Desalination and Water Treatment
www.deswater.com

doi: 10.5004/dwt.2018.22790

127 (2018) 213–221
September

Ablution gray water qualitative assessment and treatment by submerged membrane bioreactor: a case study in Jordan

Ziad Al-Ghazawi[a], Ahmad Qasaimeh[a,*], Khalid Bani-Melhem[b]

[a]*Department of Civil Engineering, Faculty of Engineering, Jordan University of Science and Technology, Irbid 22110, Jordan, Tel. +96227201000 Ext: 22139; emails: alghazawi@gmail.com (Z. Al-Ghazawi), argg22@yahoo.com (A. Qasaimeh)*
[b]*Department of Water Management and Environment, Faculty of Natural Resources and Environment, The Hashemite University, P.O. Box 150459, Zarqa 13115, Jordan, Tel. +962795634630; email: k_banimelhem@yahoo.com*

Received 1 December 2017; Accepted 7 July 2018

ABSTRACT

This study assesses ablution gray water and its treatment at JUST (Jordan University of Science and Technology). A submerged membrane bioreactor (SMBR-pilot plant) is used to treat ablution water that generated from mosque at JUST. The inflowing gray water is conveyed to sedimentation tank, aerated for biological processing, and then ultrafiltrated via membrane utilizing vacuum pump. The SMBR was operated for 33 d at constant flow rate of 5 m^3/d. An acclimatized seed of mixed liquor suspended solids with concentration of 2,200 mg/L was used in bioreactor. A complete retention for activated sludge was maintained in the bioreactor. Individual membranes with constant spacing between filter plates and their absolute evenness ensure a precisely distributed flow and backflushing procedures. The average removal efficiencies are 80% for chemical oxygen demand; 89% for BOD_5; 95% for turbidity; and 100% for total suspended solids. Furthermore, the SMBR pilot plant successfully removed part of nutrients, where the average removal efficiencies are 43% for ammonium; 29% for nitrate; and 50% for phosphorus. The average removal efficiency of *Escherichia coli* bacteria is 88%. This work provides useful practical information about ablution gray water and the technical feasibility of treatment. Overall the produced effluents embrace excellent quality that meets the Jordanian and International standards for gray water reuse. The treated ablution gray water performs important nonconventional source of water in arid and semi-arid areas.

Keywords: Gray water; Membrane; Ultrafiltration; SMBR; Reclaimed water

1. Introduction

Gray water treatment has received considerable attention in Middle East and North Africa (MENA) as a valuable nonconventional source of water during the last few years due to rigorous water shortage, population growth, and water pollution increase [1–4].

With suitable treatment, gray water could be utilized for many useful applications [3–5]. The treated gray water can be used in nonpotable reuse applications: groundwater recharge, landscaping, and plant growth [5]. Several countries have issued regulations and standards for gray water treatment and reuse, such as the United States and Australia. These regulations set out the technical requirements for the sustainable management [6]. Hence, based on the gray water characterization and its regulations, the selection and operation of treatment technologies are specified [7].

Investigations into the treatment and recycling of gray water have been reported since the 1970s [8–10]. Many technologies have been developed to treat the gray water, these technologies range from simple to complex treatment processes [11–13]. A wide range of physical [14,15], chemical [16–18], and biological [19–21] processes have been applied for gray water treatment and recycling. Biological based technologies such as rotating biological contactor [19], biological aerated filters [22], and aerated bioreactors were

* Corresponding author.

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investigated [23]. Most of the current treatment systems are those incorporate membrane bioreactors [24–26].

The membrane bioreactor has many advantages over conventional wastewater treatment processes including: small reactor volume requirements, high effluent quality, high performance of physical retention of pathogens, higher volumetric loading, and reduced sludge production [27].

In this study, a different kind of gray water according to ablution is being assessed and treated for a case study in Jordan. The virtues of this work are recognized due to the integrated application of sedimentation, aerobic degradation, and membrane ultrafiltration. The submerged membrane used herein has a unique merit of individual spaced membrane filter plates that have high surface area and self-cleaning criteria. This work provides useful practical information about ablution gray water and the technical feasibility of treatment. Therefore, treated ablution gray water should be considered as an important nonconventional source of water that contributes strongly to the water demand in arid and semi-arid areas like MENA.

