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Research Article / Araştırma Makalesi

EFFECTS OF VARYING INLET IRON AND MANGANESE CONCENTRATIONS ON SLOW SAND FILTER PERFORMANCE

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ABSTRACT

In this study a laboratory-scale slow sand filter (SSF) is used for removal of iron and manganese and the effects of various inlet concentrations on removal efficiency were investigated. SSF was operated at a filtration rate of 0.2 $m.h^{-1}$ with two different synthetic inlet waters (Run1 and Run2). Iron and manganese concentrations in two runs were 1.09±0.13$mg.L^{-1}$–1.06±0.10 $mg.L^{-1}$ for Run1 and 2.02±0.15 $mg.L^{-1}$–2.10±0.14 $mg.L^{-1}$ for Run2. In Run1, the removal efficiencies of 96.3±2.48%, 92.3±6.1%, 92.6±5.7%, and 55.3±8.3% were obtained for turbidity, iron, manganese and total organic carbon (TOC), respectively. In Run2, on the other hand, the removal efficiencies were obtained as 97.9±1.3%, 93.1±8.1%, 94.4±5.8%, and 55.5±6.8%, respectively. Results suggested that the SSF was the most efficient in turbidity removal at a filtration rate of 0.2 $m.h^{-1}$. Sequence analyses of DGGE bands from Run1 and Run2 were also performed and results indicated that a range of bacteria were present, with 16S rRNA gene sequences similar to groups such as G*allionella*, *Leptothrix*, *Crenothrix*, and an uncharacterized environmental clone.
Keywords: Slow sand filter, iron-manganese removal, microbial community, schmutzdecke.

FARKLI GİRİŞ DEMİR VE MANGAN KONSANTRASYONLARININ YAVAŞ KUM FİLTRESİ PERFORMANSINA ETKİLERİ

ÖZ

Bu çalışmada demir ve mangan giderimi için laboratuvar ölçekli yavaş kum filtresi kullanılmış ve farklı giriş konsantrasyonlarının filtre verimi üzerine etkisi araştırılmıştır. Yavaş kum filtresi, 0,2 $m.sa^{-1}$ filtrasyon hızında iki farklı sentetik giriş suyu ile çalıştırılmıştır (Run1 ve Run2). Sentetik giriş sularındaki demir ve mangan konsantrasyonları sırasıyla 1,09±0,13$mg.L^{-1}$ ve 1,06±0,10 $mg.L^{-1}$ (Run1) ile 2,02±0,15 $mg.L^{-1}$ ve 2,10±0,14 $mg.L^{-1}$ (Run2) olarak belirlenmiştir. Run1 için bulanıklık, demir, mangan ve toplam organik karbon (TOK) giderim verimleri sırasıyla %96,3±2,48; %92,3±6,1; %92,6±5,7 ve %55,3±8,3 olarak belirlenmiştir. Run2 için ise giderim verimleri sırasıyla %97,9±1,3; %93,1±8,1; %94,4±5,8 ve %55,5±6,8 olarak hesaplanmıştır. Sonuçlara göre, 0,2 $m.sa^{-1}$ filtrasyon hızında çalıştırılan yavaş kum filtresi bulanıklık giderimi açısından en yüksek verimle çalışmıştır. Run1 ve Run2 için elde edilen DGGE bantlarında sekans analizleri de gerçekleştirilmiş olup, sekans analizi neticesinde G*allionella*, *Leptothrix*, *Crenothrix* ve henüz tanımlanmamış mikrobiyal türlerin arıtımdan sorumlu olduğu tespit edilmiştir.
Anahtar Sözcükler: Yavaş kum filtresi, demir-mangan giderimi, mikrobiyal topluluk, schmutzdecke.

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1. INTRODUCTION

Virtually all natural waters including surface waters, soil pore waters, and groundwaters [1] contain colloidal particles. Groundwater sources, being one of the most important drinking water source all over the world [2, 3], are facing contamination by a number of heavy metals (e.g., As, Fe, and Mn). Ma et al. [1] reported from previous studies that colloidal matter facilitates the transport of contaminants (e.g., heavy metals, radioactive pollutants, and organic matter). Hedegaard et al. [2] stated that groundwaters usually require treatment before using due to the fact that concentrations of inorganic and organic compounds such as iron (II), manganese (II), ammonium, arsenic and pesticides may exceed drinking water guidelines [4]. The presence of these metals in high concentrations in water sources prevents their use as potable water sources. More importantly, the use of such waters containing iron and manganese can result in congestion in the transmission lines and several health problems.

Slow sand filtration is a commonly used technique for water treatment, which employs physical, chemical and biological mechanisms [5]. Slow sand filters have been proven to offer the advantages of simple construction and maintenance as well as low operating costs [6]. Nitzsche et al. [7] reported the use of household sand filters as low-cost and efficient method for removing As, Fe, and Mn from groundwater in rural areas of Vietnam. In Europe, on the other hand, the most commonly employed technique for manganese removal is conventional aeration-rapid sand filtration. This technique is also advantageous in that, because no chemicals ($KMnO_4$, O_3, Cl_2) are utilized, it offers a cost-effective and environmentally friendly solution for oxidation of Mn^{2+}. During the period of ripening of virgin filter media, the efficiency of manganese removal in slow sand filtration strongly depends on the ability of filter media to adsorb dissolved manganese [8].

