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Evaluation of direct water reclamation from municipal wastewater by disk tube reverse osmosis membrane (DT-RO) based compact process

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ABSTRACT

Water reclamation from wastewater treatment plants (WWTPs) with small footprint is required for sustainable water management in areas where the land resources available for building WWTPs are limited, for example, developing countries under rapid urbanization. Different from current water reclamation process (conventional activated sludge + reverse osmosis) with long procedures, a concept of compact municipal wastewater treatment process based on disk tube reverse osmosis (DT-RO) for direct water reclamation was proposed and initially evaluated with actual wastewater in this study. Flux of 35.6 LMH under operation pressure of 25–28 bar was achieved with water recovery of 90%. With a simpler pretreatment procedure, it is feasible to achieve high water quality satisfying even the most stringent national municipal wastewater discharge standard in China. The proposed process demonstrated advantages on better energy efficiency for its compact design with limited pretreatment and avoiding destroying organics by energy-intensive aerated biological treatment. Organic matters and nutrients (nitrogen and phosphorus) were concentrated in the retentate, which could perform as pre-concentration for next step recovery. The proposed concept provided an alternative option for water reclamation by compact DT-RO process with high energy efficiency and potentials for resource recovery.

Keywords: Water reclamation; Disk tube reverse osmosis; Compact process; Reverse osmosis; Resource recovery

1. Introduction

Water issues including water shortage and water pollution have been considered as one of the most serious challenges for human sustainable developments all over the world. Water reclamation, as a feasible way to enhance water management, could achieve the goals of enlarging water resource and controlling pollution simultaneously [1,2]. Recently, more and more wastewater treatment plants (WWTPs) have been required for upgradation to match more stringent discharge standard for water reclamation. NeWater project in Singapore has demonstrated a great success in water reclamation for indirect portable reuse of wastewater [3]. Except for water reclamation, it is also proposed that the WWTPs should contribute more to support sustainable development of local community. For instance, more comprehensive resources recovery including nutrients (nitrogen and phosphorus) and their maximum reuse is expected [2,4]. The energy self-sufficiency as a feasible concept has also been proposed and applied for some WWTPs [5–7].

Meanwhile, one goal which is not commonly considered with high priority, yet is critical in practical situation, is to reduce the large footprint of WWTPs. On the one hand, for developing countries, China for instance, fast urbanization

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and unexpected extension of city area border result in extremely limited land for WWTPs construction [8]. On the other hand, footprint of WWTPs is generally large. Especially for those designed for water reclamation, it is common to add additional treatment units (tertiary treatment) after former conventional process. This directly makes WWTPs footprint even larger with long treatment process and leads to strain for land resources supply. In China, more and more WWTPs in highly urbanized cities are considered to be rebuilt underground. However, the high cost for expanding underground space also requires reduction of WWTPs footprint. Therefore, it is crucial to develop novel compact water reclamation process to solve this contradiction.

Reverse osmosis (RO) process, which usually applies spiral wound membrane module, is the most common and successful water reclamation technology [9,10]. It has been widely used all over the world due to its high effluent quality. However, as shown in Fig. 1(a), current RO-based water reclamation process consists of long procedures due to physical and chemical vulnerability of RO membranes. The process includes conventional municipal wastewater (MW) treatment followed by multimedia filtration, microfiltration (MF) or ultrafiltration (UF) as pretreatment for RO, which is never considered as compact[11,12]. To avoid the complex pretreatment widely used for spiral wound RO module, a specially designed module, disk tube reverse osmosis (DT-RO), is proposed in this study to develop novel compact water reclamation process. The main feature of DT-RO module is open-channel structures combined with short feed flow paths. This design guarantees unrestricted and fully turbulent feedwater flow system, which prevents pollutants easily depositing on the membrane surface and also minimizes concentration polarization and physical flow impediments. It is reported that fouling issue is effectively controlled by DT-RO system for feed filtrates with a silt density index (SDI) as high as 20 [13,14]. In other words, DT-RO module could endure higher fouling potentials than spiral wound RO module, which therefore be used to design compact process with much shorter procedures as shown in Fig. 1(b). By now, DT-RO system has been used in treating recalcitrant solutions with increased turbidity and high SDI including seawater, landfill leachates, juice concentrates and liquid anaerobic digestate [15,16]. However, the operational feasibility of DT-RO system for water reclamation from MW as a compact process is unknown and has not been investigated in previous literatures.

In this study, we built small-scale DT-RO facility and evaluated direct water reclamation from actual MW by the compact process based on DT-RO with batch experiments. The aims of this paper were to investigate the feasibility of this concept by determining (i) performance of compact DT-RO process without complex pretreatment during direct MW filtration, (ii) energy consumption and saving potentials of compact design, (iii) water quality achieved with fluctuating influent quality and its potential for satisfying water reclamation standards in China, and (iv) the potentials of concentrating organic matters, N and P in retentate as pre-concentration for more comprehensive resource recovery.

