https://doi.org/10.31436/iiumej.v21i2.1245

A COMPARATIVE STUDY ON TREATMENT TECHNOLOGIES FOR SEWAGE RECLAMATION: A FOCUS ON THE DISINFECTION PROCESS

NOORINI IZZATI MOHAMAD MAZUKI[1], TEOW YEIT HAAN[1,2*] AND ABDUL WAHAB MOHAMMAD[1,2]

[1]*Department of Chemical Engineering and Process,*
[2]*Research Centre for Sustainable Process Technology (CESPRO),*
Faculty of Engineering and Built Environment,
Universiti Kebangsaan Malaysia, 43600 UKM Bangi,
Selangor Darul Ehsan, Malaysia

**Corresponding author: yh_teow@ukm.edu.my*

(Received: 24th September 2019; Accepted: 8th April 2020; Published on-line: 4th July 2020)

ABSTRACT: Selection of suitable disinfection technology is necessary with regards to wastewater reclamation goals. In this work, the performance of various disinfection technologies - single disinfection units and integrated disinfection systems - on local sewage was studied for non-potable reuse. Disinfection units used as stand-alone units include ultraviolet (UV) disinfection, chlorination, microfiltration (MF), and ultrafiltration (UF). The integrated disinfection system consists of UV or chlorination as the primary disinfection unit incorporated with either MF, UF, multi-media or granular activated carbon as pre-treatment. The performance of these disinfection units and integrated processes were evaluated based on the percentage of removal of biochemical oxygen demand, chemical oxygen demand, total suspended solids, ammoniacal nitrogen, nitrate nitrogen, phosphorus, *Escherichia coli*, and trihalomethane in bench-scale disinfection systems. The single unit of PES20kDa membrane and the integrated disinfection system of UF-Cl showed the most effective treatment among single disinfection units and integrated systems, respectively. The results showed that almost all disinfection units and integrated disinfection processes were useable for restricted and unrestricted area non-potable applications according to United State Environmental Protection Agency (US EPA) water reuse guidelines and managed to fulfil Singapore grey water quality for recycling.

ABSTRAK: Pemilihan teknologi penyahjangkitan kuman yang sesuai adalah perlu selaras dengan matlamat pemulihgunaan air buangan. Kajian ini adalah tentang prestasi pelbagai teknologi penyahjangkitan kuman - unit tunggal penyahjangkitan kuman dan sistem penyahjangkitan kuman bersepadu pada air sisa kumbahan tempatan dikaji bagi penggunaan semula air minuman. Unit tunggal penyahjangkitan kuman yang digunakan mempunyai penyahjangkitan kuman ultraungu (UV), pengklorinan, mikro penurasan (MF), dan ultra penurasan (UF). Manakala, sistem penyahjangkitan kuman bersepadu terdiri daripada UV atau pengklorinan sebagai unit penyahjangkitan kuman utama yang digabungkan bersama samada dengan MF, UF, multi-media atau karbon teraktif berbutir sebagai proses pra-rawatan. Prestasi unit tunggal penyahjangkitan kuman dan proses-proses bersepadu dinilai berdasarkan pada peratus penyingkiran keperluan oksigen biokimia, permintaan oksigen kimia, jumlah pepejal terampai, nitrogen ammonia, nitrogen nitrat, fosforus, *Escherichia coli*, dan trihalometana dalam sistem penyahjangkitan kuman berskala-makmal. Unit tunggal penurasan ultra membran PES20kDa dan sistem penyahjangkitan kuman bersepadu UF-Cl menunjukkan masing-

masing paling efektif dalam rawatan unit tunggal dan sistem penyahjangkitan kuman bersepadu. Keputusan menunjukkan bahawa hampir semua unit tunggal penyahjangkitan kuman dan proses penyahjangkitan kuman bersepadu boleh diguna pakai bagi aplikasi terhad dan tidak terhad mengikut garis panduan penggunaan semula air sisa rawatan yang ditetapkan oleh Agensi Pelindungan Alam Sekitar Amerika Syarikat (US EPA) dan kualiti kitar semula air sisa Singapura.

KEYWORDS: *sewage reclamation; single disinfection unit; integrated disinfection system; water reuse; Escherichia coli*

1. INTRODUCTION

Sewage reclamation has been widely practiced in various regions around the world, in line with increasing water demand and public awareness related to safe and clean water issues. Meanwhile, various studies are still on-going on the potential of wastewater reclamation and reuse in Malaysia. In early 2015, Malaysia faced water shortages that affected more than seven million users in the Klang Valley, due to drought which led to the reduction of the water level at the Sungai Selangor dam [1]. This issue indicates the importance of sustainable water management since there is no guarantee of constant water supply even for high rainfall countries. About 4,500 MLD of sewage equivalent to 25% of national potable water is being treated in Indah Water Konsortium (IWK) sewerage treatment plant (STP) in Malaysia per day with 96.7% sanitation coverage available in urban areas [2-4]. Hence, sewage effluent should be considered as a valuable resource and can provide important positive trade-off to overcome the water crisis in this country.

Sewage in Malaysia is commonly allowed to undergo preliminary, primary, and secondary treatments before being discharged into the environment. Typically, centralized STPs produced high-quality final discharge effluent that is well below the Department of Environment (DOE) Malaysia Standard A limit [5]. Given the intent to promote the reuse of treated sewage, which is considered to be a green technology initiative, the treated effluent could be used as a water resource for non-potable applications. However, the raw effluent is unsafe for direct use as it still contains high concentration of pathogens (both *Salmonella spp*. and *Escherichia coli (E. coli)* that were present at 10^5 CFU/100 mL in Malaysia sewage discharged effluent) [6]. Therefore, it is important to disinfect the final discharge effluent prior to its supply to end users to lower the risk of biological hazard.

Chlorination and ultraviolet (UV) processes are the most extensively used disinfection technologies. Chlorination has been widely investigated in the past several decades for wastewater applications. Despite numerous advantages offered by chlorination, its potential generation of carcinogenic disinfection by-products (DBPs) has made it a less favourable disinfectant [7]. On the other hand, the adoption of UV light for wastewater disinfection has grown significantly to compete with chlorination since it would not produce toxic treated effluent, is safe in operation, and has a small footprint [8,9]. Today, thousands of municipalities in North America have converted from chemical-based disinfection technology such as chlorine gas to UV [10].

As the efficiency of chlorination and UV disinfection varied depending on the characteristics of sewage's discharged effluent, both systems were suggested to be coupled with an advanced technology that could act as a physical pre-treatment prior to the primary disinfection process in order to enhance the effectiveness of chlorination or UV disinfection and improve the quality of the treated effluent to meet with the stringent wastewater reuse limit established by United State Environmental Protection Agency (US

EPA) and by other countries [11]. Membrane filtration and adsorption process could be applied as the pre-treatment to reduce the colloidal and particulate constituents in wastewater to enhance the effectiveness of the primary disinfection unit.

Adsorption technology using granular activated carbon (GAC) is a good option for the removal of macro-contaminants. GAC could perform dual functions - as an adsorbent and filter to the influent. Its ability as a macrofilter-adsorbent medium has attracted strong interest from many parties to utilize at various wastewater treatment plants [12-15]. On the other hand, membrane filtration applying a physical separation mechanism in its operating process is well-known to be able remove microbial and contaminants in sewage. Microfiltration (MF) and ultrafiltration (UF) are the membranes commonly used to remove microorganisms and turbidity. The selection on the feasible disinfection technology must be done accordingly, suitable to the target sewage reclamation's objective. Unfortunately, there are still limited numbers of studies that provide technical feasibility information on the implementation of disinfection technology in Malaysia for sewage reclamation. Hence, this research aims to study and evaluate the performance of various commercially available single disinfection units and integrated disinfection systems on Malaysia sewage for non-potable water reuse applications.

2. MATERIALS AND METHODS

2.1 Sampling of Final Discharge Effluent

Effluent used in this study was collected from a secondary effluent discharge drain at STP located in Selangor, Malaysia. Currently, the plant operates up to secondary treatment using sequencing batch reactor (SBR) system. The raw effluent discharged from this plant was stipulated under Standard B limits based on the Department of Environment (DOE) standard. Characterization of raw effluent was done immediately after each sampling to ensure the reliability of the measurements. In this study, 30 L volume of sample was required for each experiment. Hence each experiment was conducted using different batches of raw effluent.

