity of 3.8 m/h while the filter area, sand depth, particle size, and support media size were 32.6 m^2, 0.9 m, 5–14 mm, and 18–35 mm, respectively. The granular filter flow rates changed between 6.6 and 17.4 m/h, and the ammonium removal indicated a temporal and spatial alteration in the filter bed. The filter was backwashed subsequent to the filtration of 14,500 m^3 water for 7 days and the filter system was restarted to the filtration procedure 50 min after the end of the backwashing procedure while the total backwashed water volume was 200.5 m^3 (Table 4).

The performance of a full-scale RSF in the DWT using the groundwater source nitrified and pretreatment by subsurface aeration was observed for 9 months (de Vet *et al.* 2011). Results proved that subsurface aeration shifted the growth of ammonia-oxidizing prokaryotes (AOP) in the groundwater source. The cell-specific nitrification ratio in the sand media and backwashing water specimens was found to be great for the subsurface aerated sand filter, however, it was regularly low for the filter with nitrification issues.

4.2.2. Anthracite and sand filters

Gude *et al.* (2016) studied the As removal capability at three full-scale groundwater treatment plants while As concentration was between 10 and 26 mg As/L. The three treatment plants including sand and anthracite granular filters were composed of

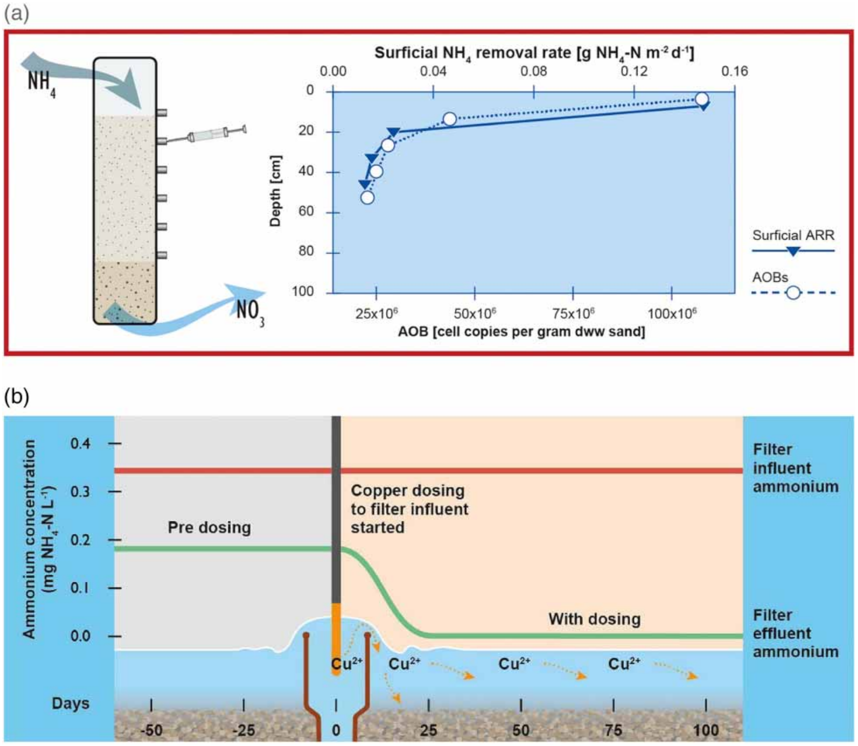

Figure 2 | (a) Schematic diagram of a pilot-scale RSF system at Islevbro water works (Lee *et al.* 2014). (b) Copper dosing impact on nitrification in the biological RSF filters (Wagner *et al.* 2016).

more than 8-year-aged filter substance and Fe and Mn contributed most to the substance of the particle coating. Fe concentrations in the backwashing water were higher than in the untreated water, indicating entrapment in the RSF as washable hydrous ferric oxide (HFO) flocs.

Abadzic & Ryan (2001) used a natural zeolite (clinoptilolite) and porous sand setting for the removal of strontium from groundwater. The impacts of ionic strength, particle size, and two pretreatments, rinsing and calcining (heating), on residue release and clogging in a clinoptilolite porous bed were evaluated. The strontium binding strength of untreated and treated clinoptilolites was measured to see if the pretreatments reduced the clinoptilolite's ability to adsorb cations. Clinoptilolite with a larger particle size generated barely less deposit discharge and clogging.

5. BAC FILTRATION AND BACKWASHING

5.1. Bioactivity and adsorption

Microorganisms can hold on to a GAC surface and constitute active biomass, converting GAC into so-called BAC (Yapsakli & Cecen 2010; Liao *et al.* 2013). The effects of the backwashing process on biomass and biofilm structure of a pilot-scale BAC filter and the backwashing process were found to enhance the removal of DOC and also, backwashing indicated a strong effect on the bacterial variety and community constitution of BAC biofilm, but these effects could be gradually regained with the filtration procedure time following the backwashing (Liao *et al.* 2015). Similar studies have indicated that filter backwashing staggered the bacterial variety tentatively, but the community was quickly renovated during the following run (Gibert *et al.* 2013; Kim *et al.* 2014). The effect of backwashing on the BAC filter technique in terms of NC-DOC removal and microbial community constitution was researched. A lab-scale BAC filter was run for up to 5 months with backwashing every 5 days, and it was discovered that when the BAC filter is backwashed at the correct frequency, certain advantages, as well as extra benefits for the coagulation procedure, can be achieved (Korotta-Gamage *et al.* 2021).