2. Materials and methods

2.1. MW characteristics

In this study, actual MW was directly taken after bar screens (grid) in the Xiao Jiahe WWTP (20,000 ton/d) in Beijing, China. There was no primary clarifier in the plants. MW sample was pretreated by removing large particles with 1 mm sieve. Considering the water quality fluctuation, two batch experiments were carried out for process evaluation with high and low chemical oxygen demand (COD), respectively. The major physicochemical characteristics of the two batch MW samples were shown in Table 1.

2.2. DT-RO set-up and experimental protocol

The DT-RO module (JinZheng, China) contained a stack of molded acrylonitrile butadiene styrene plastic spacing discs separating membrane cushions. RO membrane cushions were composed of two octagonal layers which are welded together at their periphery. Each membrane cushion

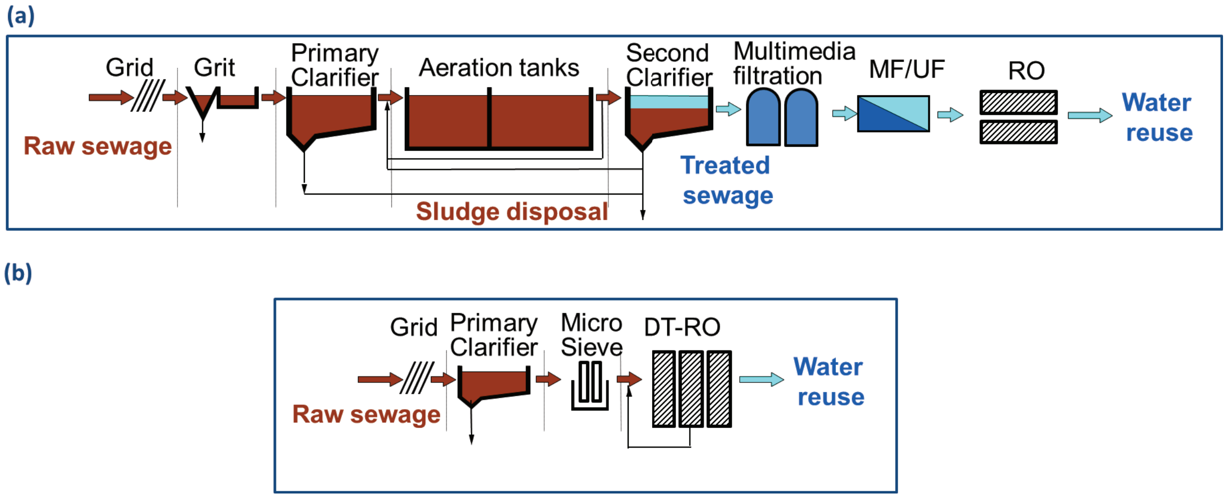

Fig. 1. Flow diagrams comparison of (a) current reverse osmosis based water reclamation process and (b) proposed compact municipal wastewater treatment process based on DT-RO.

demonstrated a working membrane area of 0.045 m^2 and the module consists of 50 cushions with a total membrane area of 2.25 m^2. RO membrane was made of cellulose acetate with molecular weight cutoff above 30 Dalton. MW was delivered into the DT-RO module by a high-pressure pump without pH control. The operation pressure and water flow rate were monitored and recorded. Flux of RO membrane was calculated by flow rate and membrane area. As shown in Fig. 2, the configuration of the DT-RO module demonstrated advantages over the traditional spiral wound module, including open-channel configuration, high turbulence of the feed stream, evenly distributed and self-cleaning hydraulic circulation, minimization of cross-flow rate and reduced risks of clogging. The channel of 6 mm was wider than 0.2 mm of spiral wound module and the flow path of 7 cm was much shorter than 100 cm of spiral wound module.

MW sample which was stored in 100-L tank was pumped into the DT-RO module for filtration. The retentate (brine) flow back to the initial tank and the permeate was sampled for analysis. System recovery (SR) was defined as the ratio of permeate volume and the initial volume. Concentration factor (CF) was calculated as the ratio of initial volume and the final retentate volume. The relationship between SR and CF could be described as following:

$$\text{System recovery (SR)} = 1 - \frac{1}{\text{Concentration factor (CF)}} \qquad (1)$$

During experiments, the operation situation including flux and pressure was obtained as the recovery increasing from 50% to as high as 90%. Meanwhile, the retentate in the tank was analyzed by measurement of COD, total nitrogen (TN) and total phosphorus (TP). The experiment stopped when recovery reached 90%.