2. Water shortage in Jordan

Jordan is one of the countries that suffer water scarcity. For example, the country required about 1,400 MCM for the year 2014, but had only 848 MCM of freshwater supply available for various uses [28].

Jordan is located in an arid to semi-arid region; it is among the water-scarce countries in the world according to the Food and Agriculture Organization of the United Nations (FAO) [29].

Jordan is facing a growing gap between water supply and water demand due to population growth, climate change, socio-economic development, and flee of refugees due to political unrest in the region. This gap forces Jordan to make efforts to overcome the unsatisfied water demand, by optimizing water usage in all sectors, and managing the reuse of nonconventional water resources such as wastewater and gray water treatment [30–32]. Traditional water usage from available resources including treated water resources are shown in Table 1 [33].

3. The case study

The ablution gray water is a major part of gray water in Islamic countries [12]. The success of separating, collecting, and treating this part of gray water will have a great concern as a nonconventional water resource.

In this study, the ablution gray water characteristics and treatment from the mosque of Jordan University of Science and Technology (JUST) is being evaluated. JUST is located in the northern side of Jordan in Al-Ramtha district, 536 m above sea level at the coordinates 32.56°N and 36.01°E (Fig. 1). JUST area exhibits dry weather where the average temperature and rainfall pertains semi-arid to arid conditions as that could be noticed from the data in Fig. 1 and Table 2.

JUST with its large campus (11 km^2) utilizes reclaimed water for irrigation from various resources, one from JUST wastewater treatment plant operating at rate of 600 m^3/d and other source is taken from Wadi Hassan wastewater treatment plant located about 4 km south of the university campus, and for this study a reclaimed gray water from JUST mosque pilot plant [35]. These sources of treated water will lower the use of freshwater for irrigation by considering blending treated wastewater effluent with freshwater resources in accordance to national WHO and FAO standards for reuse in irrigation [32].

Table 1
Water usage from different resources (2006–2015)

Year	Surface water	Ground water	Treated water	Total (MCM)
2006	280	480	80	840
2007	260	505	91	856
2008	252	499	101	852
2009	276	494	101	871
2010	280	511	103	894
2011	272	517	103	892
2012	231	509	102	842
2013	245	540	109	894
2014	259	588	125	972
2015	274	602	133	1,009

4. Materials and methods

4.1. Submerged membrane bioreactor pilot plant

The ablution gray water from JUST Mosque is being treated in this study by submerged membrane bioreactor (SMBR) pilot plant. The pilot plant is a design product from GreenLife Company of Germany (Fig. 2).

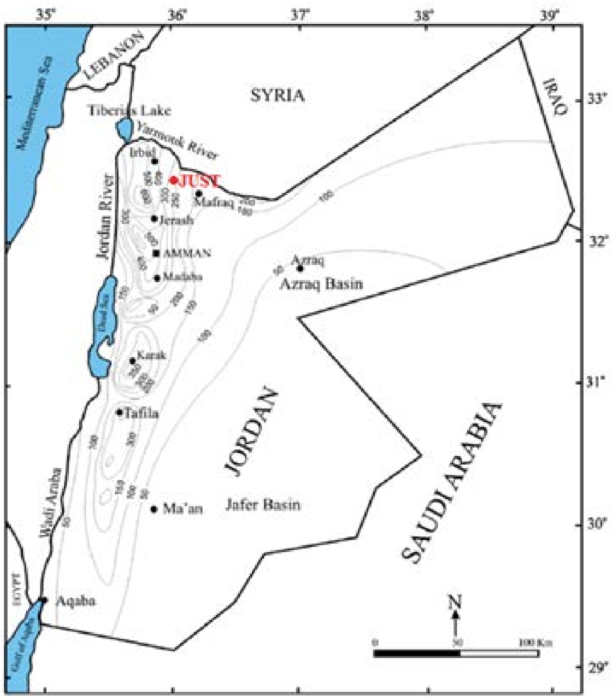

Fig. 1. JUST Mosque location and average annual rainfall distribution of long-term period of Jordan [34].

