Purification of lake water using a PES hollow fiber membrane

K. M. W. Carolyn, M. U. M. Junaidi, N. A. Hashim, M. A. Hussain, F. Mohamed Zuki, B. Mohamed Jan, N. A. Abdul Nasir and A. L. Ahmad

ABSTRACT

Water scarcity combined with increasing populations will create a massive problem of obtaining clean water sources in the future. In this research, a newly developed polyethersulfone (PES) hollow fiber membrane from Universiti Sains Malaysia (USM) is used in water purification experiments using raw water samples obtained from Varsity Lake of the University of Malaya (UM) and a lake in Taman Jaya. The raw water samples undergo water quality characteristics tests to determine their class of water quality based on national water quality standards. Both raw water samples have been characterized and belong to class II of water quality. Subsequently, both raw water samples are used in water purification experiments with two types of filtration configuration, cross-flow and dead-end. Results show that water purification using the PES hollow fiber membrane can obtain water quality of class I for both samples. However, the presence of *Escherichia coli* can still be detected in both purified water samples. From the results obtained, the fabricated PES membrane is able to filter raw water samples of WQI Class II to WQI Class I quality and adhere to drinking water standards, and the dead-end filtration configuration provides the best filtration performance.

Key words | hollow fiber, membrane technology, polyethersulfone, water separation

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INTRODUCTION

Two-thirds of the world is covered in water, of which only 2.5% is fresh water that is safe to consume, and it is evidently clear that water plays a vital role in maintaining the earth's sustainability. Water plays significant roles in different industries, whether in agriculture, medicine, industrial processes either for heating or cooling and in our daily lives too. Unfortunately, it is used up to a point where the people in some areas of the world lack clean water resources to meet water use demands, and are facing water scarcity.

Water scarcity affects more people nowadays and is expected to increase and affect more people in the future. It is worse when there is an unexpected natural disaster such as flooding. Throughout the years, floods have caused much damage and become one of the most destructive phenomena all over the world, causing the loss of thousands of lives and destruction of property worth many millions (Hussain *et al.* 2014). As recorded by the World Meteorological Organization (WMO), floods in Malaysia have occurred in the years 1926, 1931, 1947, 1954, 1957, 1963, 1965, 1967, 1969, 1971, 1973, 1983, 1988, 1993, 1998, 2001, 2006, 2007 and 2010, with a total area of 29,000 square kilometers, and more than 4.82 million people affected (Chan 2015).

Every year floods affect the east coast of the Malayan Peninsula due to the Northeast monsoon which occurs from November to March each year. Damage caused by the floods includes loss of life and destruction of infrastructure leading to loss of power. The loss of power has a further impact on the availability of water treatment and water supply, resulting in clean water scarcity. Hygienic water

doi: 10.2166/ws.2019.184

supply is difficult to achieve in the flood evacuation centers if there is no systematic management to ensure clean water is distributed continuously. Inability to provide clean water will force the people to use water of poor quality for domestic activities (See *et al.* 2017). Hence, it will essentially lead to outbreaks of various communicable diseases such as leptospirosis, malaria, typhoid, hepatitis and more. People with weak immune systems will be highly vulnerable to suffer from diarrhea, fever, eye and skin infections and more (Bariweni *et al.* 2012).

Membrane technologies have been used significantly in recent decades for purification of water, such as microfiltration, ultrafiltration (Chew *et al.* 2016) and nanofiltration. However, there is still a lack of clean water provision for communities in rural areas due to the difficulty in reaching them and the enormous expense of building a clean water pipeline. Hence, they are forced to use surface river water as their daily water source for domestic usage. However, the rate of water pollution has increased over the years so that the quality of river water makes it unusable, causing a major problem for communities in rural areas. In these situations, there is a need for society to create an advanced purification technology that is affordable in price, possible to carry everywhere and easy to use. Many researchers (Schlichter *et al.* 2000; Xu & Qusay 2004; Idris *et al.* 2007; Li *et al.* 2010; Boyd *et al.* 2012; Chew *et al.* 2016) have investigated meeting this requirement by introducing polymeric membrane technology. There are several types of polymer materials used in water purification and polyethersulfone (PES) is one of the best choices in membrane fabrication due to its durability in harsh physical and chemical conditions (Xu & Qusay 2004) and being an affordable material. Locally, Ahmad *et al.* (2015) have fabricated a PES hollow fiber (PES-HF) membrane and successfully rejected humic acid (HA) by 97.98% in 10 mg/L HA solution. In another experiment, polyvinylalcohol (PVA) was added to the PES-HF membrane and, with an air gap of 5 cm, the modified membrane achieved more than 94% of HA rejection (Ahmad & Shafie 2017). However, both studies were at laboratory scale and pilot case research is needed to prove that the fabricated PES-HF membrane can be used for real-life applications. This study will assist people to widen their knowledge about the performance of PES-HF membranes with different water sources and with different filtration configurations. This technology will therefore help improve people's lives in the future.