The formation potential (FP) of dichloroacetonitrile (DCAN) in various water sources was investigated, and the backwash procedures of BAC filters were executed using air-scouring for 5 min and water-backwashing for 10 min (Tan *et al.* 2017). The DCAN FP in the effluent of BAC filters having old GAC material was found to be higher than that in the influent when the

DCAN FP in backwash water was found to be lower than that in untreated water. For the BAC filter, the recycle ratio of less than 10% was feasible to reuse the backwash water. Kato *et al.* (2018) evaluated the potential of pepper mild mottle virus (PMMoV) as a viral procedure indicator. Its decreases during coagulation–sedimentation (CS), ozone, BAC, and RSF were contrasted with those of *E. coli*. The RSF column was used with a flow rate of 4–5 m/h and backwashed using 60 L of tap water after every test to arrange the filter bed condition.

A lab-scale biofiltration method was utilized to investigate the effects of various backwash programs on DOC removal, backwash water volume, and effluent water turbidity (Ikhlef & Basu 2017). The three dual media biofilters were operated in parallel and had 520 mm of GAC on top of 180 mm of sand, together with 15 mm of synthetic drainer as media support (Figure 3). Annexing collapse pulsing to the backwash program in nutrient-limited situations enhanced DOC removals according to water-only backwashing (13 versus 21%, respectively). Using a lower bed expansion, 20 against 30%, had no effect on DOC removal (35%) but ended in a nearly 20% saving in backwash water volume (Table 5).

Antibiotic-resistant genes (ARGs) are constantly being discovered in drinking water, posing a major public health concern. The behavior of ARGs and their possible association with bacteria in a bench-scale biofiltration system was investigated (Xu *et al.* 2020). The effect of filter media on horizontal gene transfer (HGT) was examined utilizing a model conjugative plasmid, RP1. The biofiltration system is composed of sand, GAC, GAC sandwich, and anthracite-sand biofilters. Results indicated that the absolute abundance of ARGs declined and the ARGs' abundance normalized to bacterial numbers, which indicated a growing trend in the filtered water. Backwashing can decrease the transferability of the RP1 plasmid dramatically in biofilms, and the results could increase ARGs in drinking water biofiltration treatment. In a similar study, Wan *et al.* (2021) practiced the existence of ARGs and bacterial gathering in full-scale BAC filters along the backwash circuit, exercising high-throughput qPCR and high-throughput processing. It was discovered that despite backwashing, 80.6–89.3% of the prescribed ARGs remained in the BAC filters. Given the high proceeds and comparative profusion of ARGs in BAC filters and the unprofitability of backwashing in ARG removal, more insistent downstream disinfection plans are needed, and more examination is required to appraise potential human health risks because of the insistence of ARGs in drinking water.

5.2. Ozonation and chlorination

The bioactivity and DBP precursor removal using the pilot-scale biofilters, including different filter materials (GAC, anthracite and sand), with or without pre-ozonation and chlorinated backwash at 15- and 30-min EBCTs was analyzed (McKie *et al.* 2020). The pilot system consisted of eight parallel filters ($d_f = 7.6$ cm) and the backwash process was consequent for all filters and involved 2 min of low-flow backwash with 30% expansion and 8 min of high-flow backwash with 50% expansion (Table 5).

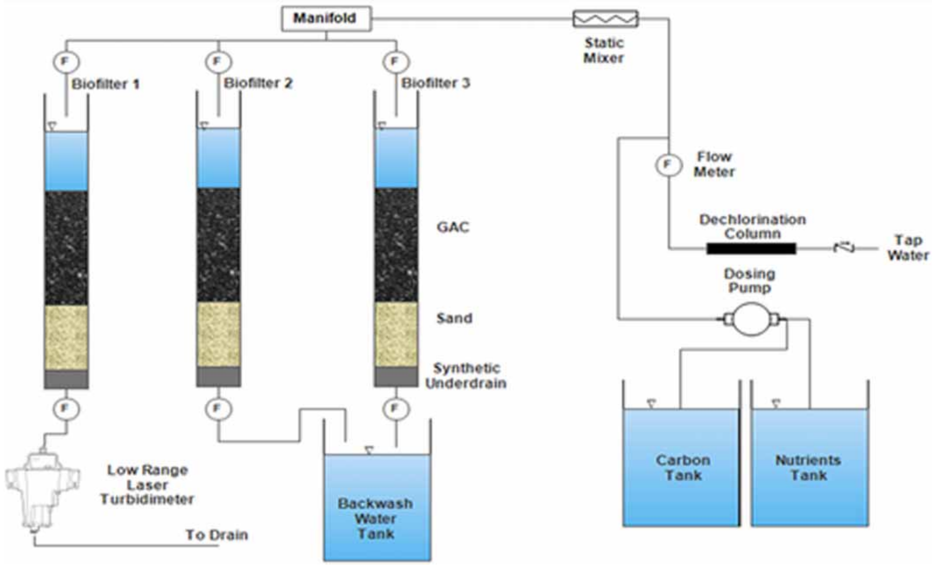

Figure 3 | Schematic diagram of a lab-scale system consisting of three DMFs (Ikhlef & Basu 2017).

