Science of the Total Environment 680 (2019) 35–43

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Applying a dynamic membrane filtration (DMF) process for domestic wastewater preconcentration: Organics recovery and bioenergy production potential analysis

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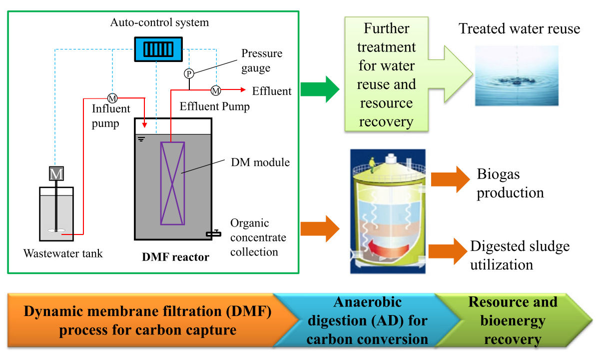
HIGHLIGHTS

- Dynamic membrane filtration (DMF) was established for wastewater pre-concentration
- DMF showed satisfactory filterability at high flux and low transmembrane pressure
- Organics recovered from domestic wastewater was 51%
- Biomethane production potential of the organic concentrate was 0.20 L CH_4/g COD
- DMF process coupling with anaerobic digestion can be energy-sufficient

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 6 March 2019
Received in revised form 5 May 2019
Accepted 6 May 2019
Available online 8 May 2019

Editor: Huu Hao Ngo

Keywords:
Dynamic membrane
Wastewater preconcentration
Resource recovery
Bioenergy production
Biomethane production potential

ABSTRACT

Wastewater is increasingly recognized as a valuable resource rather than as a waste, motivating a shift in the perspective of wastewater treatment from pollution control to resource recovery. This study proposes the recovery of organic matter from domestic wastewater for the production of bioenergy through a novel process of wastewater preconcentration based on dynamic membrane filtration (DMF). The selection of a dynamic membrane (DM) supporting material, the preconcentration performance of organics, and the biomethane production potential (BMP) of the organic concentrate were investigated. The process optimization results indicated that a DM module with a supporting material of a 25 μm stainless steel mesh with a three-layer structure, assisted by internal suspended particles derived from raw wastewater, enabled the rapid DM layer formation within 1 h. The DMF process operated under a constant high flux of 30–60 L/m^2 h at a trans-membrane pressure (TMP) of less than 40 kPa. During the continuous DMF operation, the average chemical oxygen demand (COD) of the influent, effluent and concentrate was 305, 113 and 2000–2500 mg/L, respectively, while the removal performance of other pollutants (such as nitrogen and phosphorus) varied, indicating differential retention effects for the various pollutants by the DM layer. Air back-flushing can effectively regenerate the DM layer and maintain long-term stable operation, but higher rates of TMP increase were observed for later filtration cycles, probably due to the accumulation of physically irremovable fouling. The BMP of the DMF concentrate was 0.20 L CH_4/g COD, which was comparable to the ordinary biogas yield from municipal wastewater by anaerobic digestion. The DMF process integrated with anaerobic digestion can be a promising alternative for energy-sufficient wastewater treatment.

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https://doi.org/10.1016/j.scitotenv.2019.05.080

1. Introduction

Conventional activated sludge (CAS) processes are currently prevalent in wastewater treatment in order to reach an effluent quality that meets the increasingly stringent discharge standards. This process does not comply with the goals of sustainable development due to the mineralization of organic matter by extensive aeration, resulting in a large amount of energy consumption and greenhouse gas emissions (Jin et al., 2016). In addition, biological nutrient removal technologies are adopted for the conversion and elimination of nutrients (nitrogen and phosphorus), without considering the possibility of nutrient recovery (Li et al., 2017; Jin et al., 2015). Thus, more sustainable technologies are urgently needed to address the challenges of wastewater treatment and reuse and to combine simultaneous energy and nutrient recovery.