Table 2
Average temperature and rainfall in JUST area [36]

	Avg. temperature (°C)	Avg. temperature (°F)	Precipitation/rainfall (mm)
Jan	8.9	48.0	65
Feb	9.8	49.6	62
Mar	12.4	54.3	51
Apr	16.2	61.2	15
May	20.5	68.9	5
Jun	23.8	74.8	0
Jul	25.1	77.2	0
Aug	25.5	77.9	0
Sep	23.6	74.5	0
Oct	20.4	68.7	8
Nov	15.5	59.9	30
Dec	10.4	50.7	61

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Precipitation (mm)	65	62	51	15	5	0	0	0	0	8	30	61
Min. temp. (°C)	4.1	4.5	6.7	10	13.6	16.8	18.6	19	16.9	13.7	9.3	5.5
Max. temp. (°C)	13.7	15.1	18.1	22.5	27.4	30.9	31.6	32	30.4	27.2	21.7	15.4
Long-term min–max temp (°C)[a]	0–22	0–25	1–29	4–35	8–37	12–38	15–38	16–38	14–38	10–35	5–28	2–24

[a]The average of the hottest day and coldest night of each month of the last 30 years.

Fig. 2. Gray water treatment pilot plant at JUST Mosque.

The pilot plant system is assembled of the following constituents: four identical horizontal tanks, ultrafiltration membrane filter box, vacuum pump, blowers, and sensors. The gray water undergoes three successive treatment processes: sedimentation, aerobic biodegradation, and membrane ultrafiltration. These processes are ruled by a logic-learned unit to control the flow in the system (Fig. 3). The SMBR pilot plant was operated for 33 d at constant flow rate of 5 m^3/d. An acclimatized seed of mixed liquor suspended solids(MLSS) with concentration equals to 2,200 mg/L was used in the aeration tank. A complete retention for activated sludge was maintained in the aeration tank (Table 3). The application of membrane biotechnology assures complete separation of total suspended solids(TSS) and high removal efficiency of germs. The effluent water is clear service water available for nonpotable purposes such as cleaning, irrigation, and industrial applications.

In the third stage, MicroClear® filter is the membrane filter technology that is being used for ultrafiltration after the biological degradation has been achieved. MicroClear® is a patentable product of Newterra Ltd. of Ontario, Canada. MicroClear® filters are fundamentally based on a robust plastic plate covered on both sides with an ultrafiltration membrane with pore size of about 0.04 μm. The filtrate is being drawn through the membrane by a negative pressure of 0.1 bar, where the particles and germs are securely removed. The blowers provide air bubbling for membrane self-cleaning and for further degradation of the remaining organic matters in the SMBR. Table 4 shows the design parameters and specifications of the MicroClear® membrane filter.

4.2. Water sampling

The samples were taken in October and November in 2016. The samples were taken mainly from two points of pilot plant: inlet and outlet. Each sample was analyzed for average value of the following quality parameters: chemical oxygen demand (COD), BOD_5, TSS, turbidity, *Escherichia coli* bacteria, nitrate, ammonium, and phosphorus. Table 5 shows the average values of raw gray water quality parameters with their standard deviations and samples number. The sampling procedure was conducted using proper samplers and