Slow sand filters can be built from easily accessible materials. Besides, their simple construction and operation as well as low operating costs make them very advantageous for water treatment. Nitzsche et al. [9] reported that water demand of a single household can be treated within a few minutes.

Mechanisms of treatment in sand filtration involve physical entrapment, gravity settling, adsorption, impaction, interception, straining and flocculation. The treatment occurs within the upper few millimeters of bed depth [10]. At the surface of slow sand filters forms the schmutzdecke, which is a layer of gelatinous structure typically containing sand particles, humus, algae and other microorganisms and it is the region where most of the bacterial action takes place [6]. Since the degree of treatment is closely related with the development and activity of the schmutzdecke, identification of microbial species enrolled in iron and manganese removal in slow sand filters is of great importance for improved treatment performances.

The aim of this study is to investigate the removal of iron and manganese from drinking water by slow sand filtration. For this purpose, a laboratory-scale slow sand filter was operated at a filtration rate of 0.2 $m.h^{-1}$ with synthetic water containing 1 and 2 $mg.L^{-1}$ of iron and manganese. In addition to the investigation of the relationship between removal efficiency and headloss, microbial species that are responsible for the treatment were also determined.

2. MATERIALS AND METHODS

2.1. Slow Sand Filter

The laboratory-scale slow sand filter system consists of two parallel units with dimensions 40 cm x 60 cm x 50 cm and it was operated as effluent-controlled, constant-flowrate filter. Influent water from raw water tank was fed to the system by a peristaltic pump and a common feed pipe. Periodic cleaning was performed in feeding system. A stainless steel screen that has 80 μm openings was placed on top of the nozzles to prevent sand and gravel loss. The bed consists of

the sand layer with 37.5 cm depth (0.1 mm silica sand) over 12.5 cm of gravel layer (3-4 mm), as shown in Fig. 1. A detailed design of the SSF system was previously given in Manav Demir [11].

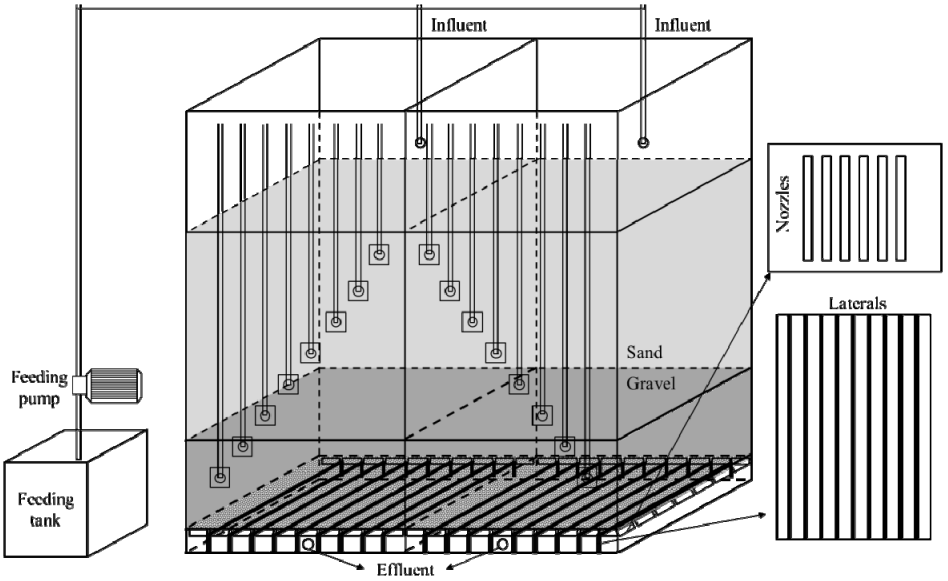

Figure 1. Laboratory-scale slow sand filter system

The slow sand filters were operated for at a filtration rate of 0.2 $m.h^{-1}$ with synthetic waters containing about 1 $mg.L^{-1}$ Fe-Mn for Run1, and about 2 $mg.L^{-1}$ Fe-Mn for Run2. $FeSO_4.7H_2O$ and $MnSO_4.H_2O$ were added to water to obtain desired concentrations of iron and manganese. For turbidity, kaolin was added to water. The system was operated for a period of 55 days in each run. Results of analyses in synthetic water are given in Table 1.