2.2 Materials

A calcium hypochlorite [$Ca(ClO)_2$] tablet manufactured by Tosoh Corporation, Japan was used as the chlorine source. Four different types of commercial flat sheet membranes: two MF membranes and two UF membranes were used in this study. HVLP00010 and PVDF021M membranes having membrane pore size of 0.45 μm and 0.2 μm were used to represent the MF membranes, respectively. Meanwhile, PVDF1001M and PES20kDa membranes having molecular weight cut-off (MWCO) at 100 kDa and 20 kDa each were selected to represent UF membranes, respectively. GAC (mesh size: 8×30, iodine value: 1000 to 1200 mg/g, ash content: < 3%) synthesized by Laju Carbon Products Sdn. Bhd, Malaysia was used as the adsorbent for pre-treatment prior to the disinfection process. Environ multi-media (EMM) capsule (height: 6 cm, diameter: 2 cm) acted as the housing for GAC was supplied by EnviroSource (M) Sdn. Bhd, Malaysia.

2.3 Bench-scale Integrated Disinfection System

The single disinfection units involved in this study include UV, chlorination, MF, and UF. Whereas, for integrated disinfection processes, UV disinfection and chlorination acted as the primary disinfection unit incorporated with MF, UF, EMM or GAC as the pre-treatment unit.

https://doi.org/10.31436/iiumej.v21i2.1245

Figure 1 shows the schematic diagram of the bench-scale integrated disinfection system comprising of MF/UF-chlorination and MF/UF-UV. Fig. 2 shows the schematic diagram of a bench-scale integrated disinfection system comprising of GAC/EMM-chlorination and GAC/EMM-UV.

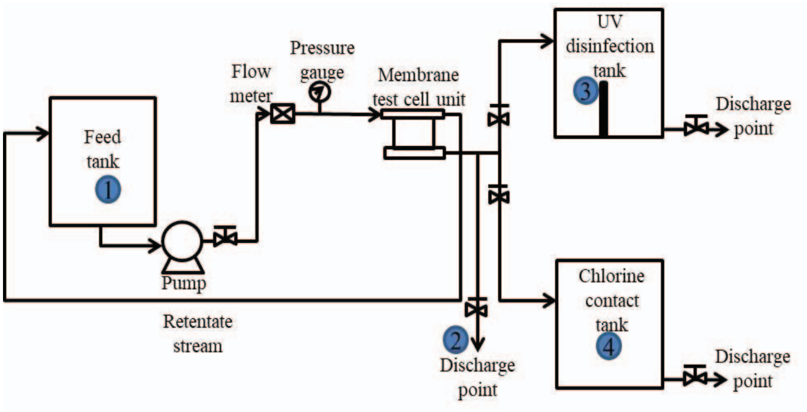


Fig. 1: Schematic diagram of bench-scale integrated disinfection system (MF/UF-chlorination and MF/UF- UV) with sampling points: (1) at feed tank (2) at discharge point after the membrane unit (3) at UV disinfection tank (4) at chlorine contact basin.

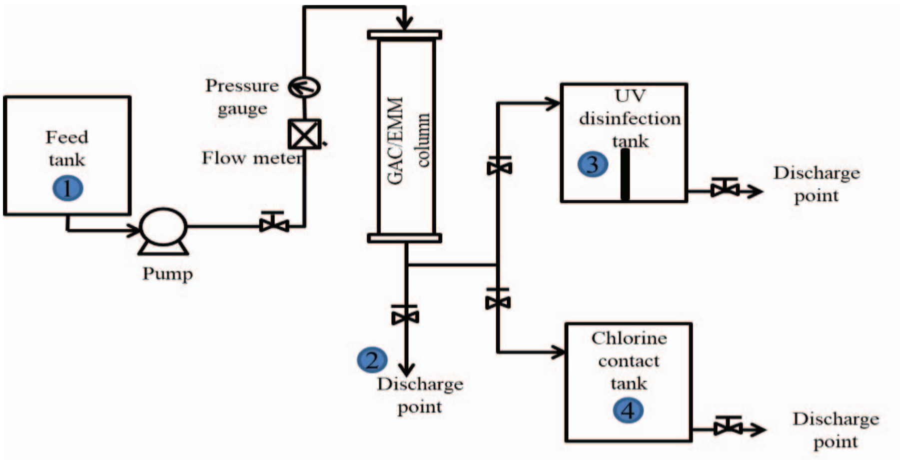


Fig. 2: Schematic diagram of bench-scale integrated disinfection system (GAC/EMM column-chlorination and GAC/EMM column–UV) with sampling points: (1) at feed tank (2) at discharge point of GAC/EMM column (3) at UV disinfection tank (4) at chlorine contact basin.

2.3.1 Preliminary Study

Preliminary study was conducted for UV disinfection and chlorination to investigate the optimum UV dosage and chlorine dosage in treating raw effluent. The selection of optimum UV dosage and chlorine dosage was determined at the condition when there was no *E. coli* detected in the treated effluent.

a) UV Disinfection

UV exposure time in treating raw effluent was varied for 5 minutes, 30 minutes, 60 minutes, 120 minutes, and 180 minutes while the intensity of UV lamp was kept constant at 15 Watts.

b) Chlorination

Chlorine dosage applied for the raw effluent ranged from 0 mg/L to 30 mg/L while the contact time for chlorine treatment was kept constant at 30 minutes.

2.3.2 Disinfection Technology

a) GAC

GAC/EMM adsorption column was filled with GAC at a filling ratio of 0.5. Next, the raw effluent was fed into GAC/EMM adsorption column from the top at constant flow rate of 50 L/day with empty bed contact time (EBCT) at 12.73 minutes.

b) EMM

EMM capsules used for EMM pre-treatment were half-filled with GAC and closed tightly. EMM pre-treatment was carried out in a GAC/EMM adsorption column where the EMM capsules were used to replace GAC in adsorption column at a filling ratio of 0.5. Subsequently, the raw effluent was fed into the GAC/EMM adsorption column from the top at constant flow rate of 50 L/day. The pre-treated raw effluent was then transferred to the primary disinfection unit for further treatment.

c) Membrane Filtration

The commercial flat sheet membrane was cut into a rectangular shape (19.1 cm × 14.0 cm) with membrane effective surface area of 155 cm^2, laid on top of the cross-flow stainless steel membrane test cell unit and clamped tightly. Operating pressure for both MF and UF membranes was 2 bar. The permeate flux (J) was determined using Eq. (1):

$$J = \frac{V}{At} \tag{1}$$

where V is the permeate volume (L), A is the membrane effective surface area (m^2), and t is the permeation time (h).

d) UV Disinfection

UV disinfection was carried out in the UV disinfection tank by immersing a 15 Watt UV-C lamp (Dolphin KW, China) at the centre of UV disinfection tank. The effective exposure area for UV disinfection was 0.3 m in diameter and 0.3 m in height. The intensity of UV light at 254 nm was measured using the PM100D optical power and energy meter with S120VC photodiode (Thorlabs, Germany) after the low-pressure UV-C lamp was switched on for 30 minutes. UV exposure time in single UV disinfection unit and integrated UV disinfection system was based on the results obtained from the preliminary study for UV disinfection. The applied UV dosage was calculated using Eq. (2) and Eq. (3) [16, 17].

$$I_{avg} = I_o \left(\frac{1 - e^{-d \times In\frac{1}{T}}}{d \times In\frac{1}{T}} \right) \tag{2}$$

$$UV\ Dosage = I_{avg} \times t \tag{3}$$

where I_{avg} is the UV-C intensity per unit area (mW/cm^2), t is the UV exposure time, I_o is the UV-C incident irradiance (mW/cm^2), d is the depth of the raw effluent perpendicular to the UV lamp, and T is the UV-C transmittance at 254 nm with cell path length of 1 cm. I_o is constant at 0.475 mW/cm^2.

https://doi.org/10.31436/iiumej.v21i2.1245

e) Chlorination

The chlorination process was carried out in a chlorination tank for 30 minutes. The chlorine dosage added to the single chlorination unit and integrated chlorination system was according to the results obtained from the chlorination preliminary study. Next, the treated raw effluent was added with 4 w/w% of $Na_2S_2O_5$ solution for de-chlorination purposes after 30 minutes of chlorination process.

2.4 Water Quality Analysis

Efficiency of commercially available disinfection units and integrated disinfection processes in treating the raw effluent was assessed based on the treated effluent quality. The measured parameters included temperature, pH, biochemical oxygen demand (BOD_5), chemical oxygen demand (COD), total suspended solids (TSS), ammoniacal-nitrogen (NH_3-N), nitrate-nitrogen (NO_3-N), phosphorus (P), *E. coli*, and trihalomethanes (THM). The percentage of removal for each parameter was calculated using Eq. (4):

$$Percentage\ of\ removal\ = \frac{(C_f - C_p)}{C_f} \times 100\% \qquad (4)$$

where C_f and C_p are the specific parameter's concentration in the feed water sample and treated effluent, respectively. The measurement for each sample was tested in triplicates.

