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Treatment performance comparison between regular O₃-BAC and O₃-BAC with rear sand filtration: verification in a full-scale study

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Abstract

Background: To improve the microbial safety of drinking water, an arrangement of O₃-BAC with rear sand filtration (O₃-BAC-sand) has been proposed. In this study, efforts were devoted to evaluate the benefits and drawbacks of O₃-BAC-sand in a full-scale water treatment plant. The performance of the two configurations was compared in terms of particles, turbidity, COD_{Mn} and typical odorants and pesticides.

Results: The O₃-BAC-sand yielded lower turbidity but higher COD_{Mn} (by approximately 7%) in the finished water than regular O₃-BAC (sand-O₃-BAC). Both systems removed odors in raw water; however, sand-O₃-BAC was more effective on septic and musty odorants. The total pesticide removals by sand-O₃-BAC and O₃-BAC-sand were 78% and 72%, respectively; though the latter had shorter activated carbon durable years.

Conclusion: The re-location of the sand filter would sacrifice the BAC efficiency in removals of organic matter and micropollutants. This tradeoff is a result of the loss of the particulate organic matter removal by sand filters, because locating the sand filter behind BAC causes particle load increase on BAC; some measures of enhanced coagulation should be suggested to improve the turbidity and particle removal. The study will be helpful for improvement of the O₃-BAC process in drinking water treatment.

Keywords: Sand-O₃-BAC, O₃-BAC-sand, Sand filter interception, Drinking water treatment

Background

Ozonation integrated with biological activated carbon (O₃-BAC) is adopted more and more often for drinking water purification because of its effectiveness in removing disinfection byproduct precursor sand synthetic organic chemicals [1]. In the treatment train, it is common practice that the O₃-BAC unit is placed after sand filtration (regular O₃-BAC: sand-O₃-BAC) [2], and the presence of some genera might play important roles in the biodegradation taking place in the BAC filter [3]. During the operation, BAC filter would provide a suitable condition for the growth of aquatic micro-animals, which could form a microorganism-protozoa-macroinvertebrate biological chain [4]. Moreover, particles harboring

bacteria, particularly some chlorine-resistant pathogens like *Legionella* and *Chromobacterium* [5], could possibly penetrate the BAC bed, and the microorganism could also get through the BAC filter, which would have impact on the drinking water quality. This has been reported in some O₃-BAC treatment plant, especially in the south subtropical region in China [6], giving rise to biological safety concerns of the drinking water. One option is O₃-BAC with rear sand filtration (O₃-BAC-sand), which provides a barrier for reducing the biological risk [7] and has been reported in previous studies [8, 9]. And the O₃-BAC-sand process has been applied in some water treatments in China such as Shanghai [10], Fuzhou [11], Jinan [12] and Jiaying [13].

Sand filtration is one key step in drinking water treatment to remove particles from raw water [6, 14], and it is also known to be inefficient for removing hydrophilic pollutants, because hydrophilic compounds do not easily

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adsorb into sand filter beds, whereas hydrophobic compounds with $\log K_{ow} > 2.5$ tend to adsorb onto particles, resulting in higher removal efficiencies (>80%) during sand filtration [15, 16]. The filter media intercept and remove particles harboring organic compounds, as well as organic particles like algae escaping from the upstream sedimentation unit [16, 17]. Consequently, post-sedimentation particulate organic matters may enter the ozonation unit when the sand filter is located downstream of the BAC filter. Furthermore, particulate organic matter can be transformed into dissolved organic carbon (DOC) during the ozonation process [18], and thus increase mass load on the BAC filter. These treatment tradeoffs should be evaluated to determine the benefits and drawbacks of the rear sand filtration for a given drinking water treatment plant.

In this paper, the treatment performance for the rear sand filter arrangement is investigated and compared through experimental studies in a full-scale drinking water treatment plant with two parallel configurations (sand–O₃–BAC and O₃–BAC–sand). Treatment performance was compared in the removal of chemical oxygen demand by KMnO₄ titration (COD_{Mn}), the only parameter of comprehensive organic material concentration in the Chinese drinking water standard, and particles, turbidity, typical odorants as well as some typical pesticides.

Materials and methods

Comparative treatment analysis

The water treatment plant of 7×10^5 m³/days capacity in Shanghai, China has two parallel treatment systems: a sand–O₃–BAC process and a modified treatment train equipped with a rear sand filter (O₃–BAC–sand). The sand–O₃–BAC system, of 4×10^5 m³/days production capacity, consists of pre-ozonation, coagulation, sedimentation, sand filtration, post-ozonation and BAC in succession. The O₃–BAC–sand system, of 3×10^5 m³/days capacity, varies in the location of sand filtration: pre-ozonation, coagulation, sedimentation, post-ozonation, BAC and sand filtration in succession. The sand–O₃–BAC and O₃–BAC–sand systems have operated for 47 and 33 months, respectively.

During the four-month study period, typical operation parameters were aluminum sulfate at 40 mg/L (8.0 mg/L as Al₂O₃ concentration) dose, 105-min sedimentation time, ozone dose of 0.5 mg/L for pre-ozonation (5 min) and 1.0 mg/L for post-ozonation (15 min), sand filtration velocity of 7.9 m/h, the empty bed contact time and filtration velocity of the BAC filter were 16 min and 8.3 m/h, respectively.