Table 1
Key physicochemical properties of two batch MW samples during experiments using DT-RO system

	Batch 1#	Batch 2#
COD (mg/L)	48	78
NH_4-N (mg/L)	8.5	16.6
TN (mg/L)	16.9	27.0
TP (mg/L)	1.8	9.7

According to solute diffusion theory, water flux for RO system could be described as follows:

$$J = A\left(P - \Delta R\right) \qquad (2)$$

where J (LMH, namely L/(m^2 h)) is flux, A (LMH/bar) is the intrinsic pure water permeance of membrane, (P–ΔR) is the net pressure for driving flux, P (bar) is operation pressure, ΔR (bar) is the total filtration resistance caused by osmosis pressure of feed solution, fouling and the system loss such as pressure drop due to friction force. To measure A value, tap water was filtrated by the DT-RO system. The resulting flux data under pressures of 3, 5, 10, 15, 20, 25 and 30 bar were recorded and used to achieve the intrinsic pure water permeance of membrane (A) via fitting to Eq. (2). During the two batch experiments, ΔR under each operation pressure was also calculated according to Eq. (2) to describe the changing of total resistances. Permeability (LMH/bar) was calculated as J (LMH) divided by P (bar).

Specific energy consumption (SEC) depended on the operational osmotic pressure. During the batch experiments, operation pressure varied depending on recovery increasing. Thus, accumulative SEC (kWh/t) of each SR was used and calculated as following to evaluate DT-RO system:

$$\text{SEC} = \sum_{\text{SR}=0}^{90\%} P * \frac{\Delta\text{SR}}{36} \qquad (3)$$

where P (bar) is operation pressure and SR is 0%, 50%, 66.7%, 75%, 80%, 83.3%, 85.7%, 87.5%, 88.9% and 90% with increase.

2.3. Analytical procedures

COD, ammonia nitrogen, TN and TP were determined by colorimetric techniques using a HACH spectrophotometer (DR 5000, HACH, USA). pH was measured using a pH meter (Sension1, HACH, USA). The three-dimensional excitation–emission matrix (EEM) fluorescence spectroscopy (F-7000 FL Spectrophotometer, Hitachi) was used to determine the types of fluorescent compounds present in the raw and filtered wastewater. The raw MW samples were filtered through 0.45 μm membrane before measurement. No dilution was carried out. Spectra information was collected with the scanning emission (E_m) spectra from 250 to 550 nm

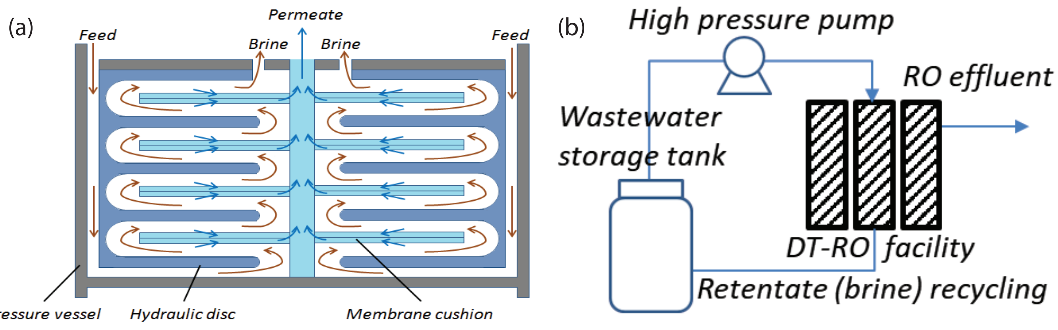

Fig. 2. (a) Construction profile of the DT-RO module and (b) batch experiment setup.

at 1 nm increases by varying the excitation wavelength (E_x) from 200 to 450 nm at 1-nm sampling intervals. The EEM spectra were plotted as the elliptical shape of contours using software Origin 8.0.

3. Results and discussion

3.1. DT-RO performance

Performance of DT-RO system was investigated. The results of operation pressure and flux are presented in Table 2. As the recovery increasing from 50% to 90%, the decrease of flux and increase of pressure were observed. For both, the two batch experiments, the flux reduced to 36 LMH from 44 and 40 LMH, respectively. However, the pressure increase of Batch 2# was faster than Batch 1# due to its worse water quality with higher COD. At recovery of 90%, the pressure of Batch 2 # was as high as 28 bar, higher than 25 bar of Batch 1#. Accordingly, permeability was in range of 1.27–2.18 LMH/bar, which was comparable with that of conventional spiral wound RO system with high recovery of 90% [17]. It should be noted that the system configuration of the used small-scale DT-RO facility is unoptimized with probably poor system energy efficiency. Considering the various filtration resistance at increasing CF, multi-stage configurations could be considered in future with optimized pressure to reduce the energy of DT-RO system [18].