3. RESULTS AND DISCUSSION

3.1 Characterization of the Raw Effluent

The characteristics of the raw effluent samples were summarized in Table 1. The data was obtained from 17 samples to minimize analytical error. The raw effluent contained a high quantity of *E. coli* in that had far exceeded the water reuse standard for any non-potable applications. High quantity of *E. coli* has high potential to be a health hazard. Hence, direct use of the raw effluent for any purpose is not suggested without an appropriate disinfection treatment. On the other hand, the wide range of the raw effluent quality indicated the need for a pre-treatment process prior to the primary disinfection unit for better disinfection performance.

Table 1: Characteristics of the raw effluent samples

Parameter	Unit	Effluent quality
Temperature	°C	21.93-28.90
pH	-	7.05-8.21
TSS	mg/L	2-21
NH_3-N	mg/L	10.00-24.03
NO_3-N	mg/L	0.02-1.11
P	mg/L	0.50-3.71
COD	mg/L	27-59
THM	µg/L	112.00-246.98
E. coli	CFU/100 mL	608-635000
BOD_5	mg/L	4-8

3.2 Preliminary Study

3.2.1 UV Disinfection

Two raw effluent samples: Sample 1 with low number of *E. coli* (~700 CFU/100 mL) and Sample 2 with high number of *E. coli* (~26000 CFU/100 mL) were sampled at different sampling periods and used as the feed water samples for the UV disinfection preliminary study. Figure 3 depicted the results obtained from the UV disinfection preliminary study. As shown in Fig. 3, 5 minutes of UV exposure time is sufficient to totally disinfect *E. coli* in Sample 1. For 5 minutes of UV exposure time, 28.14 mWs/cm² of UV dosage has been transmitted with average UV transmittance (UVT) of 72.27%. Previous study conducted by Wahid et al (2012) reported that the UV dosage needed to inactivate 1-3 log of *E. coli* in secondary wastewater effluent was in the range of 27.80 – 83.40 mWs/cm² [18]. Hence, UV dosage of 28.14 mWs/cm² used in this study was in good agreement for the UV dosage applied for disinfection.

However, 5 minutes of UV exposure time is not able to produce *E. coli* free effluent for Sample 2. 500 CFU/100 mL *E. coli* still remained in the treated effluent after exposure to 5 minutes of UV light. Hence, the UV exposure time was further prolonged. By referring to Fig. 3, 30 minutes of UV exposure time is required to fully disinfect raw effluent which contained a high quantity of *E. coli (*4.4 log). The UV dosage applied for 30 minutes of exposure time was 168.86 mWs/cm². It was in line with the finding obtained by Anastasi et al (2013), where 40-80 mWs/cm² of UV dosage was required to inactivate 1.7-1.9 log *E. coli* from secondary treated effluent [19]. Hence, approximately 160 mWs/cm² of UV dosage is required to inactivate 4 log of *E. coli* in raw effluent.

As a conclusion for the UV disinfection preliminary study, UV dosage of 28.14 mWs/cm^2 produced from 5 minutes of UV exposure time is sufficient for effluent containing low quantity of *E. coli*. On the other hand, UV dosage of 168.86 mWs/cm^2 produced from 30 minutes of UV exposure time is recommended to be applied for the single UV disinfection unit, where high UV radiation was required to penetrate through the effluent with low water quality or having huge quantity of *E. coli*.

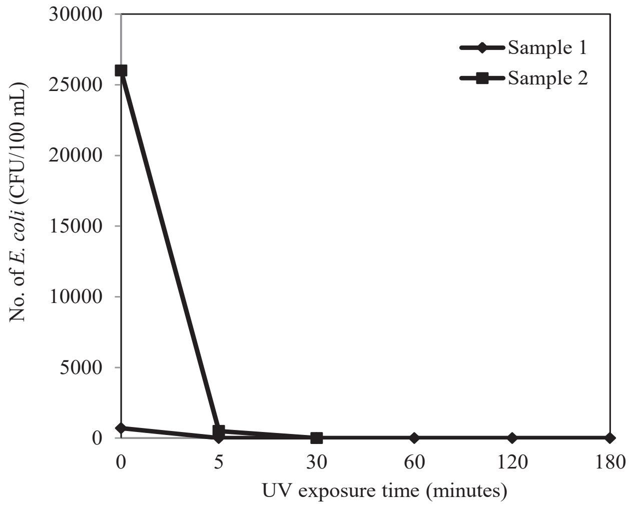
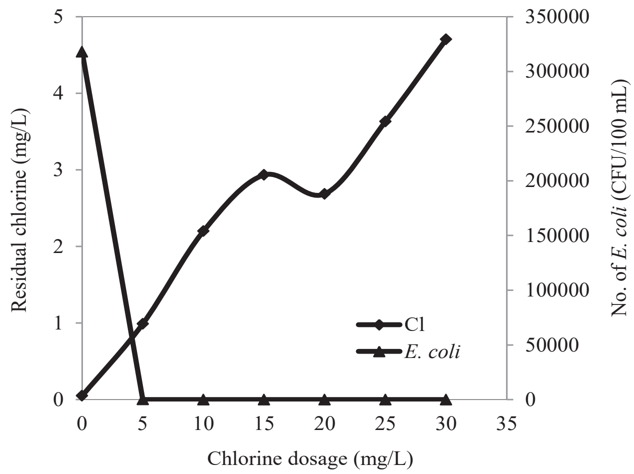


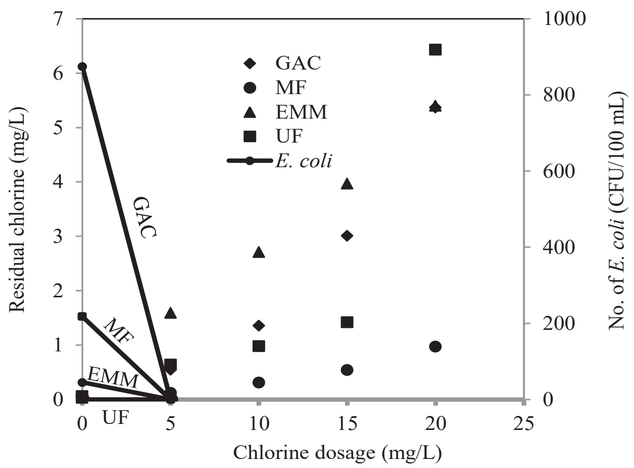
Fig. 3: Effect of UV exposure time towards *E. coli* removal for different raw effluent quality.

3.2.2 Chlorination

The raw effluent samples underwent a chlorination breakpoint study to determine the optimum chlorine dosage applied for the single disinfection unit and subsequently, the integrated disinfection system. Figure 4 showed the chlorination curve profile for both the raw effluent and the samples pre-treated with GAC, EMM, MF, and UF. As presented in Fig. 4, the chlorination curve profile for a single chlorination unit showed a typical "hump-and-dip" pattern. The "hump" zone with a peak appeared at 15 mg/L chlorine dosage corresponded to the formation of chloramines compounds in chlorinated raw effluent after chlorine reacted with inorganic reducing compounds [20]. Chloramine compounds were formed through the oxidation-reduction and substitution reactions between hypochlorite available in $Ca(ClO)_2$ (chlorine source in this study) and ammonia or ammonia-like compounds, such as amines groups, present in the raw effluent [20]. The destruction of chloramine compounds subsequently occurred at higher chlorine dosage as the chlorination curve profile switched to the "dip zone". The ammonia or ammonia-like compounds were oxidized by chlorine and produced nitrogen-free gas [21]. This phenomenon caused the concentration of residual chlorine in raw effluent to decline.



(a)



(b)

Fig. 4: Chlorination curve profile for (a) raw effluent and (b) pre-treated raw effluent.

The minimum point of the "dip zone" in the chlorination curve profile is known as the chlorination breakpoint. It indicated the minimum chlorine dosage required in a chlorination process to react with organic and inorganic substances contained in the water sample and to disinfect the bacteria as it contained persistent chloramines that had not yet been destroyed. By referring to the chlorination curve profile in Fig. 4(a), the chlorination breakpoint for the single chlorination unit is 20 mg/L. The feasibility of using 20 mg/L chlorine dosage to disinfect raw effluent in the single chlorination unit is confirmed with the absence of *E. coli* in the treated effluent after 30 minutes of chlorination contact time.