As for minimizing energy consumption or even achieving net energy production during low-intensity municipal wastewater treatment (commonly involving CODs ranging from 200 to 1000 mg/L), the efficient capture of organic matter in wastewater followed by bioenergy generation technology (such as anaerobic digestion) is an appropriate option (McCarty et al., 2011; Verstraete et al., 2009) because the COD of wastewater should be at least 2000 mg/L for the direct application of an anaerobic process for efficient energy recovery (Metclaf and Eddy, 2001). Several strategies have been attempted to capture organics from municipal wastewater via primary sedimentation, bioflocculation, high-loaded membrane bioreactor (MBR), membrane-based preconcentration, or other methods. Primary sedimentation only retained part of the settleable particulate organics with colloidal and soluble organics escaping (Wu et al., 2010). Bioflocculation is another method used for recovery of organics in the adsorption/bio-oxidation (AB) process; however, more than 30–40% of organic matter was not retained (discharged in the effluent) or was mineralized by microbial metabolism during bioflocculation (Boehnke et al., 1998). Nevertheless, a certain amount of energy consumption is needed in the bio-oxidation stage for pollutant removal to meet stringent effluent discharge requirements.

Recently, membrane filtration technologies, such as MBR, ultrafiltration (UF) and microfiltration (MF), have become increasingly prevalent for the improvement of municipal wastewater preconcentration efficiency (Faust et al., 2014; Lateef et al., 2013; Mezohegyi et al., 2012; Jin et al., 2017; Gong et al., 2017a; Gong et al., 2017b). High-loaded MBR operated under extremely low SRT (0.5–1 d) can enhance bioflocculation and organic recovery efficiency but suffers from severe fouling and substantial biodegradation of organics (Faust et al., 2014). Direct UF/MF of municipal wastewater combined with various fouling control methods has been intensively studied. A two-stage MF process with chemically enhanced backwashing showed a COD content of 10,000 mg/L in the final organic concentrate; however, the intensive use of cleaning chemicals potentially reduced membrane lifespan and increased organic matter mineralization (Mezohegyi et al., 2012). Researchers systematically studied the MF-based wastewater preconcentration process and compared different methods for effective fouling control, including enhanced coagulation, periodical air backwashing and combinations of these methods (Jin et al., 2016; Jin et al., 2017; Gong et al., 2017a; Gong et al., 2017b; Kimura et al., 2017). Under optimized coagulation and air backwashing conditions, organic concentration efficiency was maximized with a concentrate COD of 9700 mg/L (Jin et al., 2017). Although great efforts have been made to optimize direct MF systems, their practical application is hindered by continuous chemical applications and energy consumption for membrane fouling control as well as high membrane cost.

A novel dynamic membrane (DM) filtration technology might be an effective alternative for addressing these limitations of MF systems. Because DMs can be formed on inexpensive supporting meshes with large pore sizes (10–150 μm) when filtering mixed liquor containing suspended particles (such as wastewater or sludge mixture), DM filtration can attain low resistance with negligible risk of pore blocking, easy cleaning with physical methods, and low membrane cost (Fan and Huang, 2002; Hu et al., 2016; Hu et al., 2017a). To date, although DM technology has been applied to develop various anaerobic and aerobic dynamic membrane bioreactors (DMBRs) (Saleem et al., 2017; Hu et al., 2017b; >Ersahin et al., 2012; Hu et al., 2018a), direct DM filtration of municipal wastewater for organic matters recovery has rarely been investigated. Only limited studies have adopted particulate carrier/coagulant assisted DM filtration systems, which could increase the expenditures for chemical and particle recovery (Gong et al., 2014; Li et al., 2017). If internal suspended solids in raw wastewater can be used for promoting DM layer formation, the operational cost can be reduced without the addition of chemicals, and the quality of the recovered organic concentrate can be enhanced without the effects of external chemicals or particles.

In this study, a novel dynamic membrane filtration (DMF) based wastewater preconcentration process is developed and applied to direct wastewater filtration without the addition of chemicals or the implementation of complicated fouling control measures. The objectives of this study are (Aslam et al., 2017) to optimize the DMF process by selecting supporting meshes and a DM module structure; (Angelidaki et al., 2009) to investigate DM filtration behaviors and organic preconcentration performance; (Boehnke et al., 1998) to assess the applicability of a process that combines DMF and anaerobic digestion in energy-sufficient wastewater treatment through BMP tests and energy balance analysis.