The unit processing and treatment efficiency were examined for samples collected at the raw water intake and the effluents from the sedimentation, sand filtration,

post-ozonation and BAC units from May to August in 2015. Analyte included turbidity, particle counts and COD_{Mn}, odorant and pesticide compounds. For the determination of turbidity, particle counts and COD_{Mn}, a 1-L water sample was taken once or twice every week, and analyzed right after sampling. The samples for odorant determination were taken thrice in May and twice every month, stored in a refrigerator after filtration with a glass fiber filter and then taken back to the laboratory for the analyses. The samples for pesticide determination were taken once every month from the systems.

Sample preparation and analysis

The COM_{Mn}, particle size, odor compounds, and pesticides were analyzed for the collected samples. All reagents used in the experiment were of guaranteed reagent grade, and all stock solutions were prepared with Milli-Q water (Millipore). COD_{Mn} was measured on a HACH Model DR2800 spectrophotometer (HACH, USA). Soluble COD_{Mn} (SCOD_{Mn}) was obtained by measuring the samples after 0.45- μ m membrane (GF/E, Whatman, UK) filtration. Insoluble COD_{Mn} (inSCOD_{Mn}) equals Total COD_{Mn} (TCOD_{Mn}) subtracting SCOD_{Mn}.

Concentrations of 25 pesticides (Table 1) were measured using GC/MS according to Yu [19]. The flavor profile analysis (FPA) method was used to characterize the odors according to the Standard Methods for the Examination of Water and Wastewater [20]. Typical septic (dimethyl disulfide (DMDS), dimethyl trisulfide, bis(2-chloro-1-methylethyl) ether and musty (2-methylisoborneol (2-MIB)) odorants were determined by two-dimensional gas chromatography with time-of-flight mass spectrometry (GC \times GC–TOFMS) using the methods in [21].

Finally, particle size distribution was characterized on a Hybrid Particle Counter ZVL (Fuji Electric, Japan), in grab sample mode. The method measures both turbidity and particle count in 9 size ranges (1–2 μ m, 2–3 μ m, 3–5 μ m, 5–7 μ m, 7–10 μ m, 10–15 μ m, 15–20 μ m, 20–30 μ m, > 30 μ m).

Results and discussion

During the study period, the raw water turbidity ranged from 18.8 to 46.0 NTU, COD_{Mn} from 4.50 to 6.84 mg/L, counts for particles of 1–2 μ m, 2–5 μ m, 5–15 μ m and > 15 μ m from 268,836.00 to 731,408.25, from 32,278.64 to 294,281.25, from 18,726.58 to 47,688.50, and from 61.25 to 1783.08, respectively. It is also known for its septic/swampy odor occurrence and the presence of a variety of micropollutants because of pollution in source water [22].

Table 1 Information of the twenty-five pesticides compounds

No.	Compounds	CAS	Structure	Mol. wt.
1	Hexachlorobenzene (HCB)	118-74-1	C ₆ Cl ₆	284.78
2	Heptachlor	76-44-8	C ₁₀ H ₅ Cl ₇	373.35
3	1-Chloro-2-[2,2,2-trichloro-1-(4-chlorophenyl)ethyl] benzol	789-02-6	C ₁₄ H ₉ Cl ₅	354.49
4	2,2-bis(p-Chlorophenyl)-1,1,1-trichloroethane	50-29-3	C ₁₄ H ₉ Cl ₅	354.49
5	2,2-bis(p-Chlorophenyl)-1,1-dichloroethane	72-54-8	C ₁₄ H ₁₀ Cl ₄	320.04
6	2,2-Bis(4-chlorophenyl)-1,1-dichloroethylene	72-55-9	C ₁₄ H ₈ Cl ₄	318.03
7	Lindane(r-BHC)	58-89-9	C ₆ H ₆ Cl ₆	290.83
8	α-Hexachlorocyclohexane (BHC)	319-84-6		290.82
9	β-Hexachlorocyclohexane (BHC)	319-85-7		290.83
10	δ-Hexachlorocyclohexane (BHC)	319-86-8		290.83
11	Dichlorvos	62-73-7	C ₄ H ₇ O ₄ Cl ₂ P	220.98
12	Malathion	121-75-5	C ₁₀ H ₁₉ O ₆ PS ₂	330.35
13	Dimethoate	60-51-5	C ₅ H ₁₂ NO ₃ PS ₂	229.25
14	Parathion	56-38-2	C ₁₀ H ₁₄ NO ₅ PS	375
15	Parathion-methyl	298-00-0	C ₈ H ₁₀ NO ₅ PS	263.2
16	Atrazine	1912-24-9	C ₈ H ₁₄ ClN ₅	215.68
17	Deltamethrin	52918-63-5	C ₂₂ H ₁₉ Br ₂ NO ₃	505.2
18	Chlorothalonil	1897-45-6	C ₈ Cl ₄ N ₂	265.91
19	Chlorpyrifos	2921-88-2	C ₉ H ₁₁ Cl ₃ NO ₃ PS	350.59
20	Acetochlor	34256-82-1	C ₁₄ H ₂₀ ClNO ₂	269.77
21	Fenobucarb	3766-81-2	C ₁₂ H ₁₇ NO ₂	207.27
22	Butyl 2,4-dichlorophenoxyacetate	94-80-4	C ₁₂ H ₁₄ Cl ₂ O ₃	277.15
23	Machette	23184-66-9	C ₁₇ H ₂₆ ClNO ₂	311.85
24	Dicofol	115-32-2	C ₁₄ H ₉ Cl ₅ O	370.49
25	Monocrotophos	6923-22-4	C ₇ H ₁₄ NO ₅ P	223.16