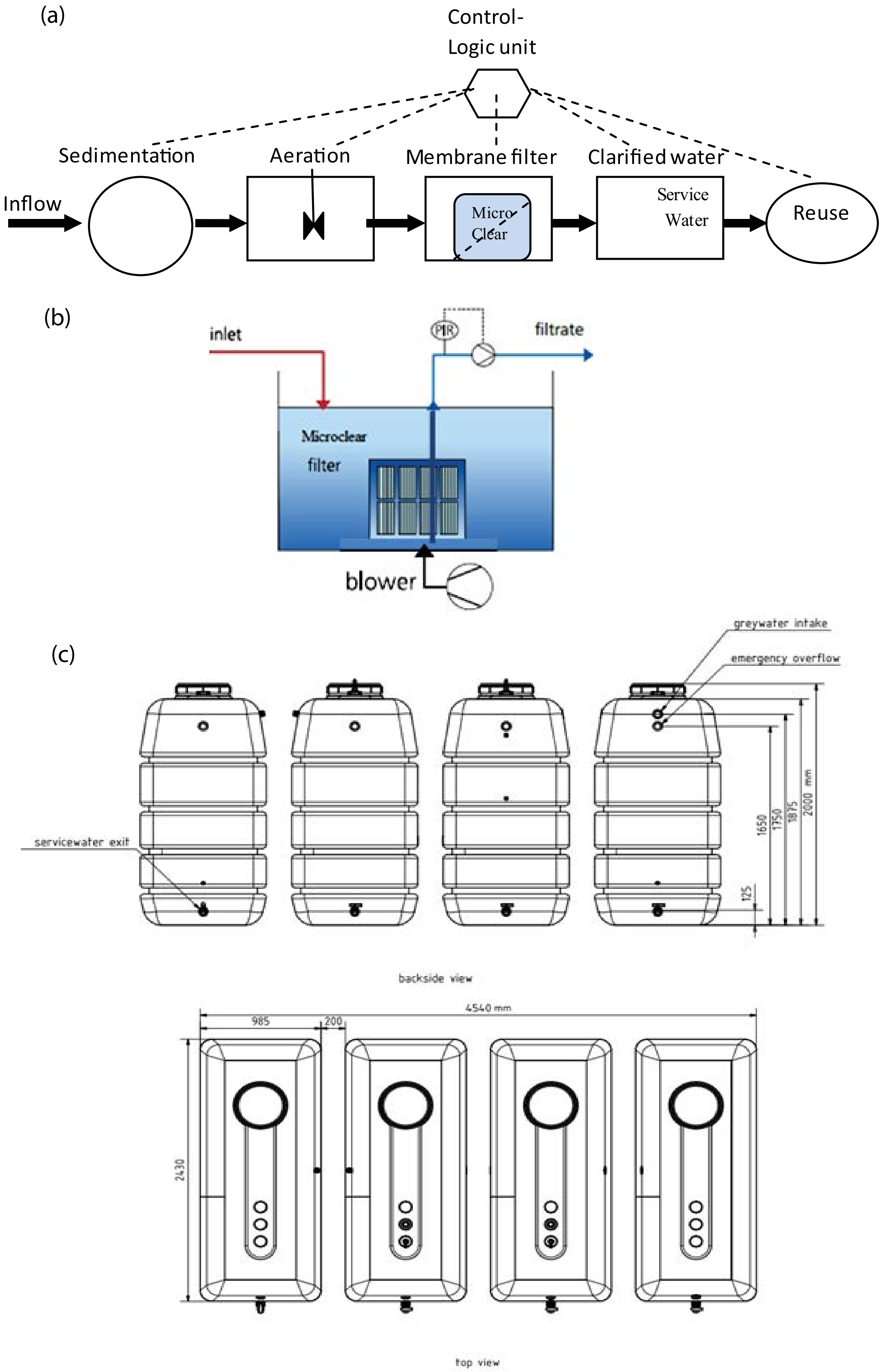

Fig. 3. (a) Schematic layout of treatment stages of the gray water treatment pilot plant, (b) SMBR, and (c) the dimension of the units.

Table 3
Design parameters for the pilot plant

Design parameter	Value
Number of tanks	4 (identical)
Tank dimension (*L* × *W* × *H*) (m)	2.430 × 0.985 × 1.875
Design flow (m^3/d)	5
MLVSS/MLSS in bioreactor	0.7–0.8
Total hydraulic detention time (d)	0.89 × 4
SRT (d)	Complete retention

Table 4
Design parameters for MicroClear® membrane filter box used in the pilot plant

Design parameter	Value
Dimension (*L* × *W* × *H*) (mm)	207 × 207 × 492
Number of boxes	2
Plate spacing (mm)	5.5
Membrane surface area (m^2)	3.5
Membrane material	Polyether sulfone (PES)
Filtration suction pressure (bar)	0.1–0.15
Backflushing pressure (bar)	0.05
Mean flux (L/m^2 h)	15–30
Max flux (L/m^2 h)	50
Cut off (kDa)	150
Retention size (μm)	0.04

containers. The samples were properly packed and labeled to ensure appropriate preservation and safe delivery. Packaging and cooling of samples was maintained to help preventing resampling. The ice chest was used to preserve the sample containers while shipping and to ensure that the sample temperature is kept within (0°C–6°C) temperature range.