Air scour was employed when only water fluidization became insufficient. Enzyme activity can respond to variances in biofilter procedures, the availability of chlorine within the backwash water, and the measurement of biomass density solely. Results approved the advantages to treated water quality connected with the execution of an ozone residual of 0.5 mg/L, the use of a GAC filter system, removing chlorinated backwash, and an enlarged EBCT. Upstream oxidant addition was utilized to scatter biologically derived filter clogging in BAC filters (de Vera *et al.* 2019). Oxidant influence was examined during pilot-scale treatment and backwashing of BAC biofilters as dual (GAC/sand) and multimedia (GAC/anthracite/sand). The filters were backwashed succeeding 168 h of filter running. To reduce biomass development, various oxidant residuals (HOCl, NH_2Cl, and H_2O_2) were optimized to react with the GAC surface in the top level of the filter bed (depth 0.5 m).

The ozone-biological activated carbon (O_3-BAC) procedure has been demonstrated to be an effective and economic technology in advanced water treatment (Liu *et al.* 2020a). During the water backwashing procedure, the bed expansion rates of the GAC sample named DT-830- BCT were selected as being between 15 and 50% and the bed expansion rate of other original GACs and carbon blends was selected as 30%. The backwashing cycle was 10 min each time (Table 5). The hydrodynamic conditions, specifically the bed expansion ratio and pressure decrease in bed, were assessed. The results showed that the water backwashing procedure had no impact on the composition ratio of GAC mixtures. Microbial colony construction in the ozone-biofiltration practices of two drinking water and two wastewater treatment plants was represented using 16S rRNA gene collocation (Gerrity *et al.* 2018). These datasets involved pre-oxidation as ozonation and chlorination, various filter media as anthracite, GAC and BAC and backwash strategies. An examination of backwashing strategies yielded two significant findings: (1) endosymbionts such as Neochlamydia and Legionella increased in comparative profusion following backwashing procedures and (2) nitrogen-fixing Bradyrhizobium possessed the microbial colony in wastewater filters managed with intermittent backwashing procedures.

Biological ion exchange (BIEX) has proven to remove natural organic matter (NOM) better than BAC (Liu *et al.* 2020b, 2022). Recently, it has been reported that ion exchange (IEX) resins can be utilized as an alternative material for biofiltration as a BIEX filter (Schulz *et al.* 2017). Figure 4 shows configurations of IEX and BIEX filters. The pilot-scale facility consisted of five parallel filters (CPVC, 5.08 cm of diameter), each filled with a 30 -cm sand sublayer (0.6 L) and a 150- cm top layer (3.0 L) of either GAC, BAC, or IEX. Three GAC filters and one BAC filter were used for NOM and ammonia removals, and the BIEX filter was found to eliminate NOM better than the BAC filter. At the top 30 cm layer, the BIEX filter obtained 81% of total DOC removal, while the GAC/BAC filters achieved only 62–66% removal. Backwash water flowrate was regulated to get 50% bed expansion, and backwash water procedure terminated after 40 min for the BIEX filter and 20 min for the GAC filter and the BAC filter when backwash water turbidity was less than 10 NTU (Table 5).

Traditional RSFs with pre-chlorination achieved haloacetic acid (HAA) biodegradation (Chuang *et al.* 2011). Treated water with 0.8 mg/L of mean residual chlorine was utilized as backwashing water. Prior to the backwashing, the dichloroacetic acid (DCAA) removals were about 50%, and a high effluent chlorine concentration of 0.68 mg/L was monitored after backwashing. By the way, restricted removal efficiencies were accompanied by an instant high chlorine effect. Because backwashing has only a minor effect on biomass detachment (Miltner *et al.* 1995; Rittmann *et al.* 2002), the transient inhibition of bioactivity was most likely completed by an instantaneously increased chlorine concentration in place of the biomass lost.