Turbidity and particles

Figure 1 shows the changes of average turbidity along the treatment processes in the two systems. Generally, the finished water in the rear sand filtration system has lower turbidity; in average, 0.12 NTU in sand–O₃–BAC vs. 0.04 NTU in O₃–BAC–sand (*p* = 0.020). The day-to-day monitoring data of the finished water also exhibited similar results (Fig. 2). For the sand–O₃–BAC system, the turbidity removal primarily occurred in the sand filtration. Turbidity removal in the O₃–BAC–sand process occurred in both the BAC and sand filters. A slight increase of turbidity after ozonation (Fig. 1) may be the result of fine particle aggregation and subsequent breakup into small sizes, a process reported in [23, 24]. Besides, oxidation of iron and manganese, which can produce some insoluble inorganics like goethite, magnetite and MnO₂, has also been reported to be responsible for turbidity increase after ozonation [25]. Changes of particle counts across the treatment train were examined in particle size ranges (Fig. 3). Clearly, in sand–O₃–BAC system, sand filtration removed particles over all size ranges, and ozonation

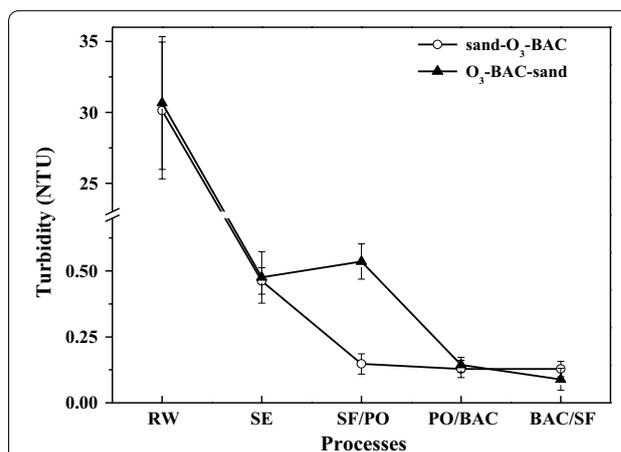
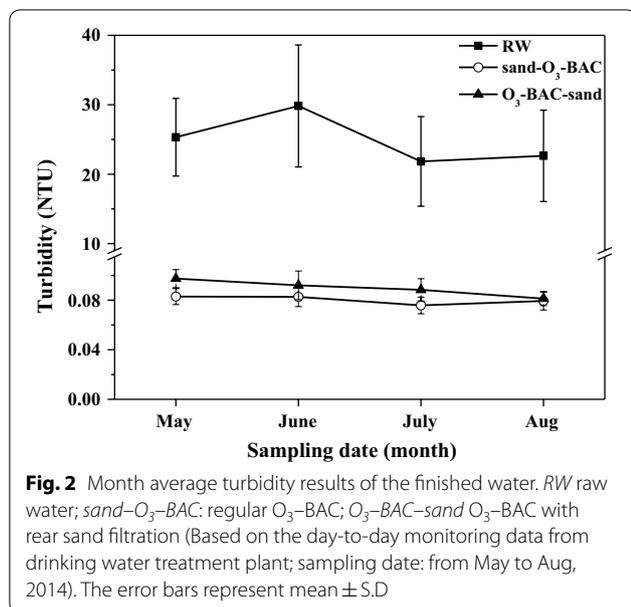


Fig. 1 Changes of turbidity along the treatment trains. RW raw water; sand–O₃–BAC regular O₃–BAC; O₃–BAC–sand O₃–BAC with rear sand filtration; SE sedimentation; SF sand filtration; PO post-ozonation. Operational conditions: pre-ozone dose 0.5 mg/L; post-ozone dose 1.5 mg/L. The error bars represent mean ± S.D



was effective in removing small particles of 1–2 μm . In O₃-BAC-sand system, significant decrease in number concentration of small particles (1–2 μm) following ozonation was in contrast to an increase for the larger particles (> 2 μm). This observation apparently agrees with previous reports [3, 26] that ozonation destabilized small particles and aggregated to form larger particles. Dissolution of some small organic particles (1–2 μm) as a result by ozonation, on the other hand, may also be possible. Interesting to note, largest particle removal occurred in the BAC unit (Fig. 3) potentially as a result of its physical filtration and biodegradation functions. The average counts for particles of 2–5 μm , 5–15 μm and > 15 μm in the finished water of O₃-BAC-sand system were 331.45, 50.06 and 3.14 count/mL, respectively, in comparison with 460.4, 109.8, and 14.0 count/mL, respectively, in sand-O₃-BAC system.

COD_{Mn}

The changes in COD_{Mn} along the treatment processes are shown in Fig. 4 and details are listed in Table 2. The COD_{Mn} value of finished water in sand-O₃-BAC system was approximately 7% lower than that in O₃-BAC-sand system. The statistically significant difference shows the better COD_{Mn} removal in sand-O₃-BAC. Similarly, day-to-day monitoring data of the finished water (Fig. 5) showed consistently lower COD_{Mn} in the finished water of sand-O₃-BAC by an average of 0.12 mg/L.

The main COD_{Mn} removal in sand-O₃-BAC system occurred in coagulation-sedimentation, BAC and sand filtration (Table 3). Post-ozonation treatment only contributed a small fraction of the overall COD_{Mn} removal.