2. Materials and methods

2.1. Experimental setup and operational conditions

A schematic diagram of the lab-scale DMF system is presented in Fig. S1 of the Supplementary material. Identical reactors were run in parallel for comparative study during the DMF optimization phase. The reactor is made of plexiglass with length × width × height = 11 cm × 6 cm × 38 cm and an effective volume of 1.1 L. No aeration or mechanical stirring is used to inhibit organics loss by microbial degradation. Each DMF reactor contains one submerged flat-sheet dynamic membrane module with a total membrane surface area of 0.02 m^2. The assembled DM module consists of a plexiglass framework and double-faced supporting meshes (such as stainless steel mesh and nylon mesh with a pore size of 10 or 25 μm) as previously reported (Hu et al., 2017a), and one outlet between the meshes for permeate extraction.

The raw wastewater fed into the DMF reactor was obtained from a local domestic wastewater treatment plant in Xi'an, China, after filtering through a coarse screen with a pore size of 5 mm. The detailed characteristics of the wastewater are reported in Table 1. To avoid potential fluctuations in water quality due to the use of practical wastewater, the daily collection of wastewater was performed at an approximately constant time (9:00–10:00 am). An influent pump (EVO-05, Singapore) connected to a liquid level sensor was used to keep a constant water level. The effluent was continuously extracted with a peristaltic pump (BT-100 Longer, USA) without periodical relaxation and backwashing. Membrane filtration experiments were conducted in constant flux mode with an initial flux of 50–60 L/m^2 h, while the filtration tests were stopped at the predetermined filtration duration or the time that constant flux could not be sustained (serious flux decline exceeding 50% is noted). An on-line pressure gauge (SIN-P400, China) combined with a paperless recorder was used to automatically monitor the TMP evolution.

2.2. Experimental design

2.2.1. Batch tests for optimizing DM module

First, the selection of DM supporting material was conducted. Commonly, several coarse pore materials, such as stainless steel mesh,

Table 1
Characteristics of the influent.

Parameter	Value range[a]
COD (mg/L)	190.1–320.5
NH_3-N (mg/L)	27.7–37.9
TN (mg/L)	46.8–49.1
TP (mg/L)	5.6–6.3
PO_4^{3-} (mg/L)	4.5–5.3
Turbidity (NTU)	85.4–150.2
UV_{254} (m^{-1})	0.15–0.33
pH	7.7–8.1

[a] Real wastewater used as the DMF influent was obtained from a local domestic wastewater treatment plant. To avoid great fluctuations in water quality, the daily collection of wastewater was performed at an approximately constant time (9:00–10:00 am) during March to June in 2018. Number of collection campaigns carried out: n = 12.

nylon mesh and nonwoven cloths, were adopted as supporting materials for DM formation (Ersahin et al., 2012). A nylon mesh (25 μm pore size) and a stainless steel mesh (25 μm and 10 μm pore sizes), supporting materials with high material strength, were chosen for comparative study in the DMF process. Three identical reactors were run in parallel, each with three DM modules installed with different supporting materials, with the focus mainly on filtration behavior in terms of filtration flux, TMP and effluent turbidity. The filtration duration of the batch tests was 24 h with operation conditions the same as mentioned in Section 2.1 because 24 h was found to be enough time to differentiate filtration performance under various testing conditions.

To enhance the organics preconcentration efficiency, the stainless steel mesh (25 μm pore size) was then subjected to further optimization of the effects of the different mesh layers (from one to three layers) on the system performance. The three reactors were run in parallel for 24 h to choose the suitable DM module structure.

2.2.2. Continuous operation of the optimized DMF process

After the batch tests, the selected DM supporting material and module configuration were further used in continuous operation to investigate the performance of the DMF with respect to the long-term filtration behaviors and physical cleaning efficiency as well as the organic retention effects. Forty-eight hours was set as an operation cycle, and at the end of one cycle the filtration was stopped, and air backwashing with surface brushing was used as the cleaning method for regeneration of the DM according to reported methods (Hu et al., 2017b). The selection of 48 h as a filtration cycle was intended to avoid the effects of frequent cleaning on organic recovery performance, to achieve an organic concentrate with a high COD concentration, and to prevent the TMP from exceeding a predetermined value of 40 kPa during long-term operation.