The COD, phosphorus, ammonium, and nitrate tests were conducted using Hach kits (LCK) and DR-5000 spectrophotometer. The accuracy of these kits for COD, ammonium, nitrate, and phosphorus are ±1.5, ±0.2, ±0.4, and ±0.006 mg/L, respectively. For TSS and BOD_5, the analysis is in accordance with the standard methods of ASTM D5907-13 and ASTM D6238-98(2011), respectively. The *E. coli* bacteria test

Table 5
Quality parameters for the raw gray water from JUST Mosque

Parameter	Average	STD[a]	Number of samples
COD (mg/L)	68.78	31.5	9
BOD (mg/L)	51.4	23.7	5
TSS (mg/L)	75.67	16.7	9
Turbidity (NTU)	23.1	18.4	9
pH	7.2	0.15	9
E. coli (MPN/100 mL)	15.5	0.4	5
NH_4-N (mg/L)	0.35	0.2	5
NO_3-N (mg/L)	6.5	0.34	5
PO_4-P (mg/L)	0.08	0.02	5

[a]Standard deviation.

was conducted using most probable number (MPN) method in Microbiology Laboratory in JUST campus (Public Safety Laboratory).

5. Results and discussion

5.1. The removal performance of the SMBR system

Samples were analyzed twice a month in July and August 2016 using Lovibond Kits. The considered results in this work are those for sampling conducted in October and November 2016 using Hach Kits. The organic content in gray water represented by COD and BOD_5 has encountered a significant reduction occurred in the aeration bioreactor. The effluent concentrations for both COD and BOD_5 are shown in Figs. 4 and 5, respectively. COD concentration of raw gray water varies from 28 to 119 mg/L with an average value of 68.78 mg/L and standard deviation SD = 31.5 after which it is reduced to an average value of effluent concentration equals to 14.1 mg/L with average removal efficiency of 80%.

With an analogical trend of COD, the BOD_5 concentration of raw gray water ranges from 12 to 74 mg/L with an average value of 51.4 mg/L and SD = 23.7 after which it is reduced by treatment to an average value of 6 mg/L with an average removal efficiency of 89%. The average organic removal efficiency for COD is less than that for BOD_5 because of nonbiodegradable organic matters available within the gray water. During the period of treatment, the removal efficiency for both COD and BOD_5 increased chronologically

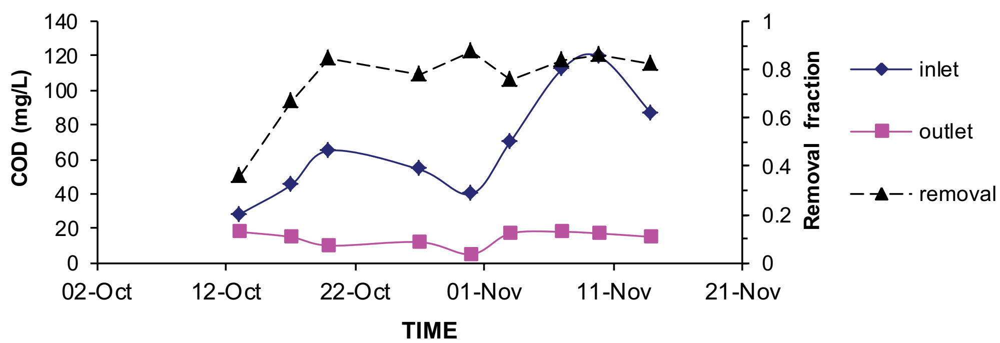

Fig. 4. COD concentration variations for gray water inflow, outflow, and removal fraction.