The objective of this study is mainly to evaluate the effect of PES-HF membrane performance in water filtration using different water sources and different system configurations, by characterization and comparison with drinking water (Engineering Services Division, Ministry of Health Malaysia, n.d.) in terms of physical properties and biological properties. The PES-HF membrane was fabricated locally at Universiti Sains Malaysia (USM).

MATERIAL AND METHODS

Pre-study (raw water characterisation tests)

The experiment started with a pre-study on the characteristics of raw water samples to determine the class of the water quality based on National Water Quality Standards (NWQS) set by the Department of Environment (DOE) (Zainudin 2010). The raw water (RW) samples used in the experiments are from Lake Varsity of the University of Malaya (RW1) and lake water from Taman Jaya Park, Petaling Jaya, Selangor (RW2). The physical properties studied include dissolved oxygen (DO), biochemical oxygen demand (BOD), chemical oxygen demand (COD), potential of hydrogen (pH), ammoniacal nitrogen (AN), total suspended solids (TSS), phosphate and nitrate levels. The presence of bacteria was examined using the coliform count plate technique.

Pure water permeability and flux test

The permeability test was conducted by passing pure water and both raw water samples for 6 hours (h) with different filtration methods through the PES-HF membrane to determine its permeability and flux. The PES-HF membrane was fabricated at USM by using the method described by Ahmad & Shafie (2017). Permeability determines the amount of water passing through the pore membrane under a certain pressure and was calculated using the equation (Goh *et al.* 2015):

$$Pure\ water\ permeability\ (PWP) = \frac{V}{tA\Delta P} \quad (1)$$

PWP = Pure Water Permeability ($kg/m^2 \cdot h \cdot Pa$)
V = Volume of the permeate collected (m^3)
t = Time over which the permeate was collected (h)

A = outer surface area of the hollow fiber membrane (m^2)
ΔP = Hydraulic pressure applied to the membrane (Pa)

Flux is defined as the volumetric flow rate of the permeate divided by the total membrane surface area and is calculated by the equation:

$$Flux,\ J = \frac{Q}{A} \qquad (2)$$

J = Flux (kg/m^2h)
Q = Volumetric flow rate of permeate (kg/h)
A = Surface area of membrane system (m^2)

Filtration experiment

Figure 1 shows a schematic diagram of the ultrafiltration experiment using the PES-HF membrane. Before filtration, the membrane undergoes a process of chemical cleaning with ethanol solution to clean the glycerol on the PES membrane that was used to preserve the membrane before usage. Throughout the experiment, there were three different filtration methods used.

The filtration process started with method A (Table 1) using RW1 and the permeate was collected in a clean bottle when it reached the target volume required. The process was repeated with filtration method B where the opening-end of the membrane was adjusted to half-open configuration. Then the process continued with filtration method C which has a dead-end configuration. Permeability and flux results of each filtration method were recorded for each conducted experiment. The filtration process was repeated with RW2.

Water quality index (WQI)

The water quality index (WQI) is a standard used to determine the water quality status and to classify the rivers as Class I, II, III, IV or V based on Interim National Water Quality Standards (INWQS). There are six main parameters taken into consideration: BOD, COD, AN (NH_3N), pH, DO and suspended solids (SS) (Zainudin 2010). WQI ranges from 0 to 100, the higher the value of WQI, the better the quality of the water tested (Zainudin 2010). Parameters for WQI and its class definitions are given in Table S1 in the Supplementary Material.