2.2.3. BMP test using organic concentrate as the substrate

A biomethane production potential (BMP) assay was conducted to access the bioenergy recovery potential of using the organic concentrate as the substrate in the DMF process. The procedures for BMP measurement were slightly modified from the reported method (Angelidaki et al., 2009; Chen et al., 2017). In detail, the BMP test was conducted in 120 mL serum bottles placed in a water bath at 37 ± 1 °C. The inoculated sludge was obtained from a lab-scale anaerobic bioreactor treating domestic wastewater (Hu et al., 2018b). The substrate was organic concentrate from the DMF process. The inoculated sludge and substrate were collected and mixed at a volatile suspended solids (VSS) ratio of 1:1, resulting in a total volume of 100 mL. Oxygen in the headspace of the bottles was purged by nitrogen gas for 2 min. When all the bottles reached approximately 37 °C, the headspace was vented using a syringe to release the pressure caused by thermal expansion. Biogas production and composition were frequently measured by the volumetric and gas chromatographic methods (Hu et al., 2018b). Duplicate measurements of BMP were conducted, and the average value was reported.

2.3. Analytical methods

The particle size distribution (PSD) of different water samples obtained during the experimental period were detected using a laser granularity distribution analyzer (LS 230/SVM+, Beckman Coulter Corporation, USA) with a detection range of 0.4–2000 μm. The measurements of chemical oxygen demand (COD), UV_{254}, ammonia (NH_3-N), total nitrogen and total phosphorus (TP) were conducted according to the standard methods (Chinese NEPA, 2002). pH was detected by a pH meter (sensION1, HACH, USA), while turbidity was measured using a turbidity meter (2100Q, HACH, USA).

3. Results and discussion

3.1. Optimization of the DMF process

3.1.1. Selection of DM supporting materials

In the DM filtration processes, a stainless steel mesh and nylon mesh are commonly adopted as supporting materials due to their high strength and low risk of irreversible fouling. Thus, according to DM filtration studies regarding the material and pore size of DM supporting material (Li et al., 2017; Saleem et al., 2017; Hu et al., 2017a), a nylon mesh (25 μm pore size) and stainless steel meshes (25 μm and 10 μm pore size) were chosen for comparative study using batch filtration tests in identical DMF reactors. As shown in Fig. 1(a), a rapid increase in TMP to more than 30 kPa during a short filtration time (less than 10 h) was observed when a nylon mesh with 25 μm pore size was used as supporting material. Upon further observation of the variation in the effluent turbidity (Fig. 1(b)), a rapid decline in turbidity was noted, indicating a rapid DM formation by the retention of suspended particles in the raw wastewater. Subsequently, the effluent turbidity started to increase and then leveled off because more fine particles passed through due to a reduced retention effect of the DM layer caused by high filtration pressure and resistance imposed on the formed DM layer.

For the stainless steel meshes of 25 μm and 10 μm pore size, similar filtration behaviors were noted, reflected by a slow TMP rise to approximately 4.7 and 10.6 kPa, respectively during the 24 h operation period. Similarly, after a rapid decrease, the effluent turbidity was constant within the range of 50–60 NTU. When batch filtration tests concluded, the DM modules were subjected to air backwashing and surface brushing, and the organic content of the concentrate (COD concentration) was measured, yielding 635, 1252, 981 mg/L for nylon mesh (25 μm pore size) and stainless steel meshes (25 μm and 10 μm pore size), respectively. The differences in the organic recovery efficiency are likely due to influent properties, such as particle size and composition; characteristics of the DM supporting material, such as pore size and structure; and the interactions between these properties. Thus, taking the TMP increase rate and particle retention efficiency (reflected by effluent turbidity and COD content in the final concentrate) into consideration, stainless steel meshes of 25 μm pore size are regarded as the most suitable supporting material for DM formation during direct wastewater filtration.

3.1.2. Selection of the structure of DM supporting materials

To further enhance the wastewater preconcentration and organic retention efficiency, the stainless steel mesh (25 μm pore size) was used to investigate the influence of mesh structure (from one to three layers). During the batch experiments, it was noted that DM modules employing one-layer, two-layer and three-layer meshes showed similar TMP change profiles, indicating a gradual increase, with final TMP values of 4.3, 6.3 and 7.5 kPa, respectively (Fig. 2