During the two experiments, Δ*R* and normalized flux under each CF are shown in Fig. 3. Similar results were observed for the both two batch experiments. As CF (recovery) rising, the total filtration resistances first increased and then arrived at stable level. However, the resistances of Batch 2# (Δ*R*2) at each pressure were 4–6 bar higher than Batch 1# (Δ*R*1), indicating the remarkable negative influence caused by worse feed solution quality. The Δ*R* difference between the two batch filtration induced by organics concentration suggested organic fouling probably led to main issue for full-scale operation [19]. For the batch experiments in this study, it was assumed that no fouling happened due to the short-term operation period. However, the fouling issue should be investigated in future with fouling cleaning strategies including chemical [20,21], physical [22,23] cleaning evaluated.

The total filtration resistance directly influenced the energy consumption of whole system. The linear development of Δ*R* was mainly caused by the increasing of feed solution osmosis pressure, which was proportional to CF. The final operation pressure arrived stable at about 9 and 12 bar for Batch 1# and Batch 2#, respectively. It should be noted that compared with flux reported by current RO-based water reclamation process (17-22 LMH), as high as 35 LMH flux was achieved in DT-RO system of this study [3]. The membrane cost for DT-RO process may raise, while techno-economic evaluation in full scale was required for further investigation.

3.2. Energy consumption evaluation

DT-RO–based process demonstrated its advantages on energy consumption by its limited units and compact process layout design. SEC of DT-RO process was valuated as shown in Fig. 4. Energy consumption of RO process was dependent on applied pressure. As CF increasing, the applied pressure also grows up. It should be noted that during the CF

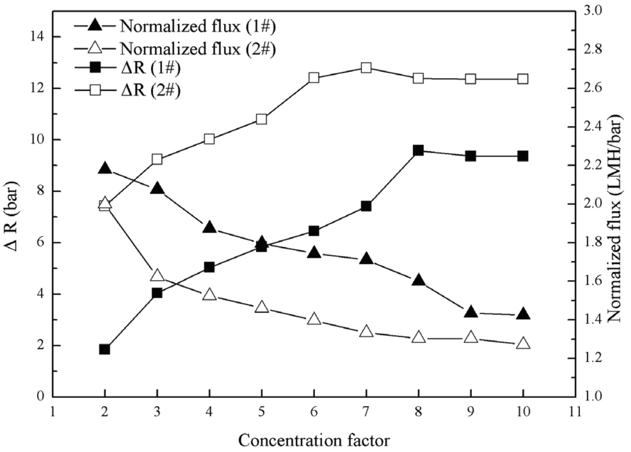

Fig. 3. Total filtration resistance and normalized flux during the two batch experiments. No membrane cleaning was conducted during experiments.

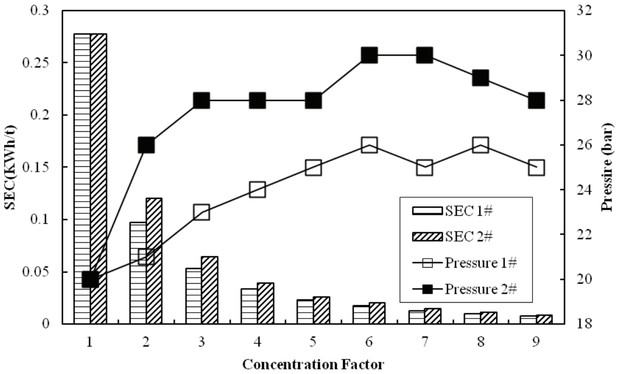

Fig. 4. Specific energy consumption (SEC) and pressure vibration as concentration factor increasing.

Table 2
DT-RO performance during water reclamation experiments

Concentration factor		1	2	3	4	5	6	7	8	9	10
Recovery		0	50	66.7	75	80	83.3	85.7	87.5	88.9	90
Batch 1#	Pressure (bar)	20	21	23	24	25	26	25	26	25	25
	Flux (LMH)	43.6	43.6	43.1	43.1	43.6	44.5	40	37.3	35.6	35.6
Batch 2#	Pressure (bar)	20	26	28	28	28	30	30	29	28	28
	Flux (LMH)	40	42.2	42.7	40.9	39.1	40	39.1	37.8	35.6	35.6

of 1, as high as 50% feed solution was recovered. However, during the CF increased from 1 to 2, only 16% volume (66% minus 50%) feed solution was recovered. The higher the CF, the lower the volume percentage. The SEC for specific CF was adjusted by multiplying the volume percentage. Thus, the SEC declined as CF increasing. The SEC sum of all the CF was considered as the whole SEC for batch experiments. Accordingly, the accumulative SEC was 0.532 kWh/m^3 for 1# and 0.582 kWh/m^3 for 2#.