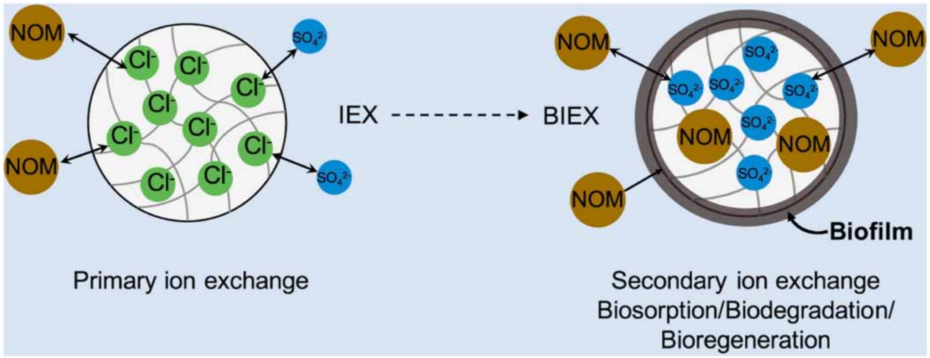

Figure 4 | Schematic configurations of IEX and BIEX filters (Liu *et al.* 2020b).

The impacts of backwashing on the abundance of ammonia-oxidizing archaea (AOA) and ammonia-oxidizing bacteria (AOB) on GAC were analyzed (Niu *et al.* 2018). The GAC was backwashed every 120 h using water having residual chlorine. Backwashing is done in two stages: lower water flow rates of 20–30 m^3 /min with an air scour of 60 m^3/min and a higher water flow rate of 60 m^3/min. Without prechlorination, backwashing assisted in the regaining of the ammonium removal potential of GAC. Otherwise, backwashing along the prechlorination duration could unfavorably influence the ammonium removal potential of GAC.

Full-scale biofiltration tests indicated that agreeable removal of biodegradable organic matter (BOM) subsequent ozonation could be obtained without agreeable particle removal (Emelko *et al.* 2006). The impact of water temperature, filter media, and backwashing procedure on particle and BOM removal from raw drinking water as well as biomass concentration in full-scale biological filters was also studied, and it was also found that a backwash program with or without air scouring did not improve TOC removal for GAC/sand or anthracite/sand filters.

The effect of various backwashing strategies on the biodegradation and adsorption techniques of BAC filters and the attached biomass concentration in the filters was examined (Liu *et al.* 2016). The possibility of using chloroacetic acids (CAAs) as indicator chemicals to estimate the biodegradation capability of BAC filters and to obtain favorable backwashing procedures to maintain the employment of the filters was also examined. Results indicated that the disinfectant-free backwashing had a restricted impact on eliminating attached biomass (50%). Chloramines-improved backwashing could substantially eliminate the attached biomass in all BAC filters (>50%). The intensity was set at 42 L/(m^2s) for all backwashing procedures to maintain a filter bed expansion ratio of nearly 30% (Table 5). During every backwash, the BAC particles were locally fluidized, and backwashing continued for 10 min.

5.3. Backwash intervals

The impacts of residual ozone and chlorine and the backwash intervals on bacterial actions and densities in pilot-scale BAC filters were estimated by actuating adenosine triphosphate (ATP) measurement and flow cytometry (Lohwacharin *et al.* 2015). The backwashing process was implemented at an airflow rate of 80 L/min for 7 min and later with chlorinated drinking water (residual was between 0.63 and 0.77 mg/L) at a water up-flow rate of 14.4 L/min for 12 min (Table 5). The residual ozone and chlorine did not impact the untouched cell ratios in the effluents, but dramatically influenced the untouched cell ratio in the backwash water. The higher ratio of high nucleic acid (HNA) and high ozone and chlorine periods demonstrated that extending the backwash interruption exposed the bacteria attached to the BAC to ozone and chlorine more strongly (Figure 5).

The association of GAC adsorption within deep-bed filters for the simultaneous removal of phosphorus and OMPs using a pilot-scale system containing GAC as the upper filter layer in DMF and as a mono-media up-flow filter was examined (Altmann *et al.* 2016). The filters are backwashed by hand after 23 h of running through air scouring and water flushing with tap water. The backwash practices were optimized individually for every filter to obtain optimum bed fluidization. Continual backwashing leads to the bedding of GAC particles compared to their size and density, with small particles near the top and large particles near the bottom of the filter column. Up-flow filtration leads to considerably lower head losses, preferable filter depth usage, and is more amenable to particle breakthrough at long backwash intervals.

The difference in dissolved organic nitrogen (DON) during a whole backwashing circuit of the biofiltration for DWT was examined (Liu *et al.* 2012). A binary setting of 70 cm GAC and 30 cm sand was utilized in the biofilters. Excluding the GAC sandwich, biofilters were backwashed by pumping with an effluent up-flow to obtain a 20–30% bed expansion for 10 min, and the system was operated constantly for 24 h after backwashing/cleaning was performed (Table 5). The importance of the result is that the shorter backwashing intervals between backwashing for the drinking water biofilter should further decline the DON concentration in biofilter effluent.