Here, ozonation functions to transfer organic molecules into smaller ones, such as acetic acid, aldehydes, and ketones, which could be assimilated into biomass in the following BAC filter [27, 28]. By contrast, in O₃-BAC-sand, COD_{Mn} was largely removed by coagulation-sedimentation and BAC, while the COD_{Mn} removal by sand filtration was negligible. It is known that sand filtration is primarily used for the removal of particles downstream of the sedimentation process unit, in which organic particles like algae and small flocs harboring organic compounds are trapped resulting in the removal of inSCOD_{Mn} [29]. Without the interception by sand filters, these particles would be oxidized directly by ozone and some would be trapped by the BAC filters.

We consider that the ozone consumption for inSCOD_{Mn} removal may have affected other unit performance such as the efficiency of bio-refractory NOM transformation by ozonation. Without the interception by sand filters in the O₃-BAC-sand system, these particles would be oxidized directly by ozone and some would be trapped by the BAC filters. The consumption of ozone by inSCOD_{Mn} could affect the removal efficiency of the bio-refractory organic compounds, including NOM, by ozonation. Moreover, BAC has actually taken on the filtration function in O₃-BAC-sand system; thus, the particle and inSCOD_{Mn} loading was higher than in sand-O₃-BAC system. The increase in particle and inSCOD_{Mn} loading to the BAC filter may change the BAC filter surfaces resulting in lower efficiency for SCOD_{Mn} biodegradation. Filter clogging also necessitates the increase in backwashing frequency, for example from once per 3 or 4 days to once a day in previous research [30], and from 102 to 72 h in this study, which would affect not only the biodegradation performance, but also the service life of BAC due to the increased wearing down of activated carbon [31].

For these reasons, the adoption of O₃-BAC with rear sand filtration in the treatment would encounter two drawbacks in COD_{Mn} removal: competition with soluble COD_{Mn} (SCOD_{Mn}) for ozone by inSCOD_{Mn}, and secondly, interference by accumulating particles in BAC to its biodegradation functions. The net result is lower COD_{Mn} removal efficiency of the rear sand filtration process (Fig. 4). To address the negative impact, Han et al. [7] suggested that up-flow BAC filtration may increase the COD_{Mn} removal by, a possibility that warrants further investigations.

Typical odorants

Over the four-month period, the FPA intensity in raw water was 5–8 for the septic odor and 4–6 for the musty odor, indicating the moderate to strong odor characteristics. In general, an FPA level of lower 3 was thought to

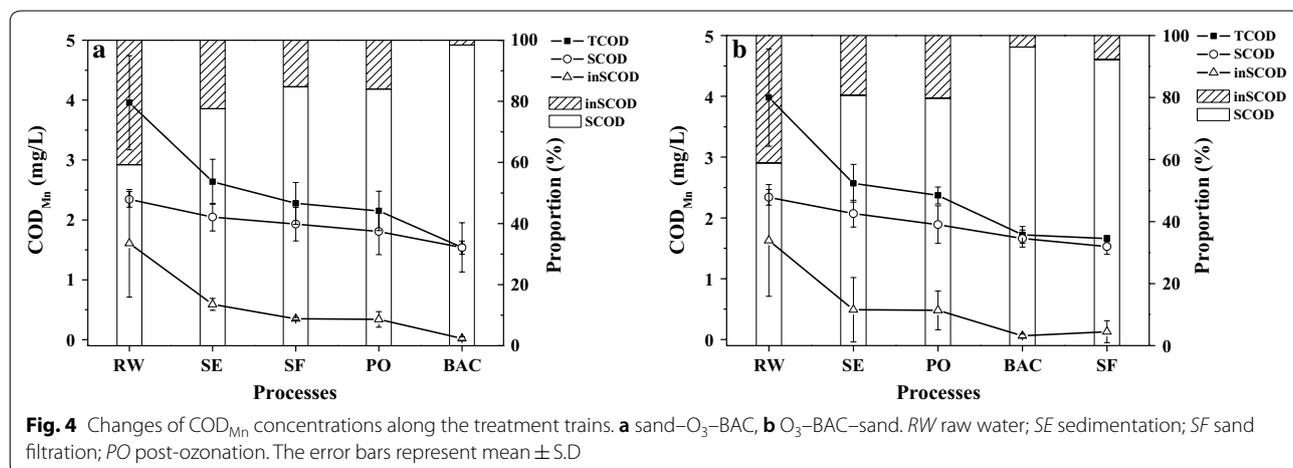
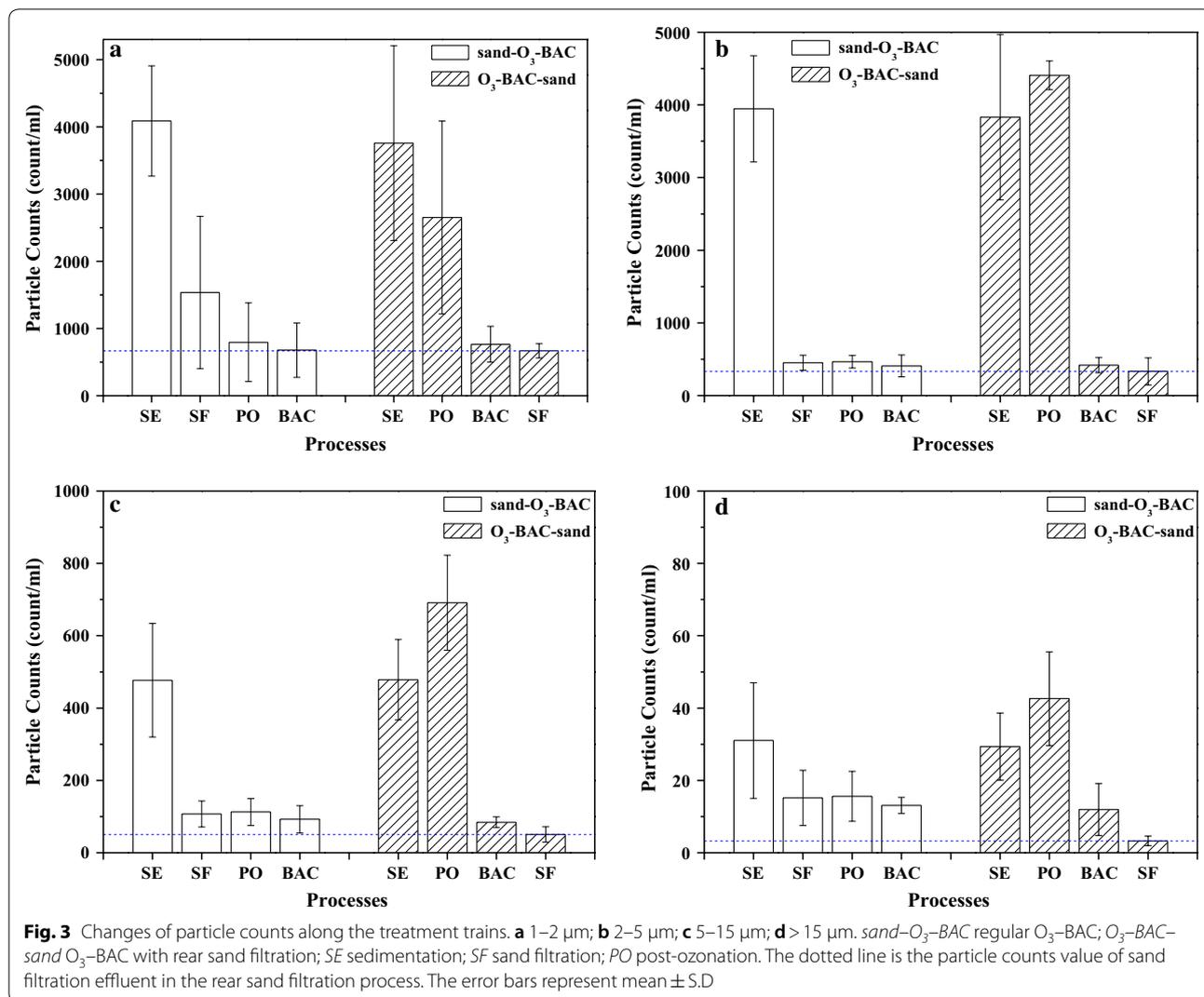