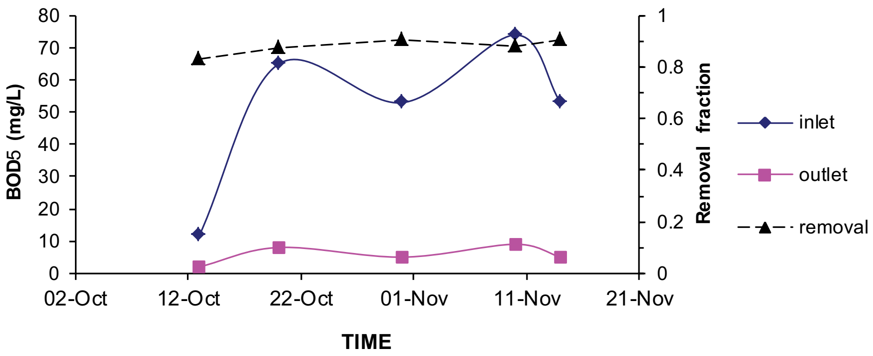

Fig. 5. BOD_5 concentration variations for gray water inflow, outflow, and removal fraction.

with the time; this is attributed to the significant increase in the population of microorganisms (mixed liquor volatile suspended solids(MLVSS)) in the aeration tank. The MLSS is also increased with similar trend while the time is running. The MLVSS/MLSS ratio varies between 0.7 and 0.8 with the time. This kinetics fashion can be seen in similar studies in the literature [1,37].

The TSS concentration in raw gray water ranges from 52 to 98 mg/L with an average value of 75.66 mg/L which is reduced by treatment to a nondetected value in the effluent with removal efficiency of 100% as shown in Fig. 6. This is due to the fact that the membrane pore size of 0.04 μm is smaller than the particles in the suspended solids. The turbidity is fluctuated in the range from 4 to 64 NTU with an average value of 23.11 NTU after which it is decreased by treatment to an average value of 1.12 NTU with average removal efficiency of 95% as shown in Fig. 7. The particles are totally retained by membrane whereas some colloids are not retained [26].

Fig. 8 shows the *E. coli* bacteria concentration variations with time; the bacteria concentration ranges in raw gray water from 5 to 16 MPN/100 mL, after which it is reduced by pilot plant treatment to the average value of 2 MPN/100 mL with an average removal efficiency of 88%. Although the membrane retention of germs may reach 4 log reductions in heavily polluted gray water, the *E. coli* bacteria concentrations in this study due to ablution are much less than that found in other gray waters, however, these value are similar to those found in ablution gray water surveyed in the literature [38].

The SMBR removed successfully part of the nutrients in the gray water, the average removal efficiency is 43% for ammonium (from 0.35 to 0.2 mg/L NH_4-N), 29% for nitrate (from 6.5 to 4.585 mg/L NO_3-N), and 50% for phosphorus (from 0.081 to 0.04 mg/L PO_4-P). The nutrients concentrations are of great concern and should be controlled when biofouling occurs on the membranes and the permeation flux is

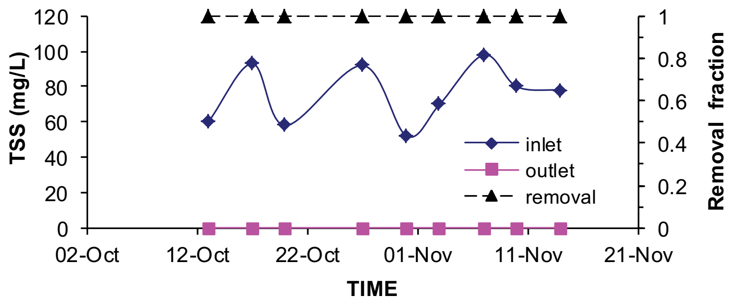

Fig. 6. TSS concentration variations for gray water inflow, outflow, and removal fraction.

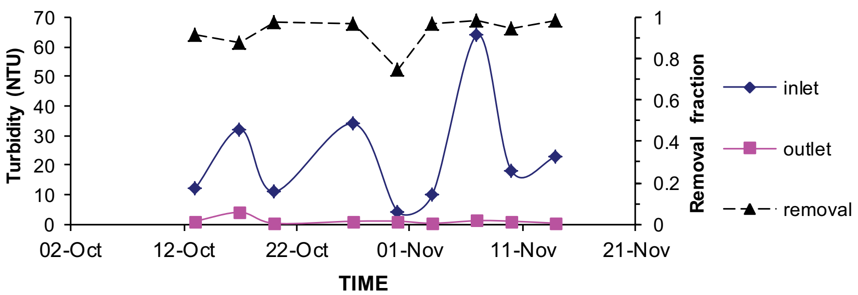

Fig. 7. Turbidity concentration variations for gray water inflow, outflow, and removal fraction.