RESULTS AND DISCUSSION

Physical observations

Figures 2 and 3 show the non-filtered and filtered water samples from RW1 and RW2. From the left, the first bottle

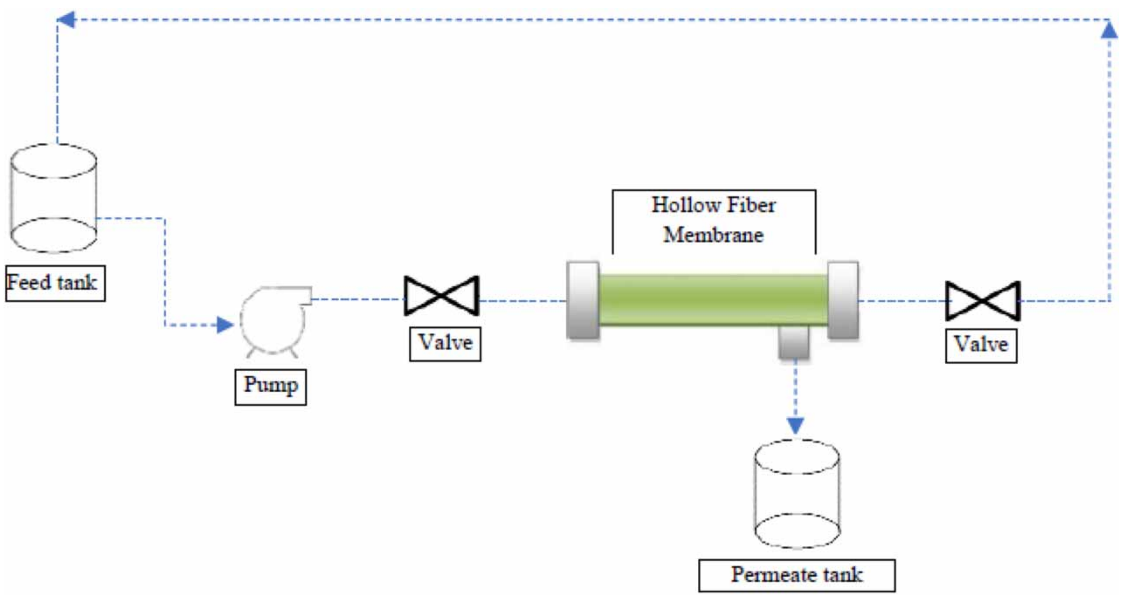

Figure 1 | Water purification process using PES hollow fiber membrane.

Table 1 | Different filtration methods used for raw water sources

	Different filtration methods
A	Cross-flow configuration fully open at the opening-end of the membrane
B	Cross-flow configuration half-open at the opening-end of the membrane
C	Dead-end configuration

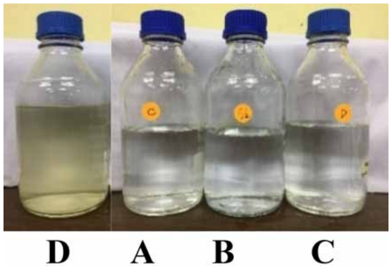

Figure 2 | Filtered water samples for RW1 using filtration methods A, B and C. D is the non-filtered water sample.

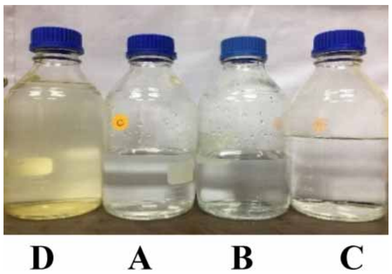

Figure 3 | Filtered water samples for RW2 using filtration methods A, B and C. D is the non-filtered water sample.

is the raw sample obtained from different locations (D), the second is the cross-flow filtration with the fully open configuration (A) followed by the half-open configuration (B) for the third bottle. The last bottle is the filtered sample from the dead-end configuration (C). Figures 2 and 3 show that the filtered samples of A, B and C are clear and transparent after the filtration process and are very different to the raw samples which are yellowish transparent liquids. However, the organic-like odour of the lake water was present in all filtered samples even after the filtration process.

Performance of the membrane

The performance of the membrane was based on permeability and flux tests of the ultrafiltration process. As shown in Figure 4, filtration method C for RW1 has the highest permeability, $0.0464\ kg/m^2 \cdot h \cdot Pa$ while filtration method A has the lowest permeability, $0.0100\ kg/m^2 \cdot h \cdot Pa$. The result is the same for sample RW2. Flow configuration A has the lowest permeability because there is less resistance (less pressure development) on the opening of the other end of the membrane due to the fully open configuration, hence water has the tendency to flow to the retentate side rather than passing through the membrane. The resistance at the opening of the membrane is higher for filtration method B, as the end of the membrane was set to half open configuration, so the higher resistance (more pressure build-up) at the end will likely force the water to permeate through the membrane. Hence, the permeability of method B is higher than method A. Filtration method C has the highest permeability due to the dead-end configuration where the other end of the membrane is fully closed. The high force of feed will force the sample to permeate through the membrane with no retentate side, hence it has the highest permeability.