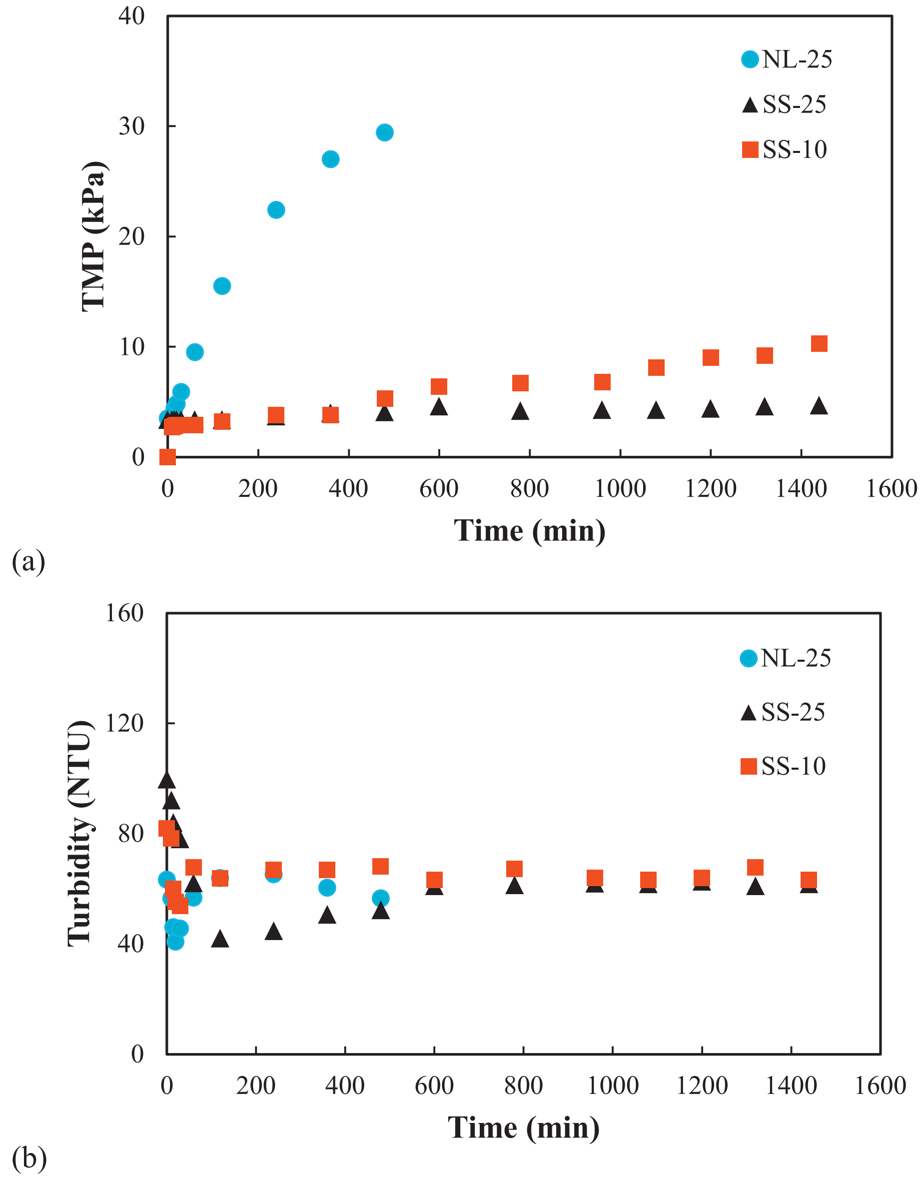

Fig. 1. Variation of (a) TMP and (b) effluent turbidity using different DM supporting materials. (NL-25, SS-25 and SS-10 mean 25 μm nylon mesh, 25 μm and 10 μm stainless steel meshes).

(a)). Correspondingly, higher filtration resistance indicated better particle rejection rates of the DM layer (Fig. 2(b)), as the three-layer structure of the stainless steel mesh always showed lower effluent turbidity compared with the other mesh structures. The final concentrate COD in the tests was 856, 920, 1200 mg/L for one-layer, two-layer and three-layer structures, respectively, thus indicating better organic preconcentration efficiency for three-layer stainless steel meshes.