Table 2 COD_{Mn} of different fractions along the treatment processes (mg/L)

	RW	SE	SF	PO	BAC
Sand-O ₃ -BAC					
TCOD	3.96	2.64	2.28	2.15	1.56
SCOD	2.34	2.05	1.93	1.81	1.54
InSCOD	1.61	0.59	0.35	0.34	0.02
O ₃ -BAC-sand					
TCOD	3.98	2.57	1.66	2.37	1.72
SCOD	2.34	2.07	1.53	1.89	1.66
InSCOD	1.63	0.49	0.13	0.48	0.06

RW raw water, SE sedimentation, SF sand filtration, PO post-ozonation

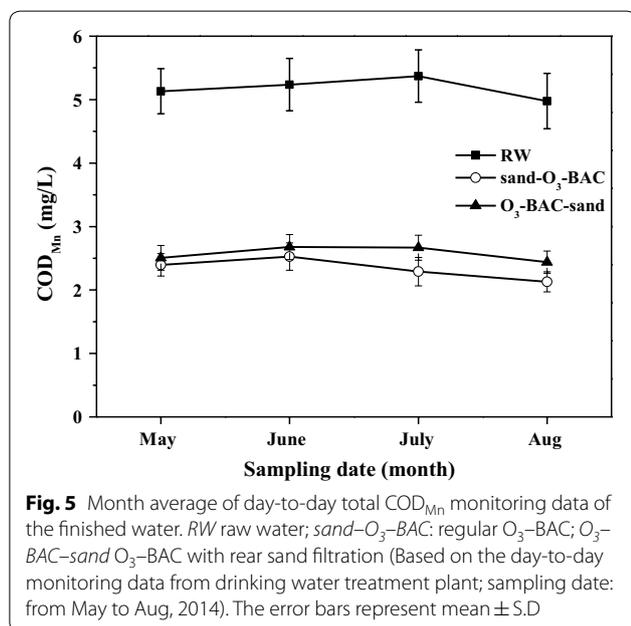


Fig. 5 Month average of day-to-day total COD_{Mn} monitoring data of the finished water. RW raw water; sand-O₃-BAC: regular O₃-BAC; O₃-BAC-sand O₃-BAC with rear sand filtration (Based on the day-to-day monitoring data from drinking water treatment plant; sampling date: from May to Aug, 2014). The error bars represent mean ± S.D

Table 3 Contribution of total COD_{Mn} removal by each unit (%)

	SE	SF	PO	BAC	Total
Sand-O ₃ -BAC	33.35	9.11	3.18	15.40	60.53
O ₃ -BAC-sand	35.44	1.55	5.00	16.23	58.22