5.4. Biofilm development

The effect of BAC filter depth and backwash impacts on biofilm development was investigated (Qi *et al.* 2019). A bench-scale set was arranged to get a better conception of microbial variety and the gathering construction of BAC biofilm with regard to successive methods, and it was found that microbial variety declined gradually along with the increment of filter depth. In terms of subsequent analysis, the level of microbial variety in the biofilm is balanced after three months of application. The backwash process had excellent effects on the gathering construction of BAC biofilms, causing microbial variety to decline at once.

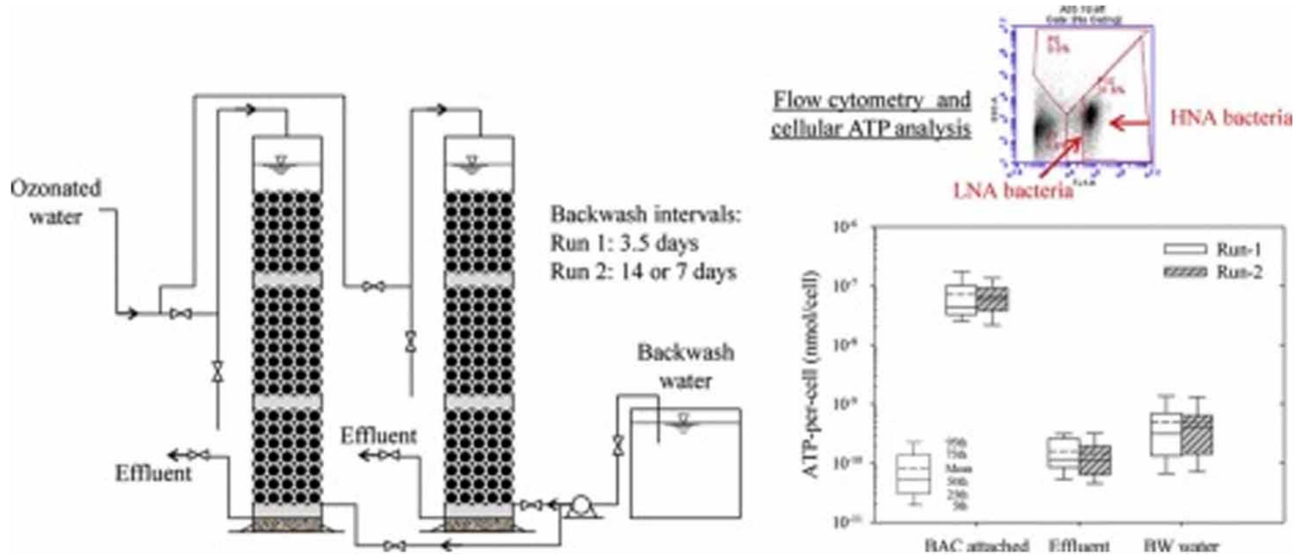

Figure 5 | Schematic diagram of the backwash interruptions in the filter media (Lohwacharin *et al.* 2015).

Bacterial gathering dynamics in a real BAC process during four sequenced seasons, exercising quantitative polymerase chain reaction and pyrosequencing, were analyzed (Kim *et al.* 2014). The BAC steadily eliminated organic carbons during the period while the water temperature essentially remained the same over the study period, and backwashing did not impact the BAC bacterial gathering. However, Kasuga *et al.* (2007) found that backwashing decreased the bacterial volume and modified the gathering in a DWTP, and similarly van der Aa *et al.* (2011) submitted a biomass decrease through backwashing in a pilot-scale GAC biofilter; inversely, Laurent *et al.* (2003) and Seredyńska-Sobecka *et al.* (2006) submitted that backwashing had no impact on biomass decrease in the lab-, pilot-, and full-scale BAC filter systems. Hozalski *et al.* (1999) found periodic backwashing did not affect biofilter performance as long as 60–80% of the biomass was retained.

The adsorption capacity of GAC filters declines with the remaining operation time. If biological movement is available in the GAC filter, organic matter is further eliminated, and thereafter the adsorption capability has been consumed. The existence of organic matter and nutrients in the influent stream causes the occurrence of a biofilm on the surface of activated carbon (Sbardella *et al.* 2018). Extracellular polymeric substance (EPS) is a significant factor in drinking-water biofilters. EPS concentrations in full-scale biofilters were studied, and the effect of backwashing on EPS concentration was analyzed (Keithley & Kirisits 2018). The impact of the EPS extraction protocol belonged to the media variety and was arranged as follows: sand > anthracite > GAC. Backwashing dramatically reduced the EPS polysaccharide concentration within the filter media, however, the majority of the biofilm stayed attached to the filter media following backwashing.

The fluidization action and its relationship with the properties of GAC particles used in water treatment operations, as well as abrasion caused by the attritional nature of the GAC media and recurrent backwashing, all contribute to particle growth and biological activity (Kramer *et al.* 2021b). For this investigation, nine various GAC samples were elected and examined, while d_{10} particle sizes varied in the range of 0.41 and 3.73 mm. The expansion extent of the virgin GAC was about 10% larger compared to the BAC and the expanded bed porosity varied between 0.6 and 0.9 while the superficial velocity (or backwashing rate) was between 36 and 108 m/h (Table 5). Because the GAC particles lose stability through attrition and collisions occurring during the backwashing procedure, the fluidization movement differs gradually. Similar research has found that increasing fraction solids and hydrodynamic shear stress cause a higher rate of biofilm detachment due to particle collision forces on biological particles in the filter setting (Turan 2000; Liu & Tay 2001).