Flux is defined as the volume of the sample flowing through the membrane per unit area per unit time. Filtration method C (Figure 5) has the highest flux, $5{,}595.81\ kg/m^2 \cdot h$ while filtration method A has the lowest flux, $777.21\ kg/m^2 \cdot h$ for RW1. The same result was obtained for RW2. The higher the pressure applied during filtration, the higher the flux as more water was forced to flow through the membrane per unit area per unit time. Filtration method C has the highest flux due to several factors, it has the highest pressure applied during filtration and the retentate side of the membrane is closed. Hence, all the raw samples were forced to penetrate through the membrane with the pressure applied.

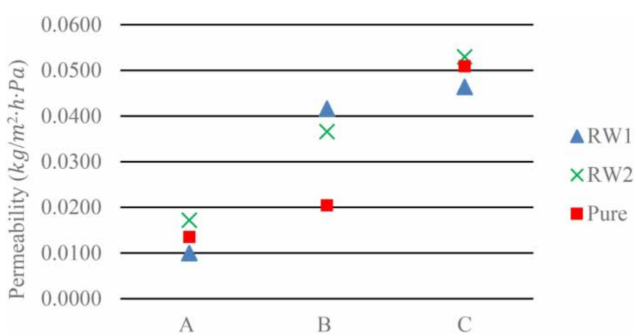

Figure 4 | Permeability vs different filtration configurations.

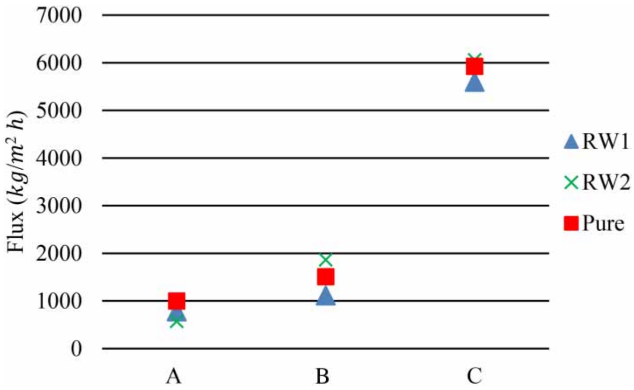

Figure 5 | Flux vs different filtration configurations.

Water quality index

WQI is a method used by the DOE to evaluate the state of water quality trends in a river by combining numerous water quality parameters into one concise and objective value. Based on the results shown in Figure 6, WQI for raw water sample (D) from RW1 (Varsity Lake) is 82.17 while RW2 (Taman Jaya) shows a value of 82.87. WQI values of both samples fall into Class II according to the Interim National River Water Quality Standards provided by the DOE (Zainudin 2010).

Samples A, B and C are differentiated by the different filtration configurations of cross-flow filtration and dead-end filtration and the result shows that WQI of filtration configuration C (dead-end) for both RW1 and RW2 filtered water samples has the highest reading. RW1 sample shows a WQI of 96.02 while RW2 sample shows 94.98. In fact, all of the filtered water has been categorized into Class I regardless of the filtration method but WQI of the dead-end configuration shows the highest reading. It had been proven twice that dead-end filtration is able to produce the cleanest filtered water of all the methods. Figure 7 shows the change in WQI with time for different configurations using RW1 over 6 hours. The dead-end filtration (configuration C) maintains the WQI reading compared to the other two configurations. The result is similar to that of the lab test performed by Ahmad & Shafie (2017), where they observed stable water flux and HA rejection during a 1-hour experiment with dead-end configuration.