In previous studies of municipal wastewater preconcentration, direct microfiltration (MF) processes showed a rapid TMP increase to more than 20 kPa and then operated under high TMPs (30–80 kPa) at a low flux ranging from 10 to 20 L/m^2 h, and chemical cleaning was necessary for the recovery of the membrane permeability (Jin et al., 2015; Jin et al., 2016; Gong et al., 2017b). Compared to the MF process, the DMF system seemed to be a low-resistance filtration option even under high filtration flux (such as 50–60 L/m^2 h adopted in this work), thus resulting in the benefits of longer filtration duration and less frequent maintenance; however, it should be noted that a tradeoff existed between low resistance filtration and membrane retention efficiency, discussed below.

3.2. Performance of the optimized DMF process during continuous operation

3.2.1. Filtration performance

After the batch tests, continuous operation of the DMF process using a three-layer stainless steel mesh (25 μm pore size) assembled membrane module was conducted to investigate DM filtration performance, considering filtration behaviors, physical cleaning efficiency and organic recovery efficiency. Fig. 3(a) shows the changes of TMP and flux with operation times of approximately 200 h. The operation period can be divided into four cycles of the predetermined filtration duration (48 h). At the end of each cycle, physical cleaning, namely, air backwashing with surface brushing, was carried out for DM regeneration. During the first two cycles, flux could be sustained in the range of 45–54 L/m^2 h; however, in the later cycles, the decline of flux was more rapid with the flux ranging from 33 to 54 L/m^2 h. In addition, after physical cleaning, some residuals (foulants) were found between the mesh layers, which was attributed to the effects of physically irremovable fouling on the stable filtration performance of the DM layer as noted in other DM filtration systems (Hu et al., 2016, 2017a). The accumulation of irremovable