Table 1. Characterization of synthetic water used in this study

0.2 $m.h^{-1}$	Run1 (1 $mg.L^{-1}$ Fe-Mn)				Run2 (2 $mg.L^{-1}$ Fe-Mn)			
	Turbidity	Iron	Manganese	TOC	Turbidity	Iron	Manganese	TOC
	NTU	$mg.L^{-1}$	$mg.L^{-1}$	$mg.L^{-1}$	NTU	$mg.L^{-1}$	$mg.L^{-1}$	$mg.L^{-1}$
Mean[a]	10.10	1.09	1.06	3.25	10.90	2.02	2.10	3.36
STD[b]	1.70	0.13	0.10	0.31	1.50	0.15	0.14	0.27
Min.	7.10	0.88	0.90	3.04	7.83	1.64	1.85	3.08
Q1[c]	8.40	1.02	1.01	3.09	9.60	1.93	2.01	3.19
Q2[d]	10.30	1.08	1.05	3.14	10.80	2.05	2.08	3.33
Q3[e]	11.20	1.18	1.09	3.24	12.15	2.12	2.18	3.41
Max.	14.10	1.56	1.35	3.99	14.60	2.36	2.48	3.95

[a]Average value in 55 samples
[b]STD: Standard deviation from 55 data points
[c]Q1: First quartile
[d]Q2: Median value
[e]Q3: Third quartile

2.2. Analysis of the Influent and Effluent of the Two SSF Operation

Influent and effluent samples were collected and analyzed for turbidity, iron, and manganese. Turbidity, iron, and manganese analysis was performed daily and the TOC analysis was performed weekly. A WTW Turb 550 IR turbidimeter was used for turbidity measurements. Total iron and manganese (soluble and insoluble) concentrations were measured by atomic absorption spectroscopy (Perkin Elmer Aanalyst 400) after the samples were prepared by acid digestion (Berghof Products + Instruments GmbH). Total organic carbon (TOC) was determined using a TOC analyzer (HACH Lange IL 550 TOC-TN Analyser, Germany). Headloss measurements were performed by manometers (plexiglass tubes) placed on the outer wall of the filters vertically at 6 cm intervals (Fig. 1).

2.3. Molecular Characterization of Microbial Community

Samples were collected from different depths of the filter bed from surface (52.5 cm – surface, 51 cm, and 44 cm). The identification of the bacteria in the mixed culture was performed using DNA extraction and PCR-DGGE (polymerase chain reaction-denaturing gradient gel electrophoresis) of partial 16S rRNA genes followed by their sequencing. DNA was extracted from the samples with an MN Nucleospin soil DNA isolation kit (Macherey-Nagel GmbH & Co. KG). Amplification of partial bacterial 16S rRNA genes of the community DNA, DGGE and analysis of sequence data were performed as previously described by Manav Demir [11].

3. RESULTS AND DISCUSSION

3.1. Turbidity and TOC Removal

During Run1, the highest and the lowest turbidity values observed in filter effluent were 0.85 NTU and 0.04 NTU, respectively. The turbidity removal efficiency was calculated as 96.3±2.4%. In Run2, the highest and the lowest effluent turbidities were 0.12 NTU and 0.08 NTU while a turbidity removal efficiency of 97.9±1.3% was calculated. The changes in influent and effluent turbidities measured during the operating period are shown in Fig. 2a for both Run1 and Run2. The determination coefficients (R^2) between removal efficiency and influent turbidity were calculated as 0.316 and 0.111 (correlation coefficients as 0.562 and 0.334) for Run1 and Run2, respectively. Results showed, for both runs, that turbidity removal efficiency is independent of influent turbidity. Similarly, the determination coefficients between removal efficiency and headloss, which is a measure of solids accumulation and filter clogging, were calculated as 0.082 and 0.093 for Run1 and Run2, respectively. Similar to that of influent turbidity, results indicated no significant dependency of removal efficiency on filter headloss. Turbidity removal efficiency of SSF was high starting from the beginning of operation and did not show significant changes during the operation. Average effluent TOC concentrations in Run1 and Run2 were calculated as 1.4±0.2 $mg.L^{-1}$ and 1.5±0.3 $mg.L^{-1}$, respectively, with average removal efficiencies of 55.3±8.3% and 55.5±6.8%, respectively (Fig. 2b).

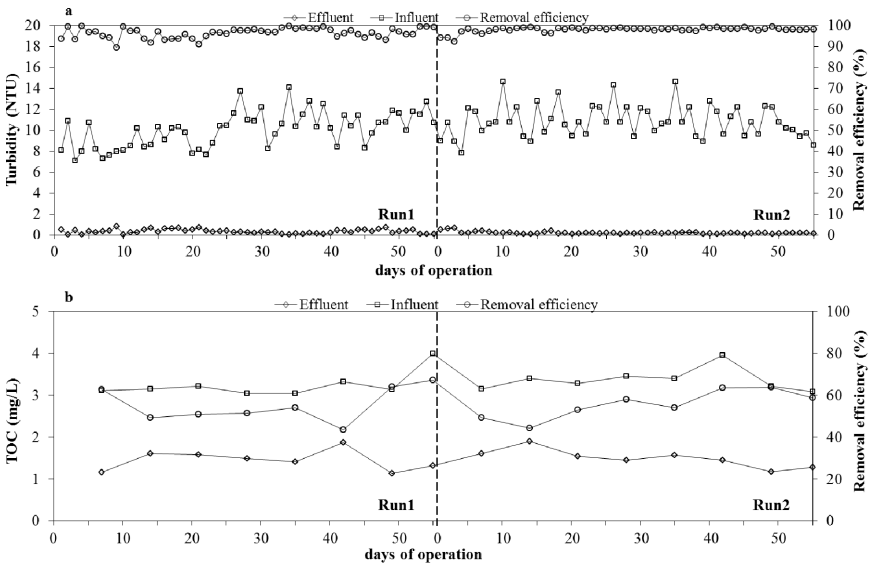

Figure 2. Experimental results of turbidity and TOC removal in SSF. (a) influent and effluent turbidities as well as removal efficiencies, (b) influent and effluent TOC concentrations as well as TOC removal efficiencies