6. MEMBRANE FILTRATION SYSTEM AND BACKWASHING

6.1. GAC/UF hybrid pretreatment

RSF is utilized nowadays as a prevailing pretreatment process to upgrade water quality before the reverse osmosis (RO) membranes in desalination facilities. RSF in newly run desalination plants requires a nearly 3-month maturation cycle before the feedwater can be adequately filtered. The potential of the biological RSF by succeeding the dynamics of bacterial colonization and metabolic action in the filter media and defining filtration performance with regard to particulate and DOC, chlorophyll a, and transparent exopolymeric particles (TEP) (Bar-Zeev *et al.* 2012). Along with the outgrowth of a microbial accumulation and biofilm growing on the filter media, significant removal of organic carbon from the source water was regularly monitored. The sampling from RSF was separated into two stages, namely a slim layer ($d = 0.5$–1 mm) and a rough layer ($d = 1$–3 mm), while the operation time was 43 days (Table 4). RSF was backwashed frequently throughout the maturation cycle, and suitability sampling was performed about 15 h after the backwashing procedure.

The micro-flocculation/sedimentation pursued by pre-ozonation in the pretreatment of feed water prior to UF membrane treatment in recycling activated carbon filter-UBW was studied (Zhang *et al.* 2017). The UF technique was examined at a filtration procedure of 60 min, and backwash was implemented at the end of every cycle. The backwash procedures were also examined at 6, 8, and 6 m^3/h for 15, 30, and 15 s, respectively. The chemical cleaning procedure for UF (every 100 days) was implemented using NaOH solution and then demineralized water backwash was operated for 10 min. The results indicated that micro-flocculation/sedimentation eliminated many particles to reduce membrane fouling arising from particulate contaminants.

The long-term effect of a BAC filter that was operated in a full-scale DWT facility to improve the removal of contaminants by the UF technique was assessed (Chang *et al.* 2022). Six BAC filters (each filter area was 81 m^2) were used to provide the whole planning capacity of 100,000 m^3/d along with a filtration rate of 8.96 m/h. Air scour and water backwash was performed every 3–6 days, with an airflow rate of 55 $m^3/(m^2h)$ for 3–5 min and a water backwash rate of 31 m/h for 6–8 min. The results indicated that BAC increased UF execution by raising the flux by about 18.5% and sustaining the filtration operation by about 45%.

Removing the nutrients and microorganisms from seawater for biofouling mitigation in seawater cooling towers without chemical usage was researched, and GAC biofiltration and UF membrane pretreatment methods were operated to decrease the nutrients and microorganisms in seawater following the original procedure (Mohammed *et al.* 2021). Figure 6 shows the GAC/UF hybrid pretreatment system GAC filtration was performed to remove the assimilable organic carbon (AOC) levels with biological filtration impact, while the UF membrane system was utilized for microorganism elimination. In the backwash stage, a controller furnished on the unit checked the backwash of the UF, and the permeate was forwarded to be pressurized from the outdoor to the indoor of the UF. Backwashing was performed for 60 s over a 48-h period. The filters were backwashed at flow rate 3.0 L/min for 15 min (Table 5), while the head loss decreased to 40% of the beginning value.

The NOM removal efficiency of a GAC filtration and a UF membrane at pilot scale system and traditional water treatment as a full-scale plant were evaluated (Marais *et al.* 2018). The UF facility was backwashed automatically every 60 min, and the backwashing period lasted 1–3 min. Backwashing the UF membrane entails driving force – either air or permeate water – along the membrane wall in the opposite direction at 0.5 bar of pressure. GAC filtration achieved great NOM removal compared to traditional water treatment. Kim & Yu (2005) also studied the elimination abilities of NOM fractions from drinking water using traditional and advanced treatment (AT) processes. Backwashing for UF cleaning is now routinely used to reject membrane fouling. Backwashing of the sand and GAC filters was implemented every day and twice a week, respectively.

The proficiency of the employment of GAC filtration and UF membrane with nonchemical pretreatment prior to desalination was investigated at the lab scale. The study was carried out in a short period of time for two various seawaters (SWs) using membranes having various molecular weight cut-offs (MWCOs) (Monnot *et al.* 2016). The GAC filter was backwashed using ultrapure water prior to the studies, and the empty bed contact time (EBCT) was chosen as 20 and 13 min for SW1 and SW2 membranes, respectively. UF provided a constant quality of the pretreated SW as it could delay the residual particles or microorganisms, and it reduced turbidity to below 0.1 NTU. Several studies (Naidu *et al.* 2013; Simon *et al.* 2013) have found that filter flow rates ranging from 25 to 50 L/h have little effect on GAC filtration yield. Using a GAC filter as a pretreatment stage before RO also causes the time and/or interval of backwashes and water cleaning to be decreased at full scale.