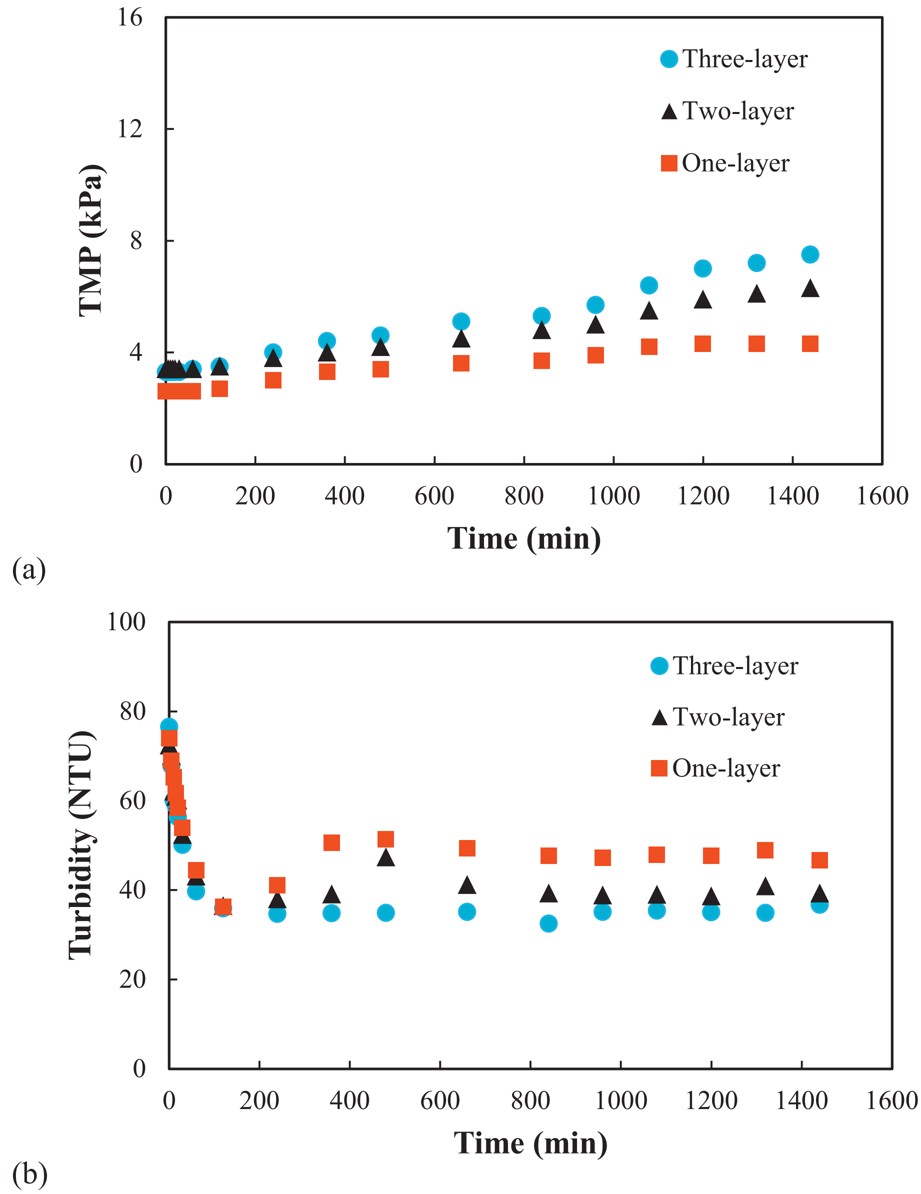

Fig. 2. Variation of (a) TMP and (b) effluent turbidity under different mesh structures.

foulants may pose adverse impacts on DM filtration behaviors as reflected by the tendency of the TMP to increase, as the rate of the increase in the TMP was higher in sequential cycles, i.e., 0.38, 0.50, 0.67 and 0.69 kPa/h for four filtration cycles.

The effluent turbidity in different cycles was not influenced by the applied physical cleaning (as shown in Fig. 3(b)). At the beginning of each cycle, effluent turbidity was as high as 58–75 NTU; however, a rapid decrease in the effluent turbidity to below 30 NTU was noted within 20 min, indicating a rapid DM layer formation by internal particles contained in raw domestic wastewater serving as DM forming materials. After stable DM layer formation, constant retention of particles in wastewater was observed, explainable by the steady effluent turbidity ranging in most cases from 20 to 50 NTU. These results were in agreement with those of a previous DM filtration system for wastewater preconcentration (Li et al., 2017). These results verified the feasibility of optimizing a DMF process for effective wastewater direct filtration. If enhanced cleaning methods, such as the chemical cleaning used in MF processes (Jin et al., 2016; Kimura et al., 2017), could be implemented to reduce physically irremovable fouling, long-term stable operation of the DMF process might be expected to yield sustainable filtration performance.

3.2.2. Particle size distribution (PSD) analysis

Fig. 4 shows the PSD of the influent, initial effluent and organic concentrate samples from the DMF process. For the influent, particle size showed a bimodal distribution with peaks located at 14 and 50 μm and covered a wide size range between 0.4 and 122 μm. After DM filtration, particles in the initial effluent presented a multimodal distribution, within a range between 0.4 and 58 μm, indicating the effective rejection of large particles (such as those larger than 58 μm). It was worth noting that DMF concentrate showed the broadest PSD ranging from 0.4 to 450 μm, indicating occurrence of the retention and aggregation of retained particles in the reactor. In MF systems, similar phenomena of increases in PSD were observed due to the size exclusion effect of the filtration membrane (Jin et al., 2015; Jin et al., 2016).

The enhancement in the influent and concentrate PSD was beneficial for the achievement of sustainable membrane filtration