3.2. Iron Removal

Average iron removal efficiencies in Run1 and Run2 were calculated as 92.3±6.06% and 93.1±8.11%, respectively, with effluent iron concentrations of 0.08±+0.05 $mg.L^{-1}$ and 0.13±0.15 $mg.L^{-1}$, respectively. Fig. 3 shows the changes in influent and effluent iron concentrations as well as iron removal efficiencies during Run1 and Run2. Results suggested that no significant correlation between influent iron concentration and iron removal efficiency. The determination coefficients were calculated as 0.109 and 0.032 correlation coefficients as 0.331 and 0.178) for Run1 and Run2, respectively, which indicates a very weak correlation between these operating parameters. For filter headloss, the determination coefficients were calculated as 0.306 and 0.258 (correlation coefficients as 0.553 and 0.508) for Run1 and Run2, respectively. The calculated values showed that iron removal efficiency increases with increasing level of clogging, which indicates a strong correlation between these two operating parameters. Iron removal efficiency increased rapidly in the first stages of operation while no significant changes were observed after a certain period of operation.

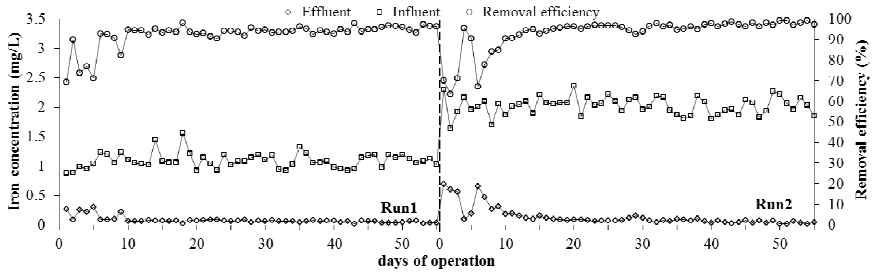

Figure 3. Experimental results of iron removal in SSF: influent and effluent iron concentrations as well as removal efficiencies.

3.3. Manganese Removal

The changes in manganese concentrations in SSF influent and effluent as well as manganese removal efficiencies for Run1 and Run2 are shown in Fig. 4. Average manganese removal efficiencies were calculated as 92.7±5.7% and 94.3±5.7% for Run1 and Run2, respectively. Clearly, there is no significant dependency between influent manganese concentration and manganese removal efficiency as the coefficients of determination were calculated as 0.004 and 0.000 (correlation coefficients as 0.063 and -0.007) for Run1 and Run2, respectively. On the other hand, the correlation coefficients between manganese removal efficiency and filter headloss were calculated as 0.604 and 0.605 (coefficients of determination as 0.365) for Run1 and Run2, respectively, which indicates a good correlation between these two operating parameters. Clearly, manganese removal efficiency increases with increasing level of solids accumulation in filter bed (clogging).

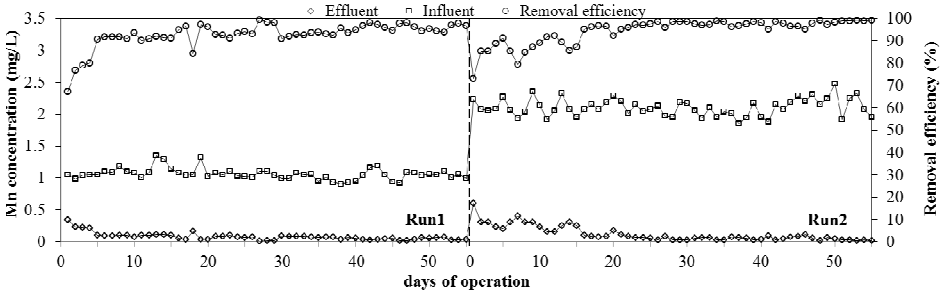

Figure 4. Experimental results of manganese removal in SSF: influent and effluent manganese concentrations as well as removal efficiencies.

3.4. Headloss

One of the important operating parameters for assessing SSF performance is the filter headloss. The changes in filter headloss with bed depth along with measured values are shown in Fig. 5 in both Run1 and Run2. Headloss increases with increasing depth from the surface of the filter bed. It is clear that, at constant filtration rate, the headloss through SSF increases with increasing iron and manganese concentrations. It is clear that schmutzdecke is the most important contributor to the headloss through SSF. After 55 days of operation in Run1 and Run2, the headloss through the SSF reached 14 cm and 24 cm, respectively, which suggests that an increase in iron and manganese concentration results in increased headloss through SSF. The results suggested that a two-fold increase in iron and manganese concentration leads to about a two-fold increase in headloss.