SE sedimentation, SF sand filtration, PO post-ozonation

be acceptable for drinking water [32]. Our previous study [22] has shown the periodic occurrence of musty odor and long-term septic odor in the Huangpu River source water. The removal of the main odors and odorants by O₃ and BAC is shown in Fig. 6. While the finished water from the two systems was odorless, the odorant removal performance was different. The raw water contained 26.7–72.4 ng/L septic odorants (total concentration of

dimethyl disulfide, dimethyl trisulfide and bis (2-chloro-1-methylethyl) ether) and 9.2–15.9 ng/L musty odorant (MIB). Overall, BAC filters in sand-O₃-BAC system removed more septic and musty odorants than those in O₃-BAC-sand system. The lower odorant removal efficiency in O₃-BAC-sand system is likely attributed to the occupation of BAC surfaces by particles and the increased frequency of backwashing. The increase of backwashing frequency could decrease the biomass amount in the BAC filter, which might lead to unstable reactor performance [33]. The biomass and activity on the BAC filter might also have an impact on the odorant removal [34], which needs further investigation.

Pesticides

As shown in Table 4, among the 25 investigated, eight pesticides [machette, hexachlorobenzene (HCB), 2,2-bis (p-Chlorophenyl)-1,1,1-trichloroethane (p,p'-DDT), dimethoate, fenobucarb, dichlorvos, acetochlor, and atrazine] were detected in the raw water. The concentration ranges from 3.94 to 646.81 ng/L, similar to those of our previous study [35]. As indicated in Table 5, the removal of pesticides was mainly contributed by ozonation (19.41%) and BAC (32.09%) in sand-O₃-BAC, while the removal was by BAC in O₃-BAC-sand system (42.58%). The total removals for sand-O₃-BAC and O₃-BAC-sand were 78.43% and 70.03%, respectively.

The lower pesticide removal by ozonation in O₃-BAC-sand might be attributed to the competition for ozone by the particulate organic matters (inSCOD_{Mn}). Because of sand filtration upstream of ozonation, sand-O₃-BAC benefited from the sand filter in removal of pesticides (14.70%) that are probably adsorbed in the particles. However, for both systems, BAC showed a relatively high removal rate for the pesticides that are mostly biorefractory, mainly because of the carbon adsorption [36, 37]. Relatively, higher pesticide removal was observed in sand-O₃-BAC than O₃-BAC-sand system, suggesting that the process offers better efficiency in the removal of micropollutants like pesticides. The difference in pesticide removal can be also potentially attributable to the performance of BAC unit process. Prior to the comparative treatability study, the sand-O₃-BAC system had already been operated by 14 months more than O₃-BAC-sand system. Such BAC condition may still retain some adsorption capacity as suggested [38] in a separate study. Separately, the specific degrading microbes in the BAC filter may have possibly developed during the filter operation, yielding additional treatment capacity. Some previous studies have shown that biodegradation plays an important role in pesticide removal in the BAC process [39].

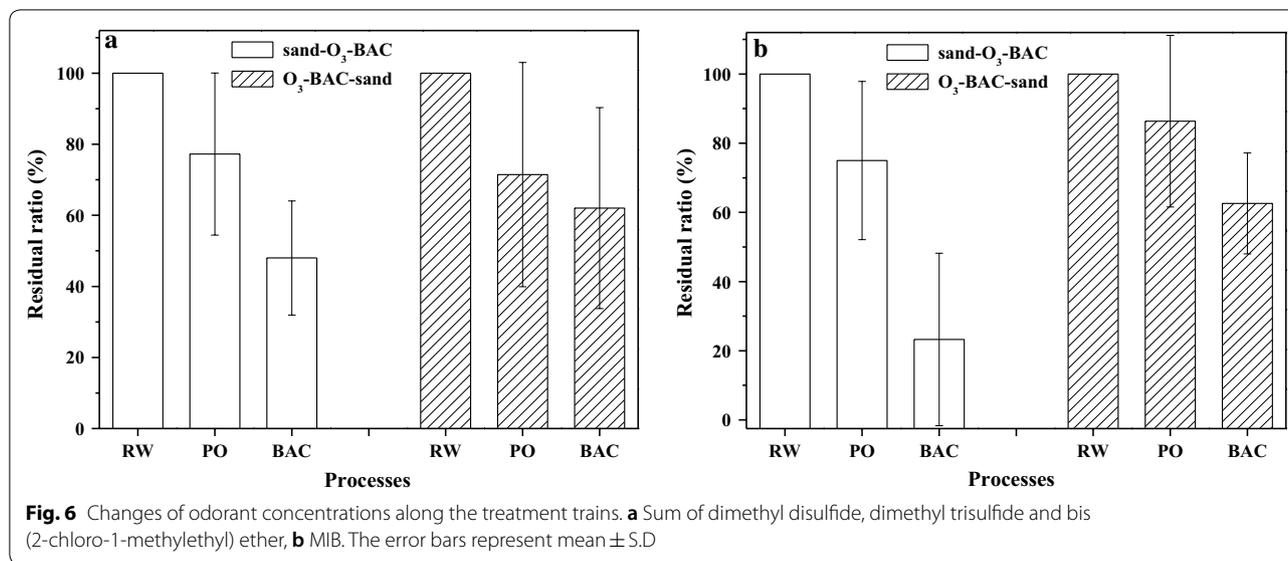


Table 4 Concentration of the detected pesticides in each treatment process (ng/L)