Monnot *et al.* (2017) used a combination of GAC adsorption and UF as a pretreatment before RO on a full-scale desalination plant. The results indicated that the GAC fixed bed could highly decrease about 20–80% of the DOC concentration and that UF could hold most of the transparent exopolymer particles (TEP) and bacteria in front of RO. The filtration time was in the range of 15 and 20 min and automated backwashes (BW) using UF permeate were managed over 1 and 2 min with a flux of 3.6×10^{-5} m/s (Table 3). They were chlorinated at the halfway point of the backwash procedure at a concentration of 0.001–0.003 kg/m^3. Besides, plenty of clean water was required for cleaning applications of the prefilter.

Gibert *et al.* (2015) followed DOC through the various stages of a DWT facility that included a traditional treatment that included coagulation/flocculation, sedimentation, and rapid sand filtration processes, as well as two parallel treatments,

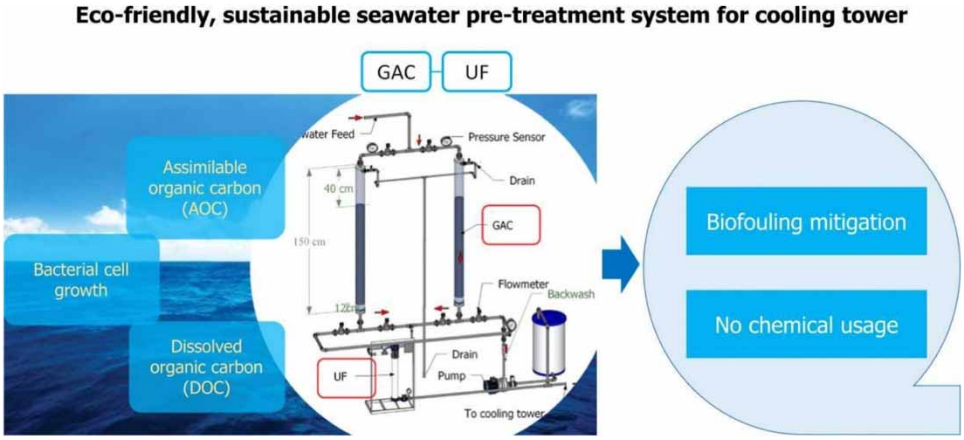

Figure 6 | Diagram of a GAC/UF hybrid pretreatment system (Mohammed *et al.* 2021).

namely ozonation and GAC filtration at an advanced treatment (AT1) and UF and RO at a membrane-based advanced treatment (AT2). GAC filters are backwashed every 2–3 days, first with air scour at a flow rate of 0.5 m^3/s for 5 min and later with treated water at a flow rate of 0.3 m^3/s for 14 min to prevent long-term clogging. Backwash stream water analysis showed that biopolymers (BP) were not only the major fraction removed by UF but also the most easily detached one during backwashing. However, it has been reported that BP was detained by cake development and easily removed with backwashing, whereas HS can cause pore blocking, enhance an intense cake layer, or be adsorbed by membrane matter, necessitating chemical cleaning to remove them from the membrane (Lee *et al.* 2004; Tian *et al.* 2013). Besides, backwash water from UF was assayed to procure an insight into the fouling reversibility of DOC fractions.

6.2. Prefiltration of wastewater effluent

The impact of three prefiltration procedures, namely multimedia filtration (MMF), GAC filtration and BAC filtration, on foulants and the performance of UF were submitted (Janssen *et al.* 2010). The MMF includes two filtration layers as anthracite and quartz sand (Table 2). The research was practiced on two different full scale wastewater treatment plants (WWTP1 and WWTP2). At WWTP1, effluent was filtrated by an MMF filter in parallel with a BAC filter and the WWTP2 effluent is solely filtrated by a GAC filter (Table 3). Samples were obtained before the weekly backwashing procedure before and after the filtration. From all the contaminants, particularly the proteins and humic, matters are eliminated by GAC and BAC filters. BAC is the sole prefiltration method that indicates the important removal of the piece between 0.1 and 0.2 μm (Table 5).

A longtime-period-application of GAC filters and their biological mobility were investigated, and lab- and pilot-scale studies indicated that the DOC in the effluent of MWT facility explained 20% of total DOC (Fundneider *et al.* 2021). A backwashing process was required to examine the biofilm buildup in the GAC filters. The repetition of backwashing procedures varied in relation to pretreatment. The backwashing repetitions of 0.1 per week for filters were performed by means of membrane pretreatment using a microfiltration (MF)/UF system and 1.2 per week for filters were performed by means of cloth filtration (CF).