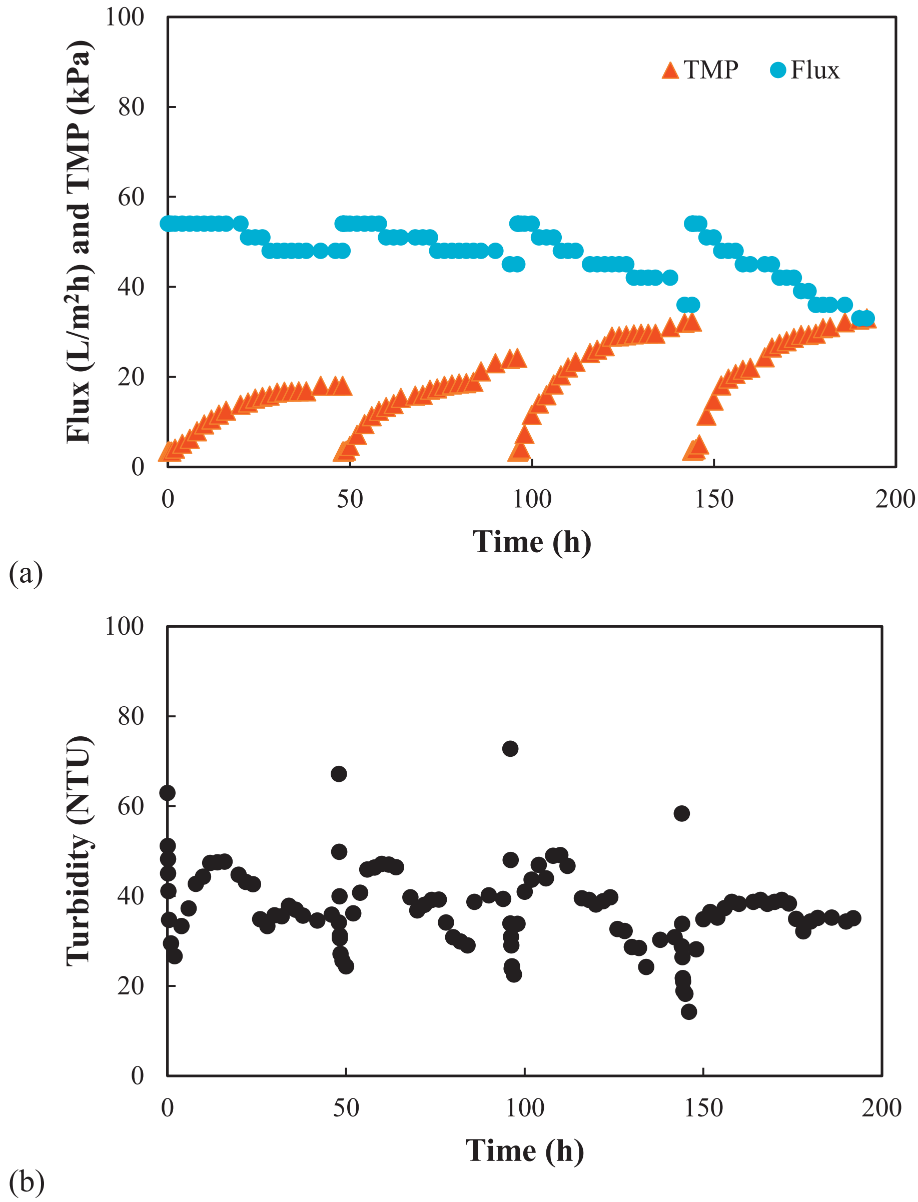

Fig. 3. Variation of (a) TMP, flux and (b) effluent turbidity during continuous DMF operation.

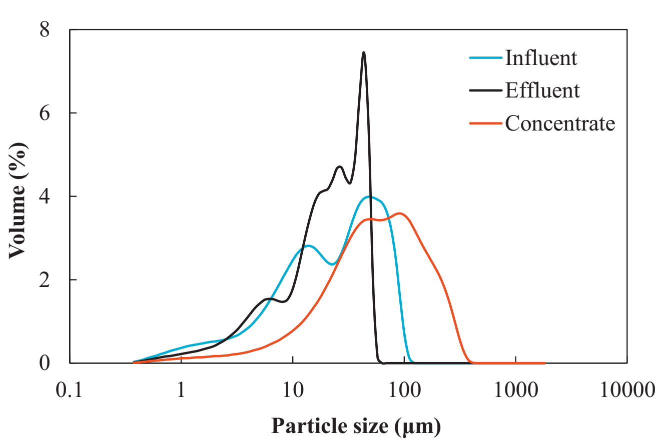

Fig. 4. Typical PSD profiles of different samples from the DMF process.

performance in the membrane-based preconcentration process. In previous studies, enhanced coagulation of the influent was adopted for membrane fouling control because after coagulation, the aggregation of fine particles (main membrane foulants) into larger sizes could reduce their tendency to move towards the membrane surface (Jin et al., 2017; Gong et al., 2017a). On the other hand, more particles and even colloids and solutes in the influent will be retained rather than passing through the membrane, thus improving organic preconcentration efficiency. With this in mind, coagulation and other strategies that can enhance influent PSD are promising subjects for future investigation.

3.2.3. COD balance and pollutant removal

The average values of the organic matter retention performance and COD mass balance of the DMF process during the continuous operation period were conducted based on four replicates (Fig. S2 in the Supplementary Material). Approximately 37% of the total COD mass passed through the DM, which was higher than the 27.4% observed in the hybrid coagulation microfiltration (