3.5. Microbial community

Information on bacterial communities that contribute to high treatment efficiency in slow sand filters is limited. Microbial community was also identified in laboratory-scale SSF. It is possible by DGGE technique to separate various sequences in a DNA sample. In DGGE, the number of bands corresponds to microbial diversity in the sample while each band represents a dominant microbial species. In sequencing results of DNA samples from DGGE, clustering was performed to identify similarities and a high similarity (> 92%) of the major bacterial species was obtained in samples from SSF for both Run1 and Run2.

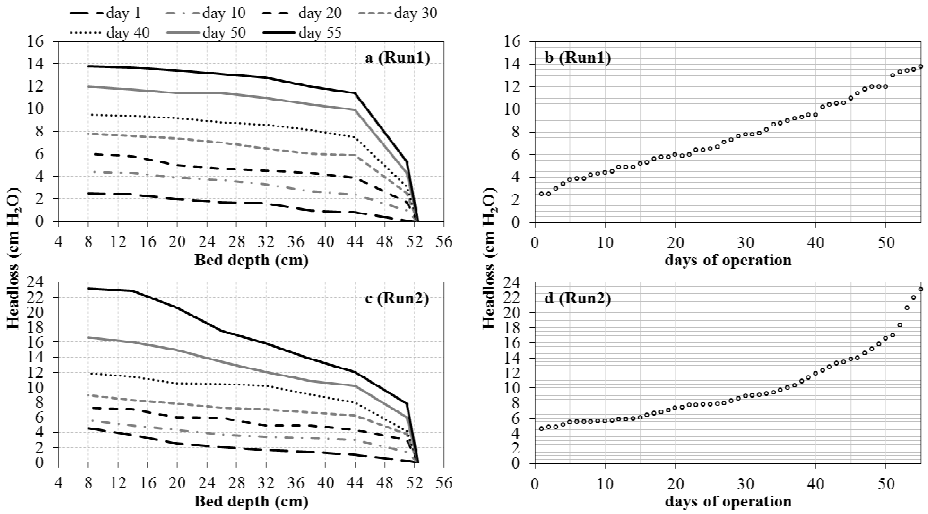

Figure 5. (a) The change in headloss at manometer ports with respect to depth in various days of operation for Run1, (b) total filter headloss with respect to time for Run1, (c) the change in headloss at manometer ports with respect to depth in various days of operation for Run2, (b) total filter headloss with respect to time for Run2.

Ten sequences from Run1 and eleven sequences from Run2 were obtained during the operation. Fig. 6 shows DGGE profile of the samples from various depths. For Run1 and Run2, microbial communities in schmutzdecke were not significantly different. For both runs, the microbial diversity decreases with increasing depth from the surface. The sequences obtained are used for comparative analyses in BLAST software and results are shown in Table 2.

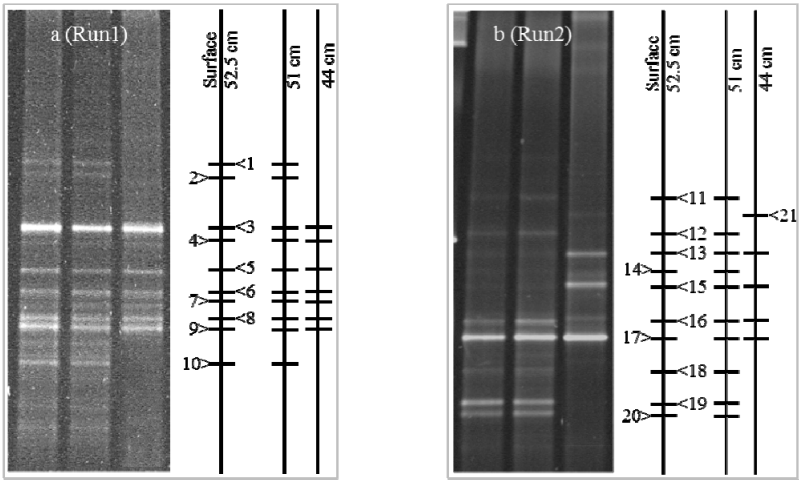

Figure 6. DGGE profiles of 16S rDNA amplified using the total genomic DNA extracted from schmutzdecke and sand collected from two systems (Run1 and Run2)

Table 2. Phylogenetic sequence affiliation and similarity to the closest relative of amplified 16S rRNA gene sequences excised from DGGE gels