On the contrary, a distinct chlorination curve profile was observed for the raw effluent pre-treated with GAC, EMM, MF, and UF in Fig. 4(b) where no chlorination breakpoint was detected. Pre-treatment using GAC, EMM, MF, and UF was expected to improve the quality of the raw effluent, thus reducing the chlorine dosage to react with reducing compounds, ammonia, and nitrogenous organics in the pre-treated effluent. Referring to chlorination curve profile in Fig. 4(b), no *E. coli* was detected in pre-treated raw effluent dosed with 5 mg/L of chlorine after 30 minutes chlorination contact time. Hence, 5 mg/L of chlorine dosage is recommended to treat the pre-treated raw effluent in the integrated disinfection system that had been pre-treated with GAC, EMM, MF, or UF.

3.3 Performance Study of the Single Disinfection Unit

Table 2 summarizes the treated effluent quality for single disinfection unit, while Fig. 5 shows the performance of the single disinfection unit on each measuring parameters. As shown in Fig. 5, most of the single disinfection units achieved outstanding performance on *E. coli* removal where no *E. coli* was detected in the treated effluent. The UV dosage (168.86 mWs/cm^2) and chlorine dosage (20 mg/L) determined from preliminary study were effective in producing treated effluent free with *E. coli*. Similarly, MF and UF membranes that have smaller pore diameter than the size of *E. coli* (2.1 μm in length and 0.6 μm in width) also successfully acted as barrier to prevent the penetration of *E. coli* and suspended solids (> 0.45 μm) through the membrane filtration unit [22]. The performance of MF and UF membranes in removing particulate matters such as *E. coli* and TSS from feed water is not affected by feed water quality. Both MF and UF membranes used in this study showed a superior performance for TSS removal where the percentage of removal was 100%. Meanwhile, no significant TSS removal was observed for chlorination and UV disinfection. This is expected since the mechanism of both chlorination and UV disinfection are just to destroy pathogens in the feed water sample. Unfortunately, the PVDF021M membrane failed to achieve total removal of *E. coli* in treated effluent even though its membrane diameter was smaller than that of the HVLP00010 membrane. This is because the PVDF021M membrane has a very porous surface morphology as compared to other commercial flat sheet membranes used in this study (depicted in Fig. 6). On the other hand, although the HVLP00010 membrane has a membrane pore diameter that is larger than the pore diameter of the PVDF021M membrane, the gridded morphology structure of the HVLP00010 membrane provided a better trapping capability than the HVLP00010 membrane, where the *E. coli* was not able to penetrate through the membrane with non-straight channels.

The trend of COD removal is analogous to TSS removal where membrane filtration has shown predominant impact compared to chlorination and UV disinfection. Similar trend is observed for both COD and TSS removal since COD is considered as part of TSS. According to Falsanisi et al. [23] the reduction of COD from feed solution using a membrane filtration process is attributed to the retaining of organic compounds by molecular sieving mechanism. It is surprising that the PVDF021M membrane (MF membrane) rejects a higher percentage of COD than the PVDF1001M membrane and the PES20kDa membrane (UF membranes) with smaller membrane pore diameters. High permeate flux of the PVDF021M membrane could be the reason for this phenomenon. High permeate flux of the PVDF021M membrane contributed to fast development of a fouling layer on top of the PVDF021M membrane surface. The developed fouling layer acted as an additional barrier to the PVDF021M membrane, eventually leading to higher removal efficiency by prohibiting more organic matter from passing through the membrane. Meanwhile, no significant COD removal was observed for chlorination and UV disinfection.

Table 2: Raw effluent quality after treated with single disinfection unit obtained from two samples.

Parameter	**Unit**	**MF**	**UF**			**UV**	**Chlorination**
		HVLP00010	**PVDF021M**	**PVDF1001M**	**PES20kDa**		
Temperature	°C	26.27±2.67	24.49±1.29	26.05±0.75	27.13±2.03	27.08±0.82	22.96±0.41
pH	-	7.55±0.53	7.82±0.13	7.56±0.38	7.82±0.19	7.58±0.11	7.42±0.14
TSS	mg/L	0±0	0±0	0±0	0±0	15±4	12±5
NH_3-N	mg/L	10.37±1.23	13.09±1.15	12.22±1.58	9.71±1.23	18.96±1.78	13.65±1.04
NO_3-N	mg/L	0.83±0.28	0.55±0.27	0.93±0.19	0.79±0.28	1.55±0.57	0.33±0.23
P	mg/L	0.87±0.11	2.18±1.13	0.76±0.13	1.60±0.11	3.51±0.36	1.99±0.18
COD	mg/L	20±0	15±3	20±2	18±4	43±1	57±8
THM	µg/L	NA	NA	NA	NA	NA	223.84±49.84
E. coli	CFU/ 100 mL	ND < 1	341±176	ND < 1	ND < 1	ND < 1	ND < 1
BOD_5	mg/L	2±0	4±1	1±0	1±0	2±1	1±0

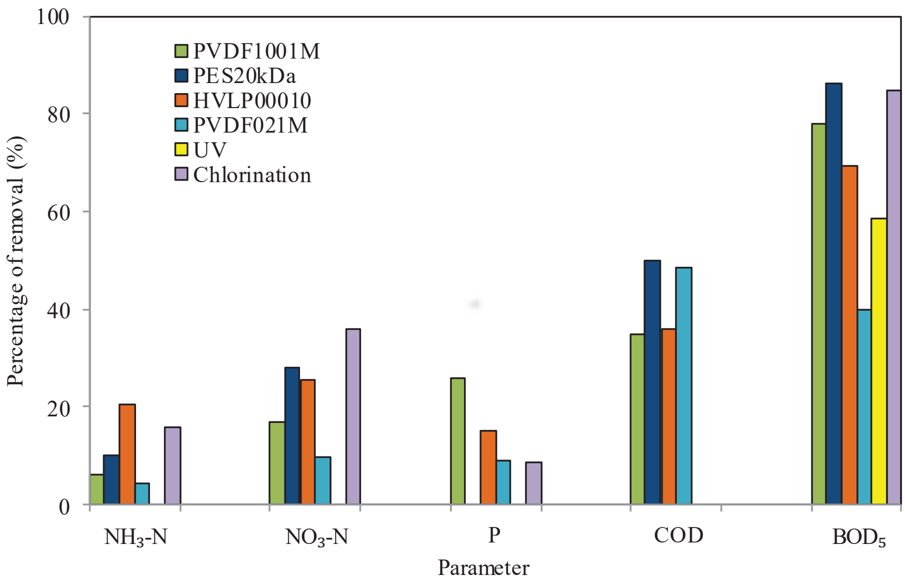
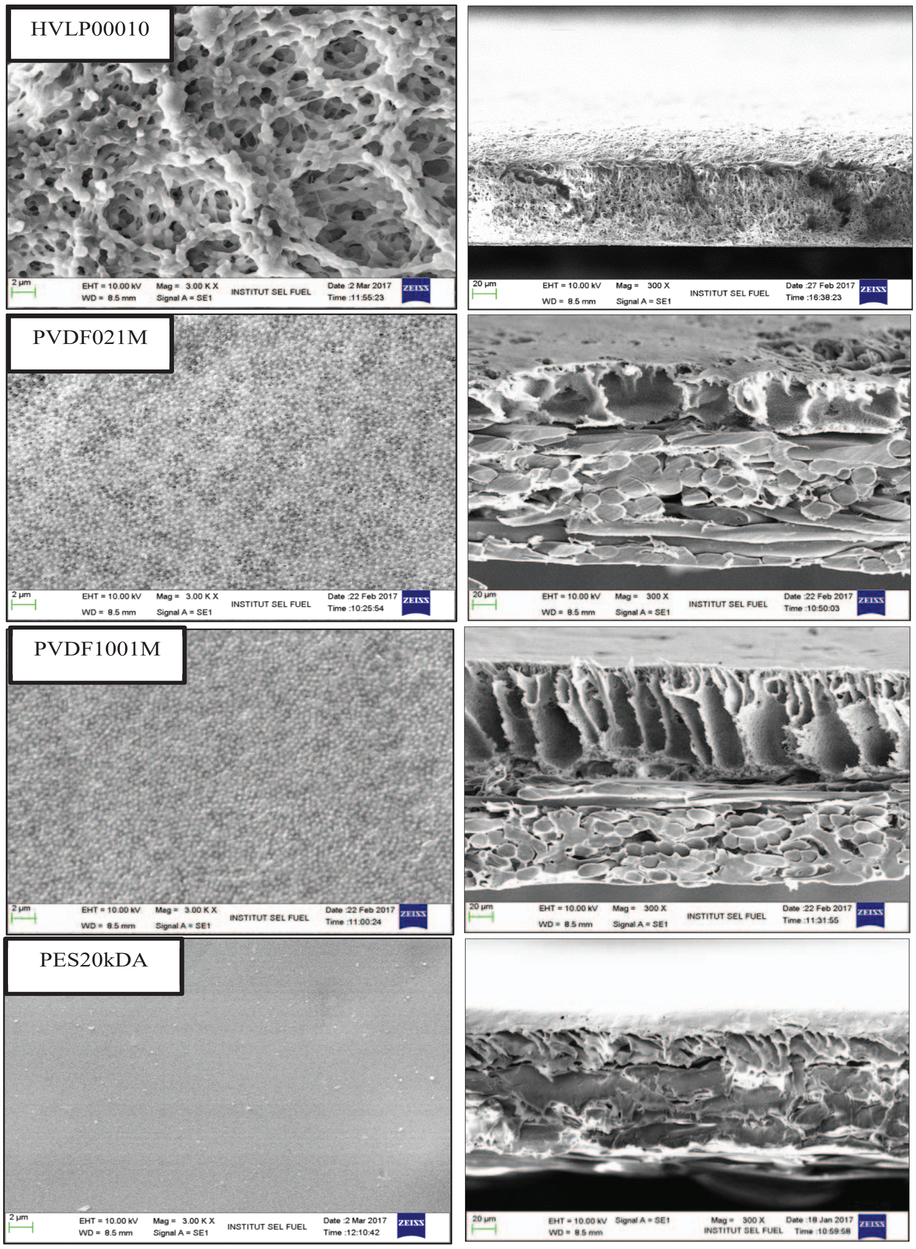