	Machette	HCB	p,p'-DDT	Dimethoate	Fenobucarb	Dichlorvos	Acetochlor	Atrazine
Sand-O ₃ -BAC								
RW	24.58	2.33	66.52	35.17	89.29	70.88	73.37	560.94
SE	22.88	1.78	0.00	30.19	78.96	64.82	67.82	544.09
SF	14.34	1.62	0.00	9.40	60.96	45.52	57.71	484.94
PO	14.13	1.78	0.00	8.65	31.01	36.88	50.80	352.08
BAC	10.52	0.71	0.00	6.43	17.01	25.66	34.05	104.71
O ₃ -BAC-sand								
RW	36.68	1.78	6.54	17.08	21.38	53.09	162.76	542.23
SE	24.98	1.31	11.48	18.17	22.53	56.90	140.62	444.58
PO	21.39	1.46	5.96	12.59	10.80	53.73	119.76	416.54
BAC	11.69	1.17	0.00	5.13	8.75	48.00	67.45	141.70
SF	13.01	0.99	0.00	3.47	23.23	40.23	53.53	117.70

RW raw water, SE sedimentation, SF sand filtration, PO post-ozonation

Conclusion

A comparison was conducted for the sand-O₃-BAC and the O₃-BAC-sand process in terms of their performance in the removal of particles, organic matter and micropollutants. On average, the results showed turbidity of 0.12 NTU in sand-O₃-BAC vs. 0.06 NTU in O₃-BAC-sand, and the average counts for particles of 2-5 μm, 5-15 μm and > 15 μm of O₃-BAC-sand were 331.45, 50.06 and 3.14 count/mL, respectively, compared to 460.39, 109.80, and 14.02 count/mL, respectively, in sand-O₃-BAC. However, the relocation of the sand filter might sacrifice efficiency in the removals of organic matter (by about 7%) and micropollutants. Thus, for the O₃-BAC-sand application, some

measures of enhanced coagulation should be suggested to improve the turbidity and particle removal, which would be helpful for enhancing the organic matter removal.

Abbreviations

O₃-BAC-sand: O₃-BAC with rear sand filtration; sand-O₃-BAC: regular O₃-BAC; DOC: dissolved organic carbon; COD_{Mn}: chemical oxygen demand by KMnO₄ titration; SCOD_{Mn}: soluble COD_{Mn}; inSCOD_{Mn}: insoluble COD_{Mn}; TCOD_{Mn}: total COD_{Mn}; GC/MS: gas chromatography and mass spectrometry; FPA: favor profile analysis; DMDS: dimethyl disulfide; 2-MIB: 2-methylisoborneol; GC × GC-TOFMS: comprehensive two-dimensional gas chromatography with time-of-flight mass spectrometry; HCB: hexachlorobenzene; p,p'-DDT: 2,2-bis (p-Chlorophenyl)-1,1,1-trichloroethane.

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Authors' contributions

KY designed the experiments, analyzed the data, and wrote the paper. KY, QYG, CMW, and PX mainly performed the particles, turbidity, COD_{Mn} , typical odorants and pesticides detection. YJY, JWY and MY reviewed and edited the manuscript. All authors read and approved the final manuscript.

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Availability of data and materials

Not applicable.

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare that they have no competing interests.