Band	Access no	Microorganism name / Organism	Sim. %	Isolation source	Reference
		Run1			
1	KF515099	*uncultured bacterium* / Bacteria	96	a	[12]
2	JF429322	*uncultured bacterium* / Bacteria	95	b	[13]
3	AB252929	*uncultured Gallionella sp.* / Betaproteobacteria	93	c	[14]
4	FM878000	*uncultured Gallionella sp.* / Betaproteobacteria	92	-	[15]
5	LN543247	*uncultured bacterium* / Bacteria	94	d	[16]
6	KF611948	*uncultured bacterium* / Bacteria	94	e	[17]
7	AB670152	*uncultured Gallionella sp.* / Betaproteobacteria	100	f	[18]
8	GU747260	*uncultured bacterium* / Bacteria	99	g	[19]
9	JQ288616	*Uncultured Leptothrix sp.* / Betaproteobacteria	100	h	[20]
10	Z25774	*Leptothrix discophora* / Betaproteobacteria	100	-	[21]
		Run2			
11	AB670152	*uncultured Gallionella sp.* / Betaproteobacteria	100	f	[18]
12	JN936833	*uncultured Crenothrix sp.* / Gammaproteobacteria	100	i	[22]
13	HQ117914	*uncultured Gallionella sp.* / Betaproteobacteria	96	j	[23]
14	LN543247	*uncultured bacterium* / Bacteria	94	d	[16]
15	KJ670675	*uncultured bacterium* / Bacteria	96	k	[24]
16	Z25774	*Leptothrix discophora* / Betaproteobacteria	100	-	[21]
17	AB252929	*uncultured Gallionella sp.* / Betaproteobacteria	93	c	[14]
18	JQ288616	*uncultured Leptothrix sp.* / Betaproteobacteria	100	h	[20]
19	GU572372	*uncultured Leptothrix sp.* / Betaproteobacteria	95	l	[25]
20	GU747260	*uncultured bacterium* / Bacteria	99	g	[19]
21	KF611948	*uncultured bacterium* / Bacteria	94	e	[17]

a: drinking water, b: source of drinking water, c: Iron-oxidation biofilm, d: rapid sand filter of groundwater treatment, e: biofilm in drinking water distribution system, f: an Fe biofilm, g: drinking water (treatment 1), h: full-scale drinking water treatment plant green sand filter media, i: drinking water sludge, j: coastal shallow groundwater, k: BioTrap samplers in groundwater monitoring well, l: an Fe-rich seep

The bands 3, 4, 7, 11, 13, and 17 were identified as *Gallionella* sp., which is reported to be the species responsible for iron oxidation in water treatment processes [23, 18, 11]. *Gallionella* sp. were identified in both Run1 and Run2. Katsoyiannis and Zouboulis [26] reported that *Leptothrix* sp., which are identified in DGGE bands 9, 10, 16, 18, and 19, contribute to both iron and manganese oxidation in water treatment processes. The 12th band was identified as *Crenothrix* sp. and these species were reported to be one of the species contributing both iron and manganese removal [27]. The bands 1, 2, 5, 6, 8, 14, 15, 20, and 21 were identified as uncultured bacteria, which are reported in groundwaters and drinking water treatment processes.

3.6. Discussion

Differences between effluent turbidity and turbidity removal efficiencies were observed between Run1 and Run2. For Run2, higher concentrations of Fe and Mn (2 mg.L^{-1}) lead to rapid increase in headloss and it stabilized after the 10th days of operation. In both runs, turbidity removal efficiencies were observed to be over 90%. It can be concluded that slow sand filtration is an efficient method for turbidity removal in low filtration rates. Effluent concentrations of iron and manganese showed decreasing trends with time in both runs. Removal of iron in the filter and expansion of schmutzdecke resulted in significant reduction in porosity of filter bed, therefore leading to gradually decreasing effluent concentrations. In Run2, clogging was quicker than Run1 because of higher influent iron and manganese concentrations in Run2, with removal

efficiencies over 90% in both runs. Results from similar studies are given in Table 3 and compared with results of this study.

Table 3. Comparison of results from current study with the literature data

Ref. (Process)	Water source	Filtration rate (m/h)	Influent conc. ($mg.L^{-1}$)	Removal efficiency			
				Turbidity	Iron	Manganese	Organic matter
This study (SSF-Run1)	Synthetic	0.2	Fe= 1.09 Mn= 1.06	96.3±2.4%	92.3±6.06%	92.7±5.7%	55.3±8.3% (TOC)
This study (SSF-Run2)		0.2	Fe= 2.02 Mn= 2.10	97.9±1.3%	93.1±8.11%	94.3±5.7%	55.5±6.8% (TOC)
[28] (SSF)	-	-	-	< 1,0 NTU	> 67%	> 67%	< 50% (DOC)
[4] (SSF)	-	-	-	-	45%	45%	48% (TOC)
[29] (SSF)	-	-	-	< 1,0 NTU	Largely removed	Largely removed	60-75% reduction in COD
[30] (SSF)	-	-	-	< 1 NTU	30 – 90%	30 – 90%	< 15 – 25% (TOC)
[31] (PAC-MBR)	Groundwater	5	Fe^{2+}= 10-17 Mn^{2+}= 0.8-1.4	-	> 98.7%	> 91.7%	-
[32] (Biofilter)	Groundwater	3, 4, 5	Fe^{2+}= 0.8-1.5 Mn^{2+}= 1.0-1.2	-	96.2	97.7	-
[33] (GAC)	River	7.2	TOC= 3.0-3.5	-	-	-	65% (TOC) 77% (DOC)

SSF: Slow sand Filter
PAC-MBR: Powdered activated carbon-amended membrane bioreactor
GAC: Granular activated carbon
DOC: Dissolved organic carbon

4. CONCLUSIONS

Following conclusions can be withdrawn from the results of this study.