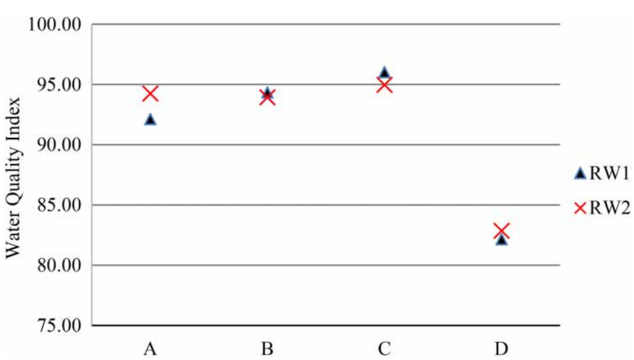

Figure 6 | WQI of filtered water samples of different filtration configurations.

Dead-end filtration can produce such a result due to certain reasons. Normally dead-end filtration is not the preferred option with a hollow fiber membrane due to its characteristic of irreversible fouling, but the occurrence of fouling is dependent on several factors, such as filtration period and concentration of suspended particles (Al-Badaii *et al.* 2013). In this research, the raw water samples obtained are considered clean and do not contain numerous suspended particles, hence the best performance of the membrane was produced during dead-end filtration as there was not much build-up of fouling on the membrane.

Although dead-end filtration shows the best performance overall, cross-flow filtration will still be the preferred option in the long run. As irreversible fouling is one of the main concerns when using a hollow fiber membrane, cross-flow filtration is able to remove the build-up from the surface of the membrane and prevent the rapid dropping of the permeate flux compared to dead-end filtration. Moreover, cross-flow filtration helps to improve the lifespan of a hollow fiber membrane by preventing irreversible fouling.

Based on the results shown for the permeate qualities of a PES membrane compared to raw water quality, it is shown that a PES membrane is able to filter a Class II water quality sample to Class I.

Dissolved oxygen

DO of the water samples analyzed ranged from 6.582 mg/l to 6.988 mg/l for RW1, and 4.048 mg/l to 6.592 mg/l for RW2 (Table 2). The highest value for both RW1 and RW2 was found using filtration method C, 6.988 mg/l and 6.592 mg/l, respectively. These results show that the permeate water, regardless of the filtration method, falls into Class II category under NWQS for Malaysian rivers (Zainudin 2010). The amount of oxygen present in water is due to the

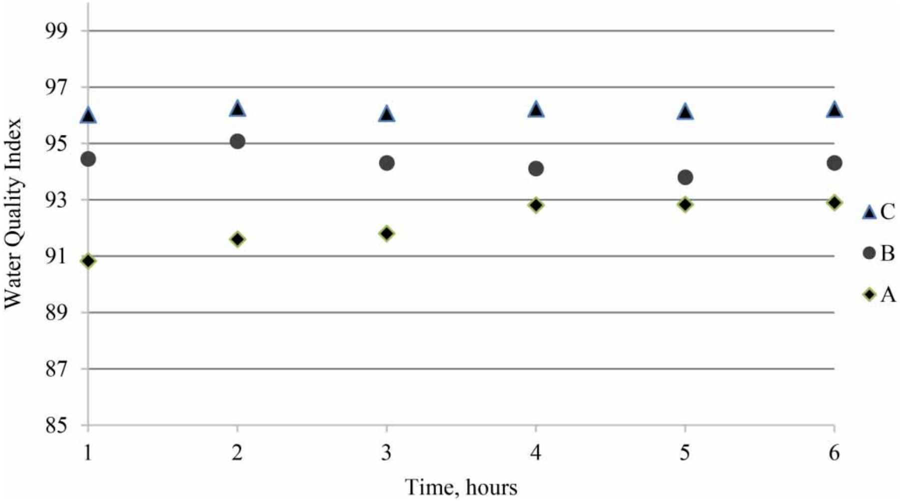

Figure 7 | Water quality index (WQI) performance with time for different filtration configurations using RW1. WQI was measured at each hour of the filtration experiment.

Table 2 | Permeate qualities for PES membrane compared to raw water quality

	RW1				RW2			
Parameter	**A**	**B**	**C**	**D**	**A**	**B**	**C**	**D**
DO (mg/l)	6.58	6.97	6.98	6.96	6.20	6.49	6.59	4.04
BOD (mg/l)	0.02	0.15	0.37	0.78	0.07	0.09	0.27	0.45
COD (mg/l)	15.40	14.40	5.60	88.20	11.20	13.60	11.40	29.60
pH	7.80	7.72	7.77	7.59	7.52	7.53	7.46	6.89
AN (mg/l)	0.09	0.05	0.05	0.12	0.03	0.0	0.03	0.10
TSS (mg/l)	7.00	0.00	0.00	16.33	6.00	1.33	2.33	14.33
Phosphate (mg/l)	8.93	4.56	6.93	14.23	8.93	4.56	6.93	14.23
Nitrate (mg/l)	0.08	0.07	0.06	0.10	0.05	0.06	0.05	0.12

result of diffusion from aquatic-plant photosynthesis and diffusion from the atmosphere.