It was reported that the SEC of full scale conventional activated sludge + reverse osmosis (CAS+RO) process (Ulu Pandan NEWater WWTP, Singapore) was 0.91 kWh/m^3 with biological process consumption of 0.31 kWh/m^3 [3,24]. The SEC of DT-RO process, much lower than the total SEC of the whole CAS+RO process, exhibits its advantage at energy efficiency. It was proposed that the NeWater CAS+RO process would be updated to be more compact by combining biological process with MF/UF with new option of MBR-RO [3]. However, even with ideal assumption that total energy for MF/UF (about 0.13 kWh/m^3) was saved, the total SEC would still be higher than that of DT-RO process. The main differences between the two process layout designs were the choice of treatment for the organic matter in feed wastewater. For the CAS+RO process, organics was removed by energy-intensive aeration process with byproduct of CO_2 and excess sludge. In comparison, DT-RO process achieved water reclamation by directly filtrating wastewater with both organics and nutrients (N and P) retained and concentrated in retentate. It is proposed that anaerobic treatment of retentate could convert the concentrated organics into methane with energy recovery, instead of "destroying" them by aerobic biological process [25]. In fact, by efficient organics pre-concentration and following energy recovery by anaerobic process, energy self-sufficiency was possible [26–28].

It should also be noted that the energy consumption of this study was inferred based on small-scale DT-RO system. For the full-scale application for DT-RO based process, more detailed investigation with various feed wastewater conditions was required in future. Also, no energy recovery device was applied for DT-RO evaluation in this paper, indicating its possibility of energy efficiency improvement with further process upgradation and optimization.

3.3. Effluent water quality analysis

COD, TP, TN and NH_4-N of effluents were measured to evaluate its potentials for water reclamation. Three different water quality standards in China were used for discussion. National first level A for WWTP discharge was the first one of water quality standards designed for WWTP water reclamation, which was issued in 2002 with revision and widely applied for many WWTPs in environmentally sensitive areas. Beijing Level A from integrated discharge standard of water pollutants was regional standard suitable for situation when wastewater was discharged in sensitive water body in Beijing region. National level IV for surface water body was used to justify water quality of natural surface water body; however, now it also was being discussed for WWTPs water reclamation in China [29,30].

For the low-strengthen MW such as Batch 1#, it was possible to nearly satisfy even the most stringent standard. As shown in Fig. 5, for the Batch 1#, except for TP slightly exceeding the Beijing level A (0.3 over 0.2 mg/L), the effluent satisfied the requirements of all the three standards.

However, for the Batch 2# with higher pollutant load whose influent TP was as high as 9.7 mg/L, the effluent TP was the main issue with value of 3.6 mg/L, far from the standards' requirements. The main reason was that biological processes prior to RO were avoided which otherwise removed phosphorus by sludge discharge, leading to high TP faced by membrane filtration. Besides, as TP increasing at high CF, the TP was even higher in filtrates. It should also be noted the effluent TN and NH_4-N only met the reclamation standard of first class A, beyond the other two more stringent standards. To improve effluent quality and also guarantee the compactness of process, simple and quick pretreatments should be discussed in future, such as coagulation process to remove part of pollutants (e.g., TP and suspended solid) prior to RO.

As shown in Fig. 6, the EEM spectra of MW before and after DT-RO treatment were analyzed to describe the pollutants removal by the system. EEM spectra provided spectral information about the chemical compositions in MW including protein-like and humic-like organic compounds with fluorescence characteristics. For the original MW (Fig. 6(a)), the first main peak (Peak A) was observed at the excitation/emission wavelengths (E_x/E_m) of 270–280/330–350 nm, while the second peak was located at E_x/E_m of 220–230/330–350 nm (Peak B). Both two peaks were reported to be associated with protein-like substance in MW. Peak A was related to tryptophan protein-like substances while Peak B was related to aromatic protein-like substances [31,32]. For the effluent, two main peaks in EEM spectra were observed in similar location with that of original MW, shown in Fig. 6(b). However, it should be noted that selectively removal happened. Compared with the remarkable reduction in fluorescence intensity of Peak A, the decrease of Peak B fluorescence intensity was limited.

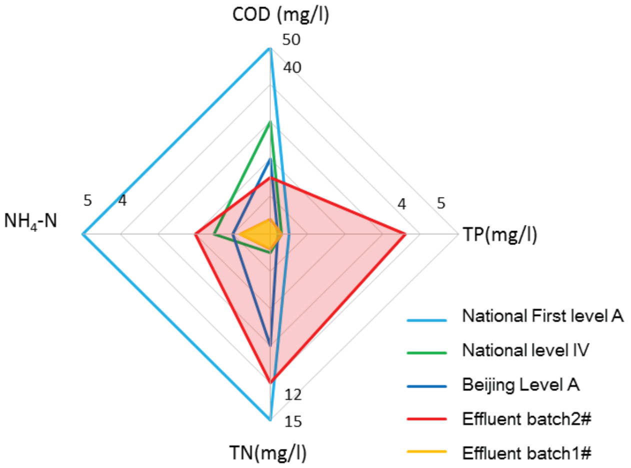

Fig. 5. Evaluation of two batch experiments effluents with different water quality standards in China (light blue lines: National First Level A for WWTP discharge; green lines: National level IV for surface water body; deep blue lines: Level A for WWTP discharge in Beijing region; yellow area: effluent of Batch 1#, red area: effluent of Batch 2#).