Fig. 5: Performance of single disinfection unit.

With regards to the BOD_5 removal illustrated in Fig. 5, the PVDF021M membrane contributed to the lowest BOD_5 removal, followed by UV disinfection, HVLP00010 membrane, PVDF1001M membrane, chlorination, and PES20kDa membrane with the removal percentage of 39.38, 58.70, 69.24, 77.95, 84.79, and 86.28%, respectively. Low

https://doi.org/10.31436/iiumej.v21i2.1245

BOD_5 removal by the PVDF021M membrane is probably due to large membrane pore diameter and non-gridded structure of the membrane. Hence, the trapping capability of the PVDF021M membrane towards *E. coli* is the weakest among the other membranes. Whereas, the PES20kDa membrane with the smallest membrane pore diameter is most vulnerable for the rejection of microorganisms among other membranes. Meanwhile, the average removal of BOD_5 concentration by UV disinfection could have been influenced by the presence of activated *E. coli* after UV disinfection. The presence of residual organic substrate that has not been removed during UV disinfection supported the regrowth of *E. coli* in the treated effluents. In contrast, chlorination accomplished considerably high BOD_5 removal, which proved its capability as an oxidizing agent to oxidize organic compounds. In addition, unlike UV disinfection, microorganisms that have been inactivated by chlorination cannot undergo major repair mechanisms of damaged cells.



(a) (b)

Fig. 6: (a) Surface morphology and (b) cross-sectional micrographs of flat sheet commercial membranes at the magnification of 3000x and 300x, respectively.

On the other hand, single disinfection units used in this study were not able to achieve a high percentage of nutrient (NH_3-N, NO_3-N, and P) removal. Generally, both MF and UF membranes are not effective for the removal of dissolved natural organic matter (NOM), where the hydrodynamic particle size of dissolved NOM is smaller than the MF and UF membrane pore diameters [24]. However, the slight removal of the nutrients could be attributed to nitrogen-containing anions (NO_3^-) and orthophosphate (PO_4^{3-}) that are possibly rejected due to the partial repulsion caused by the negatively charged membranes. Membrane surface charge was indicated by the surface zeta potential value presented in Fig. 7 [25]. As presented in Fig. 7, all flat sheet commercial membranes used in this study were negatively charged and increased at the trend of PVDF021M < PVDF1001M < PES20kDa < HVLP00010. Although the HVLP00010 membrane is a MF membrane with larger pore diameter, the segmented morphology of the HVLP00010 membrane has provided good trapping capability to the membrane in improving its rejection efficiency. Meanwhile, UV radiation, which only affects the pathogens, is not able to contribute in nutrient removal. Chlorination showed a better performance on nutrient removal as compared to UV radiation in which the percentage of removal for NH_3-N, NO_3-N, and P was 15.71, 36.00, and 8.67%, respectively. Still, the percentage of removal of NH_3-N, NO_3-N, and P is still not as high as expected. Theoretically, the destruction of chloramine by free chlorine at chlorination breakpoint concentration will release nitrogen (N_2) gas and allowed for the oxidation of NH_3. However, there is only a slight “dip” zone in the chlorination curve profile for our study. As a result, less chloramine was destructed by the limited available free chlorine, resulting in slight removal of NH_3-N and NO_3-N (15.71 and 36.00% of removal, respectively).

The effectiveness of the chlorination process is always compensated by the coupling of carcinogenic disinfection by-products such THM [26]. Table 3 showed the concentration of four THM compounds including chloroform ($CHCl_3$), bromodichloromethane ($CHBrCl_2$), dibromochloromethane ($CHBr_2Cl$), and bromoform ($CHBr_3$) presented in raw effluent and chlorination treated effluent. High concentration of $CHCl_3$ in the feed solution has contributed to the high concentration of $CHCl_3$ in the treated effluent after the chlorination process, exceeding the Ministry of Health (MOH) Malaysia guidelines. Thus, the utilization of chlorination treated effluent could be risky and harmful. Therefore, pre-treatment prior chlorination is necessary where a suitable pre-treatment method is expected to reduce the THM value of feed solution.

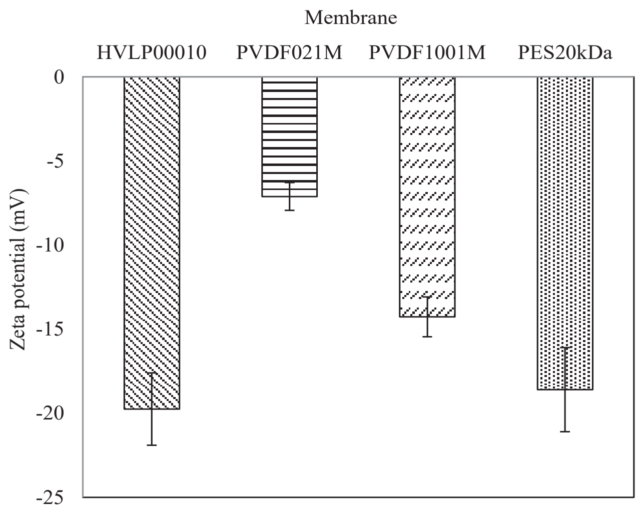


Fig. 7: Membrane surface charge for the commercial flat sheet membranes.

Table 3: THM concentration in raw effluent, chlorination treated effluent, and MOH guidelines

Compound	Raw effluent [µg/L]	Chlorination treated effluent [µg/L]	MOH guidelines [µg/L]
$CHCl_3$	213.70±33.07	222.02±51.66	200
$CHBrCl_2$	0.45±0.24	1.11±1.11	100
$CHBr_2Cl$	0.28±0.28	0.65±0.65	100
$CHBr_3$	0.61±0.61	0.07±0.07	60

Among the single disinfection units, the PES20kDa membrane with the smallest membrane pore diameter had shown the highest rejection in most of the parameters where the percentage of removal for *E. coli*, TSS, COD, BOD_5, NH_3-N, NO_3-N, and P was recorded as 100.00, 100.00, 49.77, 86.28, 9.80, 27.88, and 42.27%, respectively. Since PES20kDa membrane filtration unit was able to remove part of the nutrients and suspended solids, it was used as the pre-treatment coupled with either UV disinfection or chlorination unit (primary disinfection process) in integrated disinfection system to further enhance the effectiveness of the primary disinfection process and to improve the water quality of the treated effluent.

3.4 Performance Study of the Integrated Disinfection System

Table 4 and Table 5 summarize the treated effluent quality from the integrated disinfection system using chlorination as primary disinfection unit and treated effluent quality from the integrated disinfection system using UV as primary disinfection unit. Meanwhile, the performance of both integrated disinfection systems is illustrated in Fig. 8.

Table 4: Treated effluent quality from integrated disinfection system using chlorination as primary disinfection unit obtained from two samples.