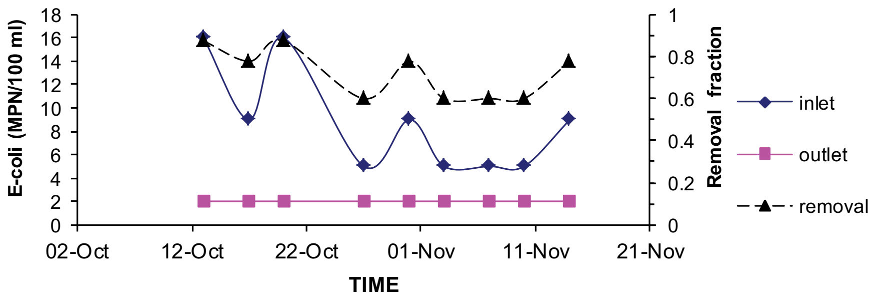

Fig. 8. *E. coli* concentration variations for gray water inflow, outflow, and removal fraction.

reduced. Nevertheless, some level of nutrients can be favorable for irrigation purposes.

The overall average values of gray water quality parameters for influents, effluents, and removal efficiencies are shown in Table 6.

The evaluation of results at maximum efficiency can be observed in Figs. 4–8, where the maximum removal efficiency of COD and BOD_5 are 88% and 91%, respectively; the maximum removal for solids is as high as 100% for TSS and 98% for turbidity; the *E. coli* bacteria maximum reduction is 88%; and the maximum removal efficiency for nutrients is 48% for ammonium, 34% for nitrate, and 51% for phosphorus.

The SMBR technology is an efficient method for gray water treatment. It combines physical separation of particles including pathogens together with aerobic biological treatment of dissolved organic matter. The SMBR technology is able to achieve satisfactory removal efficiencies of organic substances and microbial contaminations without a postfiltration and disinfection processes [39].

5.2. Membrane filter permeation performance

The membrane filter built in the pilot plant has a mean pore opening of about 0.04 µm. Bacteria, fungi, algae, and part of viruses are larger than pore size and therefore cannot pass through the membrane, while particles are held back forming deposits.

Individual membranes with constant spacing between filter plates and their absolute evenness ensure a precisely distributed flow and backflushing procedures. Optimized aeration (with continuously rising, fine air bubbles spaced at intervals) produces a cleansing effect on filter plates. This simultaneously ensures oxygen content in the membrane bioreactor. This efficient method of self-cleaning reduces the need for mechanical and chemical cleaning. The size of the air bubbles is crucial for successful air rinsing. The ventilators produce a definite bubble size that during their rise through the filter creates shear forces on the membrane. These shear forces remove particles from the membrane's surface and carry them upward out of the filter (Fig. 9). The shear forces produced by the air bubbles are more efficient while filtration is paused, since particles on the membrane's surface are no longer strongly held in place by the suction pressure during filtration. The typical operational cycle is 9 min of filtration and a 1 min pause.

Scaling, primarily caused by hardness ingredients such as calcium and magnesium, can be eliminated by chemical cleaning in acidic environment. Fig. 10 illustrates how flux is influenced by the number of chemical cleanings.

If the membrane's permeability drops below (50 L/m² h bar) after a certain operational period, then a basic cleaning is necessary.

5.3. Effluent quality parameters standards

The quality parameters concentrations for the treated gray water in this research are less than the Jordanian standards for using reclaimed water in irrigation and other domestic uses as it could be seen from Table 7.

Table 6
Average values of gray water quality parameters and removal efficiencies

Parameter	Unit	Inlet	Outlet	Removal efficiency (%)
COD	mg/L	68.77	14.1	80
BOD_5	mg/L	51.4	6	89
TSS	mg/L	75.66	ND	100
Turbidity	NTU	23.11	1.12	95
E. coli	MPN/100 mL	15.5	2	88
NH_4-N	mg/L	0.35	0.2	43
NO_3-N	mg/L	6.5	4.59	29
PO_4-P	mg/L	0.08	0.04	50