TOC removal from greywater in a BAC filter was fulfilled after a membrane bioreactor (MBR) operated for more than 900 days (Hess & Morgenroth 2021). The graywater accumulated in the building is treated with an MBR followed by a BAC filter (Figure 7). The substantial filter design along with low mean filtration velocities procured long-term TOC removal. The only care necessary was the backwashing operation. Backwashing effectively decreased the pressure lost but had no essential effect on the effluent water quality. It is demonstrated that BAC filters, in conjunction with rapidly changing flow and TOC concentrations, are an appropriate post-treatment stage for greywater treatment.

7. CONCLUSIONS

All the research cited in this article agrees that filter backwashing is an effective cleaning procedure for granular media filters and membrane systems. The following major conclusions were reached:

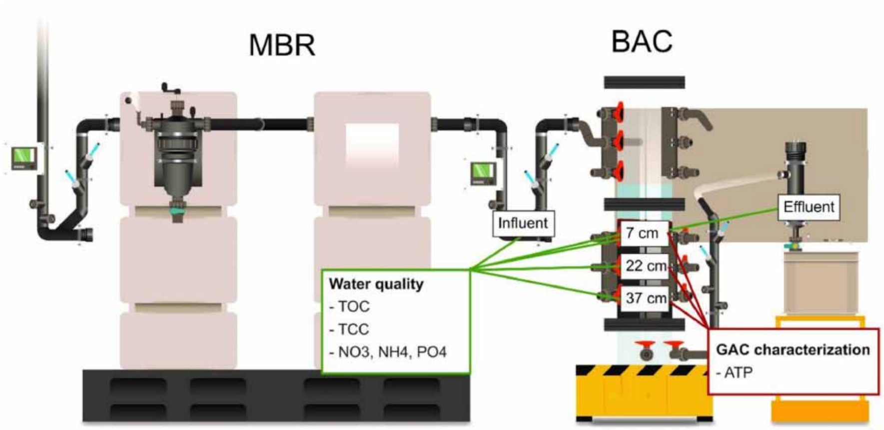

Figure 7 | Greywater treatment installation containing an MBR and a BAC filter for post-treatment (Hess & Morgenroth 2021).

- The capability of the backwash processes was examined by estimating the volumes of water required. It was found that the filter backwash method affects not only the turbidity of the effluent, while the filter is ripening, but also the time required for the filter to go to waste and the filtration cycles.
- RSFs are greatly utilized in groundwater treatment to eliminate complexes such as NH_4^+, Fe^{2+}, and Mn^{2+} to drinking water quality norms. Elimination occurs with a combination of physico-chemical and biochemical facilities. MnO_4–Fe(III) dosing increased the subsidence rate of backwash solid matters, which was attributed to an increase in Mn concentration in the backwash solid matters rather than differences in the molecular-scale composition of Fe-precipitates that form during the treatment.
- GAC filtration is an essential unit procedure in DWT and GAC filtration is composed of the following two sequential aspects: adsorption and filtration, which capture the pollutants from the water in conjunction with a backwash process that removes the pollutants. Backwashing causes significant stratification in particle size and density, and significant variations from top to bottom can be observed for all GAC filters that were backwashed in a short period of time.
- The combination of a recycled filter, used backwash water (UBW), and DWT plant is regarded as an appropriate method to improve decontamination. Besides, the reuse of AC-UBW was also conducted using an UF method. Pre-ozonation reduced the hydrophobic organic substances in the influent AC-UBW and altered the molecular weight formation of organic matter.
- Biological granular sand filters are mostly utilized to eliminate ammonium, iron and manganese from groundwater aquifers for drinking water supply. They operate continuously at dynamic substrate and hydraulic loading states, which can result in residual ammonium and nitrite levels in effluent water. Solids accumulated during the filter backwashing and ripening cycles were consistently of a biological nature, implying that biological oxidation of adsorbed manganese occurred throughout the filter operation, promoting manganese removal.
- The effects of backwashing on the biomass and biofilm structure of a BAC filter were discovered to enhance the elimination of DOC, and backwashing indicated a strong effect on bacterial variety and community constitution of BAC biofilm, but they can gradually regain with the filtration procedure time following backwashing.
- The GAC/UF hybrid system was found to be an optimal pretreatment selection to alleviate biofouling. The BAC technique in a hybrid, full-scale DWT plant in connection with UF was investigated. The results indicated that BAC increased UF execution by raising the flux by about 18.5% and sustaining the filtration operation by about 45%.
- The advancement of more useful backwash estimation indicators, the determination of the solid matters in backwash waste and the constitution of chlorination disinfection by-products, and the improvement of the performance of prefiltration techniques on foulants in the membranes during backwashing using various types of backwash water should be well regarded in future research.

AUTHOR CONTRIBUTIONS

M.T. investigated and conceptualized the study, did formal analysis, wrote, reviewed and edited the original draft.

DATA AVAILABILITY STATEMENT

Data cannot be made publicly available; readers should contact the corresponding author for details.

CONFLICT OF INTEREST

The author declares there is no conflict.

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