Biochemical oxygen demand

BOD is a parameter which indicates the amount of organic matter present in water. Lower BOD values indicate good quality water while higher BOD values represent polluted water. The concentration of BOD ranges from 0.024 mg/l to 0.788 mg/l (Table 2). The lowest BOD values are found with filtration method A of RW1 and RW2, 0.024 mg/l and 0.077 mg/l, respectively. All of the values falls into Class I water quality, which is <1 mg/l. The BOD result shows that the PES membrane is able to remove the organic matter during filtration. BOD concentrations are inversely proportional to DO concentrations, so when BOD increases, there will be a decrease in DO as the oxygen is consumed by the higher amount of organic matter in the water (Al-Badaii *et al.* 2013).

Chemical oxygen demand

COD is a measure of the capacity of water to consume oxygen during the decomposition of organic matter. The lowest COD is 5.6 mg/l for RW1 (Class I) and 11.2 mg/l for RW2 (Class II) (Table 2). Lower COD indicates less oxidizable organic material in the sample, and therefore a low pollution level. Overall, the results are acceptable as they are below the acceptable limit of NWQS, which is 50 mg/l and under (Al-Badaii *et al.* 2013).

pH

The pH of the filtered samples is maintained in the range of 6 to more than 7 (Table 2). The minor variations of pH might be due to photosynthesis and respiration cycles of algae in the water as pH is normally controlled by the factor of ionic balance between carbonate, carbon dioxide and bicarbonate ions. Overall, the range of pH is appropriate and suitable for aquatic life (Al-Badaii *et al.* 2013).

Ammoniacal nitrogen

The concentration of ammonia-nitrogen (NH_3-N) of RW1 and RW2 ranges from 0.03 mg/l to 0.12 mg/l. The lowest value of AN in RW1 is 0.05 mg/l (Class I) and 0.03 mg/l (Class I) in RW2 (Table 2). Both ranges are acceptable as the maximum threshold level of NH_3-N which supports aquatic life is 0.9 mg/l (DOE 2006). A concentration higher than 0.9 mg/l would be toxic to aquatic life.

Total suspended solids

TSS ranges from a minimum of 0 mg/l to 16.33 mg/l for both RW1 and RW2 (Table 2). The lowest TSS value of 0 mg/l for RW1 occurs with both filtration methods B and C. For RW2, the lowest TSS value was 1.33 mg/l for filtration method B. Overall, the PES membrane has the ability to filter out the suspended solids to a concentration of less than 25 mg/l, which is categorized as Class I of NWQS.

Nitrate and phosphate

Phosphate and nitrate are considered to be two of the most essential nutrients in natural water to facilitate the growth of plant material, especially algae. The specific amount of phosphorus present is critical in determining the level of growth of algae in water. Excessive amounts of nitrate and phosphate will lead to eutrophication where algae will grow to an excessive amount with overly enriched minerals and nutrients. Hence, it can cause ecological changes that result in loss of plant and animal species and also have negative impacts on the use of water (Vollenweider 1970).

The result of nitrate analysis shows a maximum of 0.12 mg/l and a minimum of 0.05 mg/l for both RW1 and RW2 (Table 2). The values of nitrate concentration are in the acceptable range according to NWQS. As for phosphate concentration, it shows a highest reading of 14.23 mg/l and a lowest reading of 4.567 mg/l (Table 2). Higher phosphate concentrations might pose a risk of eutrophication occurrence and phosphate has to be controlled to prevent algae blooms forming.

Biological observations

The purpose of coliform plate testing is to determine the suitability of drinking water: it is a standard way to indicate the presence of harmful pathogens in water. *Escherichia coli* is a type of coliform bacteria and its presence is a strong indication of animal waste contamination or sewage (Ishii *et al.* 2006). Based on drinking water quality standards provided by the Ministry of Health of Malaysia, there should be no coliforms present in raw water and drinking water quality (Huang *et al.* 2015).