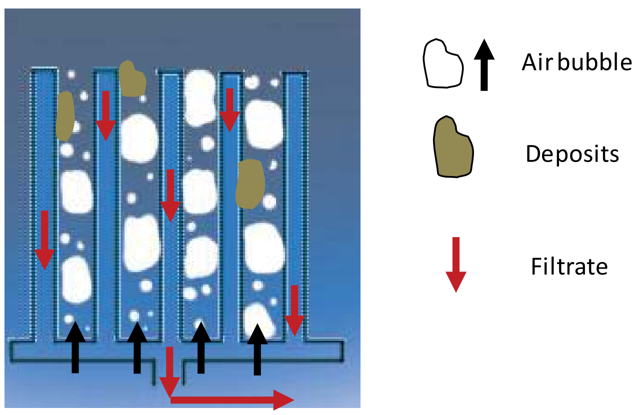

Fig. 9. Mechanism of permeation and air-bubble rinsing within the membrane filter.

Table 7
Jordanian standards for reclaimed domestic wastewater for 2006 [40]

Parameter	Unit	Cooked vegetables, parks, playgrounds, and sides of roads within city limits	Fruit trees, sides of roads outside city limits, and landscape	Field crops, industrial crops, and forest trees	Water discharge to wadies, streams, and water bodies	Artificial recharge of groundwater aquifers
		A	B	C		
Biological oxygen demand	mg/L	30	200	300	60	15
Chemical oxygen demand	mg/L	100	500	500	150	50
Dissolved oxygen	mg/L	>2	–	–	>1	>2
Total suspended solids	mg/L	50	150	150	60	50
pH	Unit	6–9	6–9	6–9	6–9	6–9
Turbidity	NTU	10	–	–	–	<2
Nitrate	mg/L	30	45	45	45	30
Total nitrogen	mg/L	45	70	70	70	45
Escherichia coli	MPN or CFU[a]/100 mL	100	1,000	–	1,000	<2.2
Intestinal helminths egg	Egg/L	≤1	≤1	≤1	≤1	≤1

[a]Most probable number or colony forming unit.

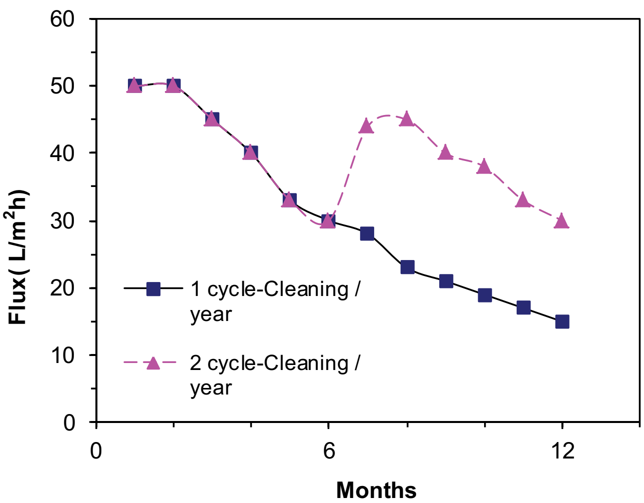

Fig. 10. Permeation flux with time for MicroClear® membrane filter.

The SMBR pilot plant components and processes are designed to assure that the quality of the effluent service water (nonpotable) fulfills the requirements of the European (EU) guidelines for bathing water quality (76/160/EEC and 2006/7/EC) [41]. The treated gray water in this study is also compliant to German National Standard DIN 19650 (1999) class 2 [42].

6. Conclusion

The overall performance of SMBR was evaluated; the effluents have high qualities that meet the Jordanian and international standards of gray water reuse for irrigation and other domestic applications. The average removal efficiencies are 80% for COD, 89% for BOD_5, 95% for turbidity, 100% for TSS, 88% for *E. coli* bacteria, 43% for NH_4-N, 29% for NO_3-N, and 50% for PO_4-P. It is hoped that continuing efforts to optimize SMBR treatment will render the reuse of gray water as a cost-effective asset in the overall water budget of many arid communities in the MENA region like Jordan. Future investigations aim at integrating SMBR system with artificial intelligent modeling, optimization, and control techniques.

Acknowledgments

GreenLife is acknowledged for providing the pilot plant. Abdalla Awawdeh and Weam Mehdawi are acknowledged for collecting the water quality data during this study.

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