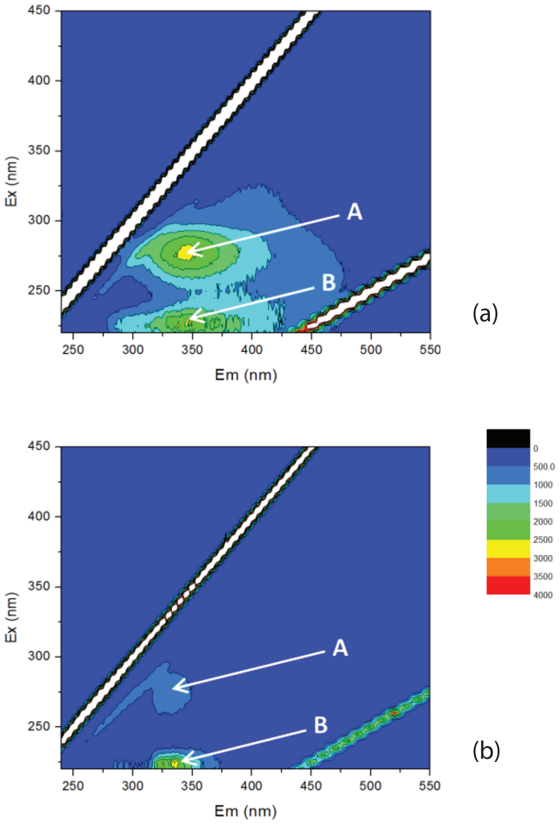

Fig. 6. (a) EEM spectra of original MW and (b) effluent of DT-RO system.

Table 3
Rejection of COD, TP, TN and NH_4-N by DT-RO system

	Batch 1#	Rejection (%)	Batch 2#	Rejection (%)
COD (mg/L)	4	91.7	14	82.1
TP (mg/L)	0.3	83.1	3.6	62.9
TN (mg/L)	1.3	92.3	12.3	54.4
NH_4-N (mg/L)	0.8	90.6	2	88.0

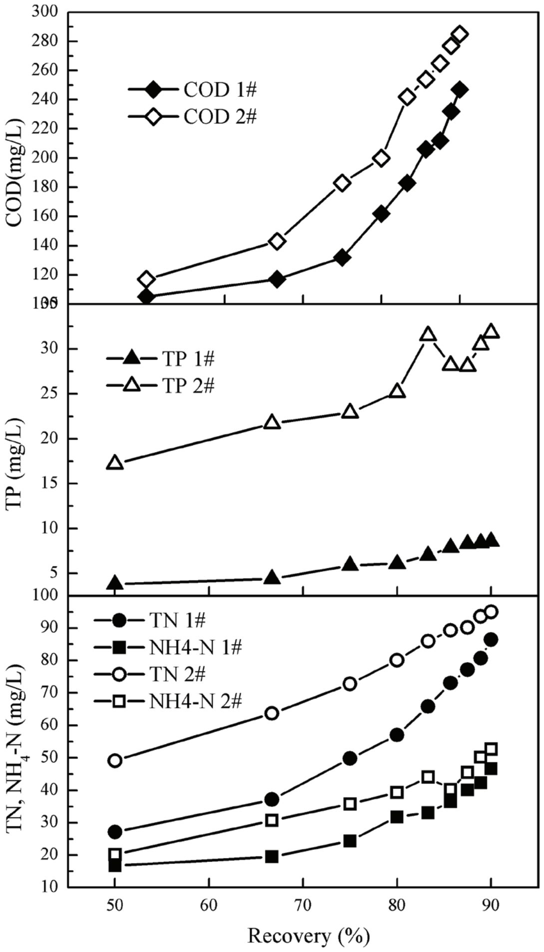

Fig. 7. Concentration of COD, TP, TN and NH_4-N in retentate.

3.4. *Concentrating of COD, TP, TN and NH_4-N in retentates*

Besides water reclamation, the DT-RO–based compact process also provided potentials for enhancing recovery for nitrogen, phosphate and even organic matters. One general reason and obstacle for their limited recovery from MW was their relatively low concentrations, which led to economically unfeasible for recovery [23,33]. However, the high rejection of DT-RO process could effectively retain the relative contents in retentate in concentrated status [34]. The rejection of COD, TP, TN and NH_4-N by DT-RO system was measured and is shown in Table 3. Generally, the rejection for all contents during Batch 1# experiment was much higher than those of Batch 2#.