Based on the results shown in Figure 8 on the coliform plates for RW1 and RW2, the number of coliforms ranged from a minimum of 22 to a maximum of too numerous to count (TNTC). There are *E. coli* present in the untreated lake water, based on several blue dots appearing in sample D for both lake samples. Meanwhile, the lowest number of coliforms (observed from the red dot appearances) is found on the permeate sample from the dead-end filtration method while the highest number was found in the raw water sample of both RW1 and RW2. However, no blue dots appear in all filtered water samples, leading to the conclusion that all filtration methods can remove *E. coli* from both water sources. Further treatment is recommended to remove the other coliforms, such as ultraviolet (UV) light, ozonation or chlorination (Pal *et al.* 2006).

Comparison of filtered water with drinking water quality

The best filtered water quality based on all three different configurations is dead-end filtration (C) as it has the highest

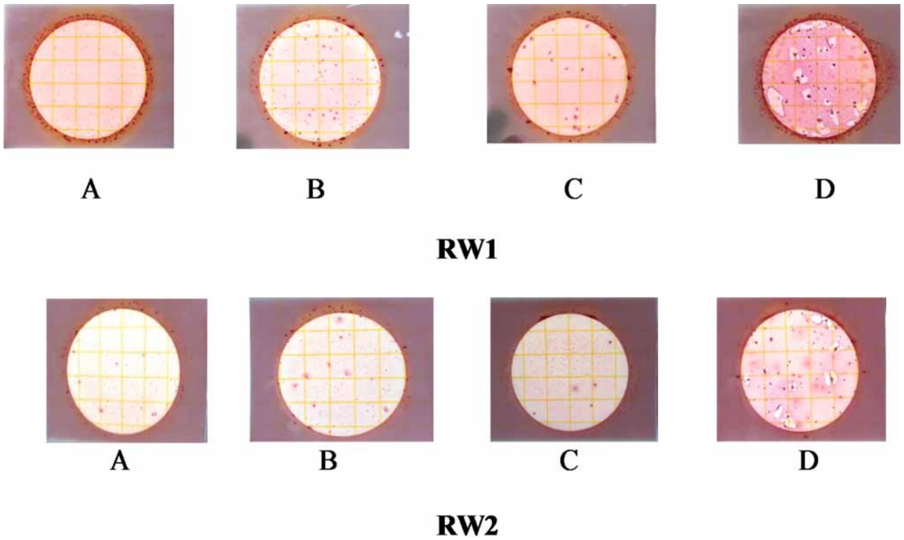

Figure 8 | Coliform count plates.

concentration of DO, is in the suitable range of pH, and has the lowest concentrations of AN and nitrate (Table 3). After comparison with drinking water standards from the DOE, the filtered water is found to comply with the standard and is suitable to be a source of drinking water (Huang *et al.* 2015).

CONCLUSION

Both the raw water samples from Varsity Lake at the University of Malaya and lake water from Taman Jaya Park are characterized as Class II of NWQS by the DOE. The permeability of the dead-end filtration method is the highest due to the highest resistance of water flow when the opening-end of the membrane is fully closed, while filtration method A has the lowest permeability due to the lowest resistance applied. Dead-end filtration also has the highest flux due to the higher pressure applied. Although all three filtered water samples were categorized as Class I of NWQS, dead-end configuration shows the best WQI and adherence to drinking water standards. The fabricated PES membrane is able to filter raw water samples of WQI Class II to WQI Class I water quality and adhere to drinking water standards, and the dead-end configuration can provide the the best filtered water quality.

Table 3 | Comparison of parameters of filtered water and drinking water quality

Parameter	RW1 Method C	RW2 Method C	Drinking water standard
DO (mg/l)	6.988	6.592	6.0–9.0
pH	7.757	7.460	6.5–9.0
AN (mg/l)	0.050	0.033	Max: 1.5
Nitrate (mg/l)	0.060	0.050	Max: 10

ACKNOWLEDGEMENTS

Deepest gratitude to University Sains Malaysia (USM) in providing the PES-HF membrane for this project. The author would like to convey great gratitude to the University of Malaya for the research funding via Bantuan Penyelidikan Kecil (BKP), BK016-2017 and Research University (RU) Grant RU019Q-2017.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this paper is available online at https://dx.doi.org/10.2166/ws.2019.184.

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First received 21 July 2019; accepted in revised form 22 November 2019. Available online 9 December 2019