- Turbidity removal efficiency of SSF is satisfactory immediately after starting the filter and the removal efficiency is independent of influent concentrations.
- Iron and manganese removal efficiencies are not functions of influent concentrations. The performance of the filter in iron and manganese removal rely on the level of clogging of SSF and after a certain level no significant changes are observed in removal efficiencies.
- *Gallionella* sp., *Leptothrix* sp., *Crenothrix* sp., and *uncultured bacteria* were identified in the laboratory-scale SSF, which contribute to iron and manganese removal in the filter. Therefore, they play major roles in the removal of iron and manganese in the slow sand filter. This information could help future researchers design slow sand filters with selected microbial species for better performance.

The results showed that slow sand filters can be used successfully for iron and manganese removal from groundwaters.

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REFERENCES / KAYNAKLAR

[1] Ma J., Guo H., Lei M., Wan X., Zhang H., Feng X., Wei R., Tian L., Han X., (2016) Blocking effect of colloids on arsenate adsorption during co-transport through saturated sand columns, *Environmental Pollution* 213, 638-647.

[2] Hedegaard M.J., Arvin E., Corfitzen C.B., Albrechtsen H.J., (2014) Mecoprop (MCPP) removal in full-scale rapid sand filters at a groundwater-based waterworks, *Science of the Total Environment* 499, 257–264.

[3] Albers C.N., Feld L., Ellegaard-Jensen L., Aamand J., (2015) Degradation of trace concentrations of the persistent groundwater pollutant 2,6-dichlorobenzamide (BAM) in bioaugmented rapid sand filters, *Water Research* 83, 61-70.
[4] EPA Storm Water Technology Fact Sheet Sand Filters, EPA 832-F-99-007, 1999.
[5] Grace M.A., Healy M.G., Clifford E., (2016) Performance and surface clogging in intermittently loaded and slow sand filters containing novel media, *Journal of Environmental Management* 180, 102-110.
[6] D'Alessio M., Yoneyama B., Kirs M., Kisand V., Ray C., (2015) Pharmaceutically active compounds: Their removal during slow sand filtration and their impact on slow sand filtration bacterial removal, *Science of the Total Environment* 524–525, 124–135.
[7] Nitzsche K.S., Weigold P., Lösekann-Behrens T., Kappler A., Behrens S., (2015) Microbial community composition of a household sand filter used for arsenic, iron, and manganese removal from groundwater in Vietnam, *Chemosphere* 138, 47–59.
[8] Bruins J.H., Petrusevski B., Slokar Y.M., Huysman K., Joris K., Kruithof J.C., Kennedy M.D., (2015) Biological and physico-chemical formation of Birnessite during the ripening of manganese removal filters, *Water Research* 69, 154-161.
[9] Nitzsche K.S., Lan V.M., Trang P.T.K., Viet P.H., Berg M., Voegelin A., Planer-Friedrich B., Zahoransky J., Müller S.K., Byrne J.M., Schröder C., Behrens S., Kappler A., (2015) Arsenic removal from drinking water by a household sand filter in Vietnam — Effect of filter usage practices on arsenic removal efficiency and microbiological water quality, *Science of the Total Environment* 502, 526–536.
[10] Patil D.S., Chavan S.M., Oubagaranadin J.U.K., (2016) A review of technologies for manganese removal from wastewaters, *Journal of Environmental Chemical Engineering* 4, 468–487.
[11] Manav Demir N., (2016) Experimental Study of Factors that Affect Iron and Manganese Removal in Slow Sand Filters and Identification of Responsible Microbial Species, *Polish Journal of Environmental Studies* 25 (4), 1453-1465.
[12] Dai Y., Zhang J., Xie S., (2016) Bacterial communities in drinking water distribution systems, Available from: http://www.ncbi.nlm.nih.gov/nuccore/KF515099 [accessed Oct 27, 2016].
[13] Liu Z., Huang S., Sun G., Xu Z., Xu M., (2012) Phylogenetic diversity, composition and distribution of bacterioplankton community in the Dongjiang River, China, *FEMS Microbiol. Ecol*. 80 (1), 30-44.
[14] Sakurai K., Tazaki K., Yamaguchi K., (2006) Identification of bacteria in an iron-oxidation biofilm at Shibayama lagoon, Ishikawa, Japan, Published Only in Database (2006), Available from: http://www.ncbi.nlm.nih.gov/nuccore/AB252929 [accessed Oct 27, 2016].
[15] Blothe M., Roden E.E., (2009) Microbial iron redox cycling in a circumneutral-pH groundwater seep, *Appl. Environ. Microbiol*. 75, 468-473.
[16] Gulay A., Tatari K., Musovic S., Mateiu R.V., Albrechtsen H.J., Smets B.F., (2014) Internal porosity of mineral coating supports microbial activity in rapid sand filters for groundwater treatment, *Appl. Environ. Microbiol*. 80, 7010-7020.
[17] Douterelo I., Sharpe R., Boxall J., (2014) Bacterial community dynamics during the early stages of biofilm formation in a chlorinated experimental drinking water distribution system: implications for drinking water discolouration, *J. Appl. Microbiol*. 117, 286-301.
[18] Mitsunobu S., Makita H., Kikuchi S., (2016) Biogenic iron oxyhydroxides characterized by directly coupled phylogenetic and chemical speciation, Available from: http://www.ncbi.nlm.nih.gov/nuccore/AB670152 [accessed Oct 27, 2016].
[19] Kwon S., Moon E., Kim T.S., Hong S., Park H.D., (2011) Pyrosequencing demonstrated complex microbial communities in a membrane filtration system for a drinking water treatment plant, *Microbes Environ*. 26, 149-155.