As recovery increasing, the concentration of COD, TP, TN and NH_4-N in retentate kept growing up. As shown in Fig. 7, concentration of COD, TP, TN and NH_4-N of 90% recovery increased to 280, 35, 95 and 50 mg/L, respectively (Batch 2#). It was expected the higher recovery, the more concentrated results achieved. The concentrated status indicated that the compact process could perform as the pre-concentration for resource recovery, especially for N and P recovery.

4. Conclusions

In this study, the concept of direct water reclamation from MW by DT-RO–based compact process was proposed and initially evaluated by batch tests of small-scale system with actual wastewater. The tested compact DT-RO system achieved operation of 36 LMH at 25–28 bar with water recovery of 90%. Accumulative SEC of 0.532–0.582 kWh/m^3 for batch experiments was achieved demonstrating advantages on better energy efficiency for its compact design with short pretreatment and avoiding destroying organics by energy-intensive aerated biological process. It was feasible to achieve high water quality satisfying water reclamation standard of national first class A in China. COD, TP, TN and NH_4-N were concentrated in the retentate, which could be considered as pre-concentration for next-step resource recovery. Compared with conventional dual-membrane system such as CAS+RO, the proposed DT-RO–based reclamation process provided alternative option with advantages on compactness, energy efficiency and resources recovery potentials.

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References

[1] Q.K. Tran, D. Jassby, K.A. Schwabe, The implications of drought and water conservation on the reuse of municipal wastewater: recognizing impacts and identifying mitigation possibilities, Water Res., 124 (2017) 472–481.

[2] W. Verstraete, P.V.D. Caveye, V. Diamantis, Maximum use of resources present in domestic "used water", Bioresour. Technol., 100 (2009) 5537–5545.

[3] J.-J. Qin, K.A. Kekre, G. Tao, M.H. Oo, M.N. Wai, T.C. Lee, B. Viswanath, H. Seah, New option of MBR-RO process for production of NEWater from domestic sewage, J. Membr. Sci., 272 (2006) 70–77.

[4] Z. Jin, H. Gong, K. Wang, Application of hybrid coagulation microfiltration with air backflushing to direct sewage concentration for organic matter recovery, J. Hazard. Mater., 283 (2015) 824–831.

[5] B. Wett, K. Buchauer, C. Fimml, Energy Self-sufficiency as a Feasible Concept for Wastewater Treatment Systems, IWA Leading Edge Technology Conference, Singapore, 2007, pp. 21–24.

[6] L. Hernández Leal, H. Temmink, G. Zeeman, C. Buisman, Bioflocculation of grey water for improved energy recovery within decentralized sanitation concepts, Bioresour. Technol., 101 (2010) 9065–9070.

[7] H. Gong, Z. Jin, X. Wang, K. Wang, Membrane fouling controlled by coagulation/adsorption during direct sewage membrane filtration (DSMF) for organic matter concentration, J. Environ. Sci., 32 (2015) 1–7.

[8] W. Chen, W. Zhang, Y. Fan, W. Jiao, Wastewater reclamation and reuse in China: opportunities and challenges, J. Environ. Sci., 39 (2016) 86–96.

[9] A. Suárez, T. Fidalgo, F.A. Riera, Recovery of dairy industry wastewaters by reverse osmosis. Production of boiler water, Sep. Purif. Technol., 133 (2014) 204–211.

[10] M.A. Shannon, P.W. Bohn, M. Elimelech, J.G. Georgiadis, B.J. Mariñas, A.M. Mayes, Science and technology for water purification in the coming decades, Nature, 452 (2008) 301–310.

[11] J. Thompson, A. Rahardianto, H. Gu, M. Uchymiak, A. Bartman, M. Hedrick, D. Lara, J. Cooper, J. Faria, P.D. Christofides, Rapid field assessment of RO desalination of brackish agricultural drainage water, Water Res., 47 (2013) 2649–2660.

[12] M.T. Khan, M. Busch, V.G. Molina, A.H. Emwas, C. Aubry, J.P. Croue, How different is the composition of the fouling layer of wastewater reuse and seawater desalination RO membranes?, Water Res., 59 (2014) 271–282.

[13] C.G. Kim, T.I. Yoon, M.J. Lee, Characterization and control of foulants occurring from RO disc-tube-type, membrane treating, fluorine manufacturing, process wastewater, Desalination, 151 (2003) 283–292.

[14] T.A. Peters, High advanced open channel membrane desalination (disc tube module), Desalination, 134 (2001) 213–219.