Parameter	Unit	UF-Cl		GAC-Cl		EMM-Cl	
		Influent	Effluent	Influent	Effluent	Influent	Effluent
Temp.	°C	25.67±2.93	25.03±1.97	23.12±0.12	22.90±0.80	26.17±2.93	22.10±0.60
pH	-	7.70±0.18	7.20±0.04	7.33±0.11	7.69 ±0.05	7.21±0.22	7.13±0.38
TSS	mg/L	2±0	0±0	4±2	1±1	4±1	2±1
NH_3-N	mg/L	12.08±2.08	1.92±1.79	11.50±3.80	7.25±4.45	7.76±7.54	6.00±6.00
NO_3-N	mg/L	0.70±0.39	1.13±0.00	1.10±0.00	0.62±0.47	0.74±0.32	0.80±0.31
P	mg/L	1.63±1.13	1.70±0.02	1.99±1.21	3.82±0.15	2.05±1.15	1.75±0.87
COD	mg/L	35±2	23±5	31±1	15±1	63±31	27±0
THM	µg/L	215.04±34.20	171.81±2.73	215.04±34.20	161.52±37.04	215.04±34.20	177.44±2.54
E. coli	CFU/ 100 mL	9004±8396	ND < 1	26850±26150	ND < 1	22276±4276	ND < 1
BOD_5	mg/L	7±1	0±0	5±1	0±0	3±1	0±0

With regards to the *E. coli* removal presented in Fig. 8, almost all integrated disinfection systems are successful in producing treated effluent with no *E. coli* contamination. This result indicated that 5 mg/L chlorine dosage and 58.43 mWs/cm^2 UV dosage determined from preliminary study are able to disinfect all *E. coli* detected in raw effluent with the assistance of a pre-treatment unit. It is known that the performance of chlorination and UV disinfection greatly depends on the turbidity of the feed solution [27]. As mentioned by Winward et al (2008), the removal of TSS constituents from water samples could reduce the shielding effect which restricted the chlorine from accessing the cellular components of *E. coli* [28]. Similarly, low TSS content in the water sample allow the direct transmittance of UV light towards the targeted microorganisms for disinfection purposes. Hence, PES20kDA, GAC, and EMM pre-treatment units which help to reduce the TSS content in raw effluent had eventually helped in increasing the efficiency of chlorination and UV disinfection processes in integrated disinfection systems.

Table 5: Treated effluent quality from integrated disinfection system using UV as primary disinfection unit obtained from two samples.

Parameter	Unit	UF-UV		GAC-UV		EMM-UV	
		Influent	Effluent	Influent	Effluent	Influent	Effluent
Temp.	°C	25.67±2.93	26.35±2.25	26.17±2.93	22.10±2.00	26.17±2.93	26.50±2.80
pH	-	7.70±0.18	7.63±0.17	7.21±0.22	7.54±0.29	7.21±0.22	7.59±0.32
TSS	mg/L	2±0	0±0	4±1	1±1	4±1	3±2
NH_3-N	mg/L	12.08±2.08	6.72±0.62	7.76±7.54	5.60 ±5.60	7.76±7.54	7.07±7.07
NO_3-N	mg/L	0.70±0.39	1.11±0.01	0.74±0.32	0.11±0.07	0.74±0.32	0.66±0.46
P	mg/L	1.63±1.13	0.42±0.91	2.05±1.15	2.21±1.35	2.05±1.15	0.97±0.82
COD	mg/L	35±2	23±2	63±31	50 ±40	63±31	56±27
E. coli	CFU/ 100 mL	9004±8396	ND < 1	35500±17500	ND < 1	22276±4276	9±9
BOD_5	mg/L	7±1	2±1	3±1	3±1	3±1	1±1

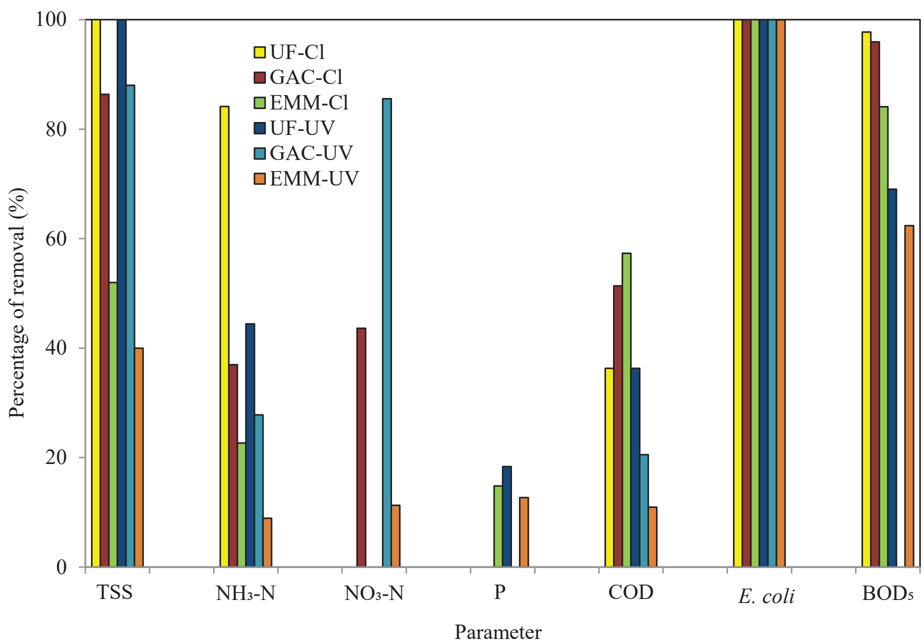


Fig. 8: Performance of integrated disinfection system.

As a comparison for TSS removal, the UF membrane is the most promising pre-treatment unit that had greatly reduced the TSS content in raw effluent through sieving effect. Therefore, greatest TSS removal is achieved by the integrated disinfection system using the UF membrane as a pre-treatment unit. The performance of an integrated disinfection system on TSS removal is followed the trend of EMM < GAC < UF. EMM and GAC pre-treatment units use the same type of adsorbent. However, the percentage of TSS removal for the EMM pre-treatment unit is slightly lower as compared to the GAC pre-treatment unit due to the loose packing of adsorbents in the EMM column. Fewer adsorption sites are available for the attachment of suspended solids, thus contributing to lower efficiency of the EMM pre-treatment unit.

With regards to the COD removal presented in Fig. 8, the integrated disinfection system using chlorination as primary disinfection unit revealed higher COD removal as compared to the integrated disinfection system using UV as primary disinfection. Besides, it is found that the trend of COD removal by integrated disinfection system using UV as primary disinfection unit is analogous to the trend of TSS removal. Hence, with higher TSS removal by UF membrane filtration unit, greater COD removal is observed for UF-UV. However, a different trend of COD removal is observed for the integrated disinfection system using chlorination as a primary disinfection unit, where the COD removal is decreased in the sequence of EMM-Cl < GAC-Cl < UF-Cl. This trend basically depends on chlorine demand needed by the system. High removal efficiency of UF pre-treatment towards organic matters has contributed to higher quality of pre-treated effluent. With the same chlorine dosage in each integrated disinfection system using chlorination as a primary disinfection system, there will be excess free residual chlorine in UF-Cl. This will eventually lead to higher COD value in UF-Cl as the excess free residual chlorine is part of the factor contributing to COD concentration. Whereas, for EMM and GAC pre-treatment where the efficiency is not so high, the remaining organic matter in the pre-treated effluent are bonded with free chlorine, therefore greatly reducing the COD concentration in the treated effluent.

For BOD_5 removal, all integrated disinfection systems using chlorination as a primary disinfection unit successfully resulted in treated effluent with high BOD_5 removal. The BOD_5 removal followed the trend of EMM-Cl < GAC-Cl < UF-Cl. High removal of BOD_5 by integrated disinfection systems using chlorination as the primary disinfection unit is due to the effectiveness of the pre-treatment unit and also the chlorination process, where the chlorination process is able to disinfect the microorganisms contained in the raw effluent. Comparatively, integrated disinfection systems using UV as a primary disinfection unit had lower BOD_5 removal than integrated disinfection systems using chlorination as a primary disinfection unit. This is because although UV has the function of disinfecting the microorganisms in the raw effluent, its efficiency is not as high as chlorination. On the other hand, low percentage removal of BOD_5 for GAC-UV is influenced by the high P content in GAC-UV treated effluent. High P content in treated effluent will speed up eutrophication, support the microorganisms (recovered *E. coli* or non-disinfected pathogens) for cell synthesis and energy transport, thus accelerating the microbial activity to consume more DO and lower the BOD_5removal [29,30].

With regards to nutrient (NH_3-N, NO_3-N, and P) removal as depicted in Fig. 8, a wide range of nutrient removal was obtained by the integrated disinfection systems used in this study. The percentage of NH_3-N, NO_3-N, and P removal was at the range of 8.90-84.15, 0.00-85.55, and 0.00-18.36%, respectively. The percentage of nutrient removal greatly depended on the pre-treatment efficiency and dosage applied in the primary disinfection unit. UF-UV presented the greatest NH_3-N removal among integrated disinfection system using UV as primary disinfection. Nitrification process (depicted in Eq. (5)) is expected to occur during pre-treatment of UF-UV. Long membrane filtration time increased the DO level in pre-treated effluent due to continuous flow of retentate back to the inlet tank. With the added oxygen into the effluent, NH_3-N is converted into NO_3-N.

$$NH^{4^+} + 2O_2 \rightarrow NO_3^{\,-} + 2H^+ + H_2O \tag{5}$$

This postulation is supported by the addition of NO_3-N content in treated effluent by UF-UV and UF-Cl, in which no NO_3-N removal was achieved. Whereas, GAC and EMM pre-treatment showed inconsistent performance in treating nutrients. This could be because GAC and EMM are insufficient in providing effective adsorption sites for the nutrient adsorption. However, more activated carbon contained in the GAC column provided larger effective adsorption sites for the nutrients to adsorb onto it and therefore had greater adsorption capacity as compared to the EMM column. Comparatively, the integrated disinfection system using chlorination as primary disinfection unit generally exhibited higher NH_3-N removal than integrated disinfection system using UV as primary disinfection unit. The addition of $Ca(OCl)_2$ in the chlorination process has increased the oxidation level in pre-treated effluent [10]. Hence, a higher amount of NH_3-N was removed from the raw effluent through the nitrification process (as indicated by Eq. (5)).

With regards to P removal, only a low amount of P is able to be removed by integrated disinfection systems using EMM as pre-treatment. Although much research reported that GAC has the capability to adsorb P, the leaching of P from the GAC surface into treated effluent due to weak physical attachment of P onto the GAC surface during its synthesis process has opposed the removal of P from raw effluent. However, P leaching effect was less significant in the EMM pre-treatment unit as the GAC content in the EMM column was less than that of the GAC column. Meanwhile, the inconsistent P removal by integrated disinfection system using UF as a pre-treatment unit could be due to the PES20kDa membrane surface defect.

As compared to single the disinfection unit, the integrated disinfection system using chlorination as a primary disinfection unit is able to reduce the THM content in the treated effluent. This could be attributed to the existence of a pre-treatment unit in the integrated disinfection system. Pre-treatment such as UF, GAC, and EMM manage to remove part of THM and NOM from raw effluent either by physical sieving mechanism or adsorption. NOM is the precursor for THM formation [31]. Lower THM concentration in pre-treated effluent and less NOM for the further formation of THM will therefore reduce the THM concentration in treated effluent from the integrated disinfection system using chlorination as a primary disinfection unit. The treated effluent from the integrated disinfection system using chlorination as primary disinfection unit is able to comply with MOH guidelines. Thus, the treated effluent is safe for recycle and reuse purposes.

3.5 Treated Effluent Quality Compared to Water Reuse Guidelines

To date, no water reuse guideline has been developed by Malaysian authorities to facilitate the recycling and reuse of treated water in Malaysia. Attributed to this, several water reuse guidelines presented in Table 6 - United States Environmental Protection Agency (US EPA) water reuse guidelines and Singapore grey water quality were chosen as the benchmark to determine the adaptability of treated water quality for reuse purposes [11,32]. The US EPA water reuse guidelines is an international guideline that has been widely recognized for water reuse in restricted area applications and unrestricted area applications. As these US EPA water reuse guidelines might not be representative of the Asia climate, Singapore grey water is a water reuse program tailored strictly for flushing of water closets and urinals, general washing (excluding high pressure jet washing and general washing at market and food establishments), irrigation (excluding irrigation sprinklers), and cooling tower makeup water [32].

Table 6: Water reuse guidelines

Parameter	US EPA [11]		Singapore grey water [32]
	Restricted area	Unrestricted area	
pH	6-9	6-9	6-9
BOD_5 [mg/L]	≤ 30	≤ 10	< 5
COD [mg/L]	-	-	-
Turbidity [NTU]	-	≤ 2	< 2
TSS [mg/L]	≤ 30	≤ 5	-
E. coli [CFU/100 mL]	-	-	ND
Fecal coliform [CFU/100 mL]	≤ 200	ND	-
NO_3-N [mg/L]	-	-	-
NH_3-N [mg/L]	-	-	-
Total THMs [µg/L]	-	-	-

Table 7: Adaptability of treated effluent from each system for water recycling and reuse

System	USEPA		Singapore grey water
	Restricted area	Unrestricted area	
HVLP00010	✓	✓	✓
PVDF021M			
PVDF1001M	✓	✓	✓
PES20kDa	✓	✓	✓
Chlorination	✓		✓
UV	✓		✓
UF-UV	✓	✓	✓
GAC-UV	✓	✓	✓
EMM-UV	✓		
UF-Cl	✓	✓	✓
GAC-Cl	✓	✓	✓
EMM-Cl	✓	✓	✓

Table 7 summarizes the adeptness of treated effluent from each system for water recycling and reuse. As presented in Table 7, almost all treated effluent from single disinfection complied with the US EPA water reuse guidelines at restricted areas except for the final effluent given by the PVDF021M membrane. This means that treated effluents from the HVLP0010 membrane, PVDF1001M membrane, PES20kDa membrane, chlorination, and UV disinfection are suitable for reuse as irrigation water (restricted area), agricultural reuse (food crops commercially processed and non-food crops), landscape impoundments, and construction. However, only treated effluents by the HVLP0010 membrane, PVDF1001M membrane, and PES20kDa membrane are able to meet US EPA water reuse guidelines for unrestricted areas. These treated effluents have added value for urban reuse, recreation, and agricultural purposes (food crops commercially processed and food crops not commercially processed). UV and chlorination are only recommended for restricted area applications due to the presence of high TSS content in treated effluent. Whereas, permeate filtered from the PVDF021M membrane did not comply with US EPA water reuse guidelines for both unrestricted areas and restricted areas. There was still a high number of *E. coli* (341 ± 176 CFU/100 mL) remaining in the treated effluent after filtering with the PVDF021M membrane. For integrated disinfection systems, almost all integrated disinfection systems complied with US EPA water reuse guidelines for unrestricted area applications except the integrated disinfection system of EMM-UV due to the presence of *E. coli*.

The adaptability of treated effluent with Singapore grey water quality presented the same trend as its adaptability with US EPA water reuse guidelines for restricted area. All disinfection units and integrated disinfection systems complied with the parameter range except the PVDF021M membrane, and integrated disinfection system of EMM-UV. Although single PVDF021M membrane and integrated disinfection system of EMM-UV compiled with pH and BOD_5 parameters of the Singapore grey water quality, high *E. coli* content in treated effluents make them fail to comply. Thus, treated effluent from these disinfection systems are not recommended for grey water reuse purposes [32].

4. CONCLUSION

- The PES20kDa membrane with the smallest membrane pore diameter was the most effective single disinfection unit with the highest rejection in most of the parameters where the percentage of removal for *E. coli*, TSS, COD, BOD_5, NH_3-N, NO_3-N, and P were 100.00, 100.00, 49.77, 86.28, 9.80, 27.88, and 42.27%, respectively.
- Almost all single disinfection units complied with the US EPA water reuse guidelines at restricted areas for the application of irrigation (restricted area), agricultural reuse (food crops commercially processed and non-food crops), landscape impoundments, construction, and industrial reuse except the PVDF021M membrane filtration unit.
- Additionally, high quality treated effluent by the HVLP0010 membrane, PVDF1001M membrane, and PES20kDa membrane are able to meet Singapore grey water quality, and US EPA water reuse guidelines at unrestricted area for urban reuse, recreation, and agricultural (food crops commercially processed and food crops not commercially processed) purposes.
- All integrated disinfection systems were effective in disinfecting the raw effluent where almost all of it achieved 100% *E. coli* removal in treated effluent. Comparatively, the integrated disinfection system using chlorination as primary disinfection unit has better performance than the integrated disinfection system using UV as primary disinfection unit.
- UF-Cl is the preferable integrated system for the greatest removal of most of the parameters from raw effluent. The percentage of removal for *E. coli*, TSS, COD, BOD_5, NH_3-N, NO_3-N, and P by UF-Cl is 100.00, 100.00, 36.32, 97.74, 84.15, 0.00, and 0.00%, respectively.
- All integrated disinfection systems complied with the US EPA water reuse guidelines for restricted area application. However, only integrated disinfection systems of EMM-UV did not manage to fulfil the Singapore grey water quality, and US EPA water reuse guidelines for unrestricted area applications.

ACKNOWLEDGEMENTS

The authors wish to gratefully acknowledge the financial support of this work by Indah Water Konsortium (IWK) Sdn. Bhd. (KK-2018-005) and Dana Penyelidikan Strategik

(KRA-2017-06). The authors also wish to acknowledge Fuel Sel Institute, UKM for SEM analysis.

REFERENCES

[1] Mohamed RMSR, Nazmi AM, Arief MM, Hashim MKA. (2016) Conventional water filter (sand and gravel) for ablution water treatment, reuse potential, and its water savings. J. Sustain. Dev, 9:35–43. doi:10.5539/jsd.v9n1p35
[2] Academy of Sciences Malaysia. (2015) Study on the Current Issues and Needs for Water Supply and Wastewater Management in Malaysia. Volume 2. Kuala Lumpur. Retrieved from https://issuu.com/asmpub/docs/wswm_volume_2
[3] Alternative Water Resource to Potentially Reduce Water Footprint [http://ensearch.org/wp-content/uploads/2013/10/PAPER-11-ALTERNATIVE-WATER-RESOURCES-AS-A-POTENTIAL-TO-REDUCE-WATER-FOOTPRINT.pdf]
[4] Cleaning the Unseen [https://www.thestar.com.my/news/nation/2016/12/04/cleaning-the-unseen-from-the-tidak-apa-attitude-of-users-to-financial-gaps-former-indah-water-konsor/]
[5] Looking For Water [https://www.thestar.com.my/news/environment/2014/06/16/looking-for-water/]
[6] Wahid MA, Tanaka H. (2012) Potential implementation of wastewater reclamation and reuse in Malaysia urban area. Int. Sustain. Civ. Eng. J., 1(1):75–83.
[7] Abarnou A, Miossec L. (1992) Chlorinated waters discharged to the marine environment chemistry and environmental impact. An overview. Sci. Total Environ., 126:173–197. doi:10.1016/0048-9697(92)90490-J
[8] Turtoi M. (2013) Ultraviolet light potential for wastewater disinfection. Ann. Food Sci. Technol., 14(1):153–164. Retrieved from https://www.researchgate.net/publication/264002288_Ultraviolet_light_potential_for_wastewater_disinfection
[9] Rodriguez-Chueca J, Ormad MP, Mosteo R, Sarasa J, Ovelleiro JL. (2015) Conventional and advanced oxidation processes used in disinfection of treated urban wastewater. Water Environ. Res., 87(3):281–288. doi:10.2175/106143014X13987223590362
[10] UV Disinfection for Wastewater [http://www.trojanuv.com/applications/wastewater]
[11] U.S. Environmental Protection Agency. (2004) Guidelines for Water Reuse. Washington.
[12] Grover D, Zhou J, Frickers P, Readman J. (2011) Improved removal of estrogenic and pharmaceutical compounds in sewage effluent by full scale granular activated carbon: impact on receiving river water. J. Hazard Mater, 185(2-3):1005–1011. doi:10.1016/j.jhazmat.2010.10.005
[13] Kim SD, Cho J, Kim IS, Vanderford BJ, Snyder SA. (2007) Occurrence and removal of pharmaceuticals and endocrine disruptors in South Korean surface, drinking, and waste waters. Water Res, 41(5):1013–1021. doi:10.1016/j.watres.2006.06.034
[14] Margot J, Kienle C, Magnet A, Weil M, Rossi L, de Alencastro LF, Abegglen C, Thonney D, Chevre N, Scharer M, Barry DA. (2013) Treatment of micropollutants in municipal wastewater: ozone or powdered activated carbon? Sci Total Env, 461:480–498. doi:10.1016/j.scitotenv.2013.05.034
[15] Gonzalez O, Bayarri B, Acena J, Perez S, Barcelo D. (2016) Treatment technologies for wastewater reuse: Fate of contaminants of emerging concern. In Advanced Treatment Technologies for Urban Wastewater Reuse The Handbook of Environmental Chemistry. Volume 45. Edited by Fatta-Kassinos D, Dionysiou D, Kummerer K. Cham, Springer; pp 5–38.
[16] Morowitz HJ. (1950) Absorption effects in volume irradiation of microorganisms. Science, 111(2879):229–230. doi:10.1126/science.111.2879.229-a
[17] Hallmich C, Gehr R. (2010) Effect of pre- and post-UV disinfection conditions on photoreactivation of fecal coliforms in wastewater effluents. Water Res, 44: 2885–2893. doi:10.1016/j.watres.2010.02.003

[18] Wahid MA, Kim I, Yamashita N, Tanaka H, Baki A. (2012) UV based process for *E. coli* and coliphage in secondary effluent for wastewater reclamation and reuse. Inst. Eng. Malaysia, 73:18–24. Retrieved from https://www.myiem.org.my/content/iem_journal_2012-361.aspx
[19] Anastasi EM, Wohlsen TD, Stratton HM, Katouli M. (2013) Survival of *Escherichia coli* in two sewage treatment plants using UV irradiation and chlorination for disinfection. Water Res, 47(17):6670-6679. doi:10.1016/j.watres.2013.09.008
[20] March JG, Gual M. (2007) Breakpoint chlorination curves of greywater. Water Environ. Res, 79(8):828–832. doi:10.2175/106143007X156736
[21] Jorgensen SE. (1993) Breakpoint chlorination. In The Removal of Nitrogen Compounds from Wastewater. Edited by Halling-Sorensen B, Jorgensen SE. Netherlands, Elsevier Science Publishers; pp. 295–304.
[22] Martins JM, Majdalani S, Vitorge E, Desaunay A, Navel A, Guine V, Daian JF, Vince E, Denis H, Gaudet JP. (2013) Role of macropore flow in the transport of *Escherichia coli* cells in undisturbed cores of a brown leached soil. Environ. Sci. Process. Impact, 15(2):347–356. doi:10.1039/c2em30586k.
[23] Falsanisi D, Liberti L, Notarnicola M. (2009) Ultrafiltration (UF) pilot plant for municipal wastewater reuse in agriculture: Impact of the operation mode on process performance. Water, 1:872–885. doi:10.3390/w2040872
[24] Ang WL, Mohammad AW, Hilal N, Leo CP. (2015) A review on the applicability of integrated/hybrid membrane processes in water treatment and desalination plants. Desalination, 363: 2–18. Doi:10.1016/j.desal.2014.03.008
[25] Mandzy N, Grulke E, Druffel T. (2005) Breakage of TiO_2 agglomerates in electrostatically stabilized aqueous dispersions. Powder Technology, 160(2):121-126. doi:10.1016/j.powtec.2005.08.020
[26] Shah AD, Mitch WA. (2012) Halonitroalkanes, halonitriles, haloamides, and N-nitrosamines: A critical review of nitrogenous disinfection byproduct formation pathways. Environ. Sci. Technol., 46:119–131. doi:10.1021/es203312s
[27] Farrell C, Hassard F, Jefferson B, Leziart T, Nocker A, Jarvis P. (2018) Turbidity composition and the relationship with microbial attachment and UV inactivation efficacy. Sci. Total Environ., 624:638–647. doi:10.1016/j.scitotenv.2017.12.173
[28] Winward GP, Avery LM, Stephenson T, Jefferson B. (2008) Chlorine disinfection of grey water for reuse: Effect of organics and particles. Water Res., 42:483–491. doi:10.1016/j.watres.2007.07.042
[29] Phosphorus and water. [http://water.usgs.gov/edu/phosphorus.html]
[30] Zhang Y, Zhang G, Wang P, Wang Q. (2017) Disinfection of municipal secondary effluents with microwave-induced electrodeless ultraviolet irradiation for water reuse. J. Chem. Technol. Biotechnol., 92(5):1017–1025. doi:10.1002/jctb.5077
[31] Hua G, Yeats S. (2010) Control of trihalomethanes in wastewater treatment. Florida Water Resour. J., April. Retrived from https://www.fwrj.com/techarticles/0410 FWRJ_tech1.pdf
[32] Technical Guide for Greywater Recycling System [https://www.pub.gov.sg/Documents/greywaterTech.pdf]