[20] Islam A.A., Tobiaso J.E., (2016) Release of manganese from groundwater treatment filter media, Available from: http://www.ncbi.nlm.nih.gov/nuccore/JQ288616 [accessed Oct 27, 2016].

[21] Corstjens P.L.A.M., de Vrind J.P.M., Goosen T., de Vrind-de Jong E.W., (1997) Identification and Molecular Analysis of the Leptothrix discophora SS-1 mofA Gene, a Gene Putatively Encoding a Manganese Oxidizing Protein with Copper Domains, *Geomicrobiol. J*. 14, 91-108.

[22] Ma G.X., Pei H.Y., Ji Y., (2016) Study on Microbial Community in Drinking Water Sludge by PCR-DGGE, Available from: http://www.ncbi.nlm.nih.gov/nuccore/JN936833 [accessed Oct 27, 2016].

[23] Lin C.F., Larsen E.I., Nothdurft L.D., Smith J.J., (2012) Neutrophilic, microaerophilic Fe(II)-oxidizing bacteria are ubiquitous in aquatic habitats of a subtropical Australian coastal catchment, *Geomicrobiol. J*. 29, 76-87.

[24] Nousiainen A.O., Bjorklof K., Sagarkar S., Nielsen J.L., Kapley A., Jorgensen K.S., (2015) Bioremediation strategies for removal of residual atrazine in the boreal groundwater zone, *Appl. Microbiol. Biotechnol*. 99, 10249-10259.

[25] Johnson K.W., McDonald W., Carmichael M.J., Rose N., Pitchford J., Windelspecht M., Karatan E., Brauer S.L., (2016) Increased abundance of Gallionella spp., Leptothrix spp. and total bacteria in response to enhanced Mn and Fe concentrations in a disturbed southern Appalachian high elevation wetland, Available from: http://www.ncbi.nlm.nih.gov/nuccore/GU572372 [accessed Oct 27, 2016].

[26] Katsoyiannis I.A., Zouboulis A.I., (2004) Biological treatment of Mn(II) and Fe(II) containing groundwater: kinetic considerations and product characterization, *Water Research* 38, 1922–1932.

[27] Li X., Chu Z., Liu Y., Zhu M., Yang L., Zhang J., (2013) Molecular characterization of microbial populations in full-scale biofilters treating iron, manganese and ammonia containing groundwater in Harbin, China, *Bioresource Technology* 147, 234-239.

[28] Tech Brief Slow Sand Filtration, A National Drinking Water Clearinghouse Fact Sheet, 2000.

[29] Visscher J.T., Paramasivan R., Raman A., Heijnen H.A., (1987) Slow Sand Filtration for community Water Supply planning, design, construction, operation and maintenance, Technical Paper No. 24, ed: International Reference Centre for Community Water Supply and Sanitation, Hague, Netherland.

[30] Haig S.J., Collins G., Davies R.L., Dorea C.C., Quince C., (2011) Biological aspects of slow sand filtration: past, present and future, *Water Science and Technology: Water Supply* 11 (4), 468-472.

[31] Du X., Liu G., Qu F., Li K., Shao S., Li G., Liang H., (2017) Removal of iron, manganese and ammonia from groundwater using a PAC-MBR system: The anti-pollution ability, microbial population and membrane fouling, *Desalination* 403, 97-106.

[32] Yang L., Li X., Chu Z., Ren Y., Zhang J., (2014) Distribution and genetic diversity of the microorganisms in the biofilter for the simultaneous removal of arsenic, iron and manganese from simulated groundwater, *Bioresource Technology* 156, 384–388.

[33] Gibert O., Lefevre B., Fernandez M., Bernat X., Paraira M., Pons M., (2013) Fractionation and removal of dissolved organic carbon in a full-scale granular activated carbon filter used for drinking water production, *Water Research* 47, 2821-2829.