[15] H. Gong, Z. Yan, K. Liang, Z. Jin, K. Wang, Concentrating process of liquid digestate by disk tube-reverse osmosis system, Desalination, 326 (2013) 30–36.

[16] T.A. Peters, Desalination of seawater and brackish water with reverse osmosis and the disc tube module DT, Desalination, 123 (1999) 149–155.

[17] A. Joss, C. Baenninger, P. Foa, S. Koepke, M. Krauss, C.S. Mcardell, K. Rottermann, Y. Wei, A. Zapata, H. Siegrist, Water reuse: >90% water yield in MBR/RO through concentrate recycling and CO2 addition as scaling control, Water Res., 45 (2011) 6141–6151.

[18] S. Lin, M. Elimelech, Staged reverse osmosis operation: configurations, energy efficiency, and application potential, Desalination, 366 (2015) 9–14.

[19] H. Elfil, Scaling tendency assessment in reverse osmosis modules, Desal. Wat. Treat., 51 (2013) 892–898.

[20] H. Gong, Z. Jin, Q. Wang, J. Zuo, J. Wu, K. Wang, Effects of adsorbent cake layer on membrane fouling during hybrid coagulation/adsorption microfiltration for sewage organic recovery, Chem. Eng. J., 317 (2017) 751–757.

[21] S.K. Lateef, B.Z. Soh, K. Kimura, Direct membrane filtration of municipal wastewater with chemically enhanced backwash for recovery of organic matter, Bioresour. Technol., 150 (2013) 149–155.

[22] G. Mezohegyi, M.R. Bilad, I.F.J. Vankelecom, Direct sewage up-concentration by submerged aerated and vibrated membranes, Bioresour. Technol., 118 (2012) 1–7.

[23] C.J. Chuang, K.Y. Li, Effect of coagluant dosage and grain size on the performance of direct filtration, Sep. Purif. Technol., 12 (1997) 229–241.

[24] V.G. Gude, Energy consumption and recovery in reverse osmosis, Desal. Wat. Treat., 36 (2011) 239–260.

[25] T. Hey, N. Bajraktari, Å. Davidsson, J. Vogel, H.T. Madsen, C. Hélix-Nielsen, J.C. Jansen, K. Jönsson, Evaluation of direct membrane filtration and direct forward osmosis as concepts for compact and energy-positive municipal wastewater treatment, Environ. Technol., 81 (2017) 264–276.

[26] H. Gong, Z. Wang, X. Zhang, Z. Jin, C. Wang, L. Zhang, K. Wang, Organics and nitrogen recovery from sewage via membrane-based pre-concentration combined with ion exchange process, Chem. Eng. J., 311 (2016) 13–19.

[27] K. Kimura, D. Honoki, T. Sato, Effective physical cleaning and adequate membrane flux for direct membrane filtration (DMF) of municipal wastewater: up-concentration of organic matter for efficient energy recovery, Sep. Purif. Technol., 181 (2017) 37–43.

[28] T. Hey, J. Väänänen, N. Heinen, C.J.J. La, K. Jönsson, Potential of combining mechanical and physicochemical municipal wastewater pre-treatment with direct membrane filtration, Environ. Technol., 38 (2016) 108–115.

[29] J. Su, D. Ji, M. Lin, Y. Chen, Y. Sun, S. Huo, J. Zhu, B. Xi, Developing surface water quality standards in China, Resour. Conserv. Recycl., 117 (2016) 294–303.

[30] X.H. Wang, X. Wang, G. Huppes, R. Heijungs, N.Q. Ren, Environmental implications of increasingly stringent sewage discharge standards in municipal wastewater treatment plants: case study of a cool area of China, J. Cleaner Prod., 94 (2015) 278–283.

[31] W. Chen, P. Westerhoff, J.A. Leenheer, K. Booksh, Fluorescence excitation-emission matrix regional integration to quantify spectra for dissolved organic matter, Environ. Sci. Technol., 37 (2003) 5701–5710.

[32] Z. Wang, Z. Wu, S. Tang, Characterization of dissolved organic matter in a submerged membrane bioreactor by using three-dimensional excitation and emission matrix fluorescence spectroscopy, Water Res., 43 (2009) 1533–1540.

[33] H. Gong, X. Wang, M. Zheng, Z. Jin, K. Wang, Direct sewage filtration for concentration of organic matters by dynamic membrane, Water Sci. Technol., 70 (2014) 1434–1440.

[34] L. Ahsan, M.S. Jahan, Y. Ni, Recovering/concentrating of hemicellulosic sugars and acetic acid by nanofiltration and reverse osmosis from prehydrolysis liquor of kraft based hardwood dissolving pulp process, Bioresour. Technol., 155 (2014) 111–115.