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References

- Peter A, von Gunten U (2007) Oxidation kinetics of selected taste and odor compounds during ozonation of drinking water. *Environ Sci Technol* 41(2):626–631
- Asami M, Aizawa T, Morioka T, Nishijima W, Tabata A, Magara Y (1999) Bromate removal during transition from new granular activated carbon (GAC) to biological activated carbon (BAC). *Water Res* 33(12):2797–2804
- Liao X, Chen C, Zhang J, Dai Y, Zhang X, Xie S (2015) Operational performance, biomass and microbial community structure: impacts of backwashing on drinking water biofilter. *Environ Sci Pollut Res* 22(1):546–554
- Schreiber H, Schoenen D, Traunspurger W (1997) Invertebrate colonization of granular activated carbon filters. *Water Res* 31(4):743–748
- Kwon S, Moon E, Kim TS, Hong S, Park HD (2011) Pyrosequencing demonstrated complex microbial communities in a membrane filtration system for a drinking water treatment plant. *Microbes Environ* 26(2):149–155
- Lu S, Shao Z, Zhong G, Chen J, Yang J, Guo J (2011) BAC filtration—disinfection—sand filtration combination technology for handling risk of microorganism leak in O₃-BAC process. In: International conference on multimedia technology
- Han L, Liu W, Chen M, Zhang M, Liu S, Sun R, Fei X (2013) Comparison of NOM removal and microbial properties in up-flow/down-flow BAC filter. *Water Res* 47(14):4861–4868
- Lu S, Chen X, Yang J, Chen J, Zhong G, Li S, Liao W (2011) Analysis of mid-positioning BAC filter technology. In: International conference on multimedia technology
- Jie Z, Chen H, Chen C, Dai X (2014) Study on the migration and inactivation of invertebrates in the advanced treatment process in waterworks. *Fresenius Environ Bull* 23(6):1314–1321
- Hong S, Tang XC, Wu NX, Chen HB (2018) Leakage of soluble microbial products from biological activated carbon filtration in drinking water treatment plants and its influence on health risks. *Chemosphere* 202:626–636
- Li C (2014) The Application of advanced treatment by ozonation and activated carbon combined process of southeast water plant in Fuzhou. *Fujian Archit Constr* 7:55–57
- Han L (2013) Full-scale Study of Yellow River reservoir water treatment with ozone-activated carbon rear-set sand filtration process. Shandong Jianzhu University
- Zhu H, Xu B, Shen L, Sun H, Ma Z, Zha R (2009) Process introduction of Guanqing waterworks of Jiaying city. *Water Wastewater Eng* 45(03):28–31
- Wotton RS (2002) Water purification using sand. *Hydrobiologia* 469(1):193–201
- Huerta-Fontela M, Galceran MT, Ventura F (2011) Occurrence and removal of pharmaceuticals and hormones through drinking water treatment. *Water Res* 45(3):1432–1442
- Nam SW, Jo BI, Yoon Y, Zoh KD (2014) Occurrence and removal of selected micropollutants in a water treatment plant. *Chemosphere* 95(1):156–165
- Nakada N, Shinohara H, Murata A, Kiri K, Managaki S, Sato N, Takada H (2007) Removal of selected pharmaceuticals and personal care products (PPCPs) and endocrine-disrupting chemicals (EDCs) during sand filtration and ozonation at a municipal sewage treatment plant. *Water Res* 41(19):4373–4382
- Nishijima W, Okada M (1998) Particle separation as a pretreatment of an advanced drinking water treatment process by ozonation and biological activated carbon. *Water Sci Technol* 37(10):117–124
- Yu Z (2011) Characteristics of the occurrence and health risk assessment of pesticides in drinking water and fish of China's major cities. Graduate University of Chinese Academy of Sciences
- APHA (2005) Standard methods for examination of water and wastewater. American Public Health Association, Washington DC
- Guo Q, Li X, Yu J, Zhang H, Zhang Y, Yang M, Lu N, Zhang D (2015) Comprehensive two-dimensional gas chromatography with time-of-flight mass spectrometry for the screening of potent swampy/septic odor-causing compounds in two drinking water sources in China. *Anal Methods* 7(6):2458–2468
- Guo Q, Yang K, Yu J, Wang C, Wen X, Zhang L, Yang M, Xia P, Zhang D (2016) Simultaneous removal of multiple odorants from source water suffering from septic and musty odors: verification in a full-scale water treatment plant with ozonation. *Water Res* 100:1–6
- Yan M, Wang D, Shi B, Wang M, Yan Y (2007) Effect of pre-ozonation on optimized coagulation of a typical North-China source water. *Chemosphere* 69(11):1695–1702
- Snider EH, Porter JJ (1974) Ozone treatment of dye waste. *J Water Pollut Control Fed* 46(5):886–894
- Roccaro P, Barone C, Mancini G, Vagliasindi FGA (2007) Removal of manganese from water supplies intended for human consumption: a case study. *Desalination* 210(1–3):205–214
- Jekel MR (1983) The benefits of ozone treatment prior to flocculation processes. *Ozone Sci Eng* 5(1):21–35
- de Souza SM, Bonilla KA, de Souza AA (2010) Removal of COD and color from hydrolyzed textile azo dye by combined ozonation and biological treatment. *J Hazard Mater* 179(1–3):35–42
- Liao XB, Zhang XJ, Wang J, Li XB, Wang CK, Chen C (2013) Application of conventional and O₃-BAC processes to treat organic matter and antibiotic pollutants in a lake in East China. *Water Sci Technol Water Supply* 13(6):1470–1477
- Hamoda MF, Al-Ghusain I, Al-Mutairi NZ (2004) Sand filtration of wastewater for tertiary treatment and water reuse. *Desalination* 164(3):203–211
- Niquette P, Prévost M, Maclean RG, Thibault D, Coallier J, Desjardins R, Lafrance P (1998) Backwashing first-stage sand-BAC filters. *J Am Water Works Assoc* 90(1):86–97
- Ek M, Baresel C, Magnér J, Bergström R, Harding M (2014) Activated carbon for the removal of pharmaceutical residues from treated wastewater. *Water Sci Technol* 69(11):2372–2380
- Suffet IH, Schweitze L, Khiari D (2004) Olfactory and chemical analysis of taste and odor episodes in drinking water supplies. *Biotechnology* 3(1):3–13
- Lahav O, Artzi E, Tarre S, Green M (2001) Ammonium removal using a novel unsaturated flow biological filter with passive aeration. *Water Res* 35(2):397–404
- Ikhlef S, Basu OD (2017) Influence of Backwash Regime on Biofilter Performance in Drinking Water Treatment. *J Chem Technol Biot* 92(7):1777–1784

35. Yang K, Yu J, Guo Q, Wang C, Yang M, Zhang Y, Xia P, Zhang D, Yu Z (2017) Comparison of micropollutants' removal performance between pre-ozonation and post-ozonation using a pilot study. *Water Res* 111:147–153
36. Chien CC, Kao CM, Chen CW, Dong CD, Wu CY (2008) Application of biofiltration system on AOC removal: Column and field studies. *Chemosphere* 71(9):1786–1793
37. Lim TT, Yap PS (2016) Treatment of RO concentrate for enhanced water recovery from wastewater treatment plant effluent. Springer, Berlin Heidelberg, pp 1–22
38. Kim WH, Nishijima W, Baes AU, Okada M (1997) Micropollutant removal with saturated biological activated carbon (BAC) in ozonation-BAC process. *Water Sci Technol* 36(12):283–298
39. van der Hoek JP, Hofman JAMH, Graveland A (1999) The use of biological activated carbon filtration for the removal of natural organic matter and organic micropollutants from water. *Water Sci Technol* 40(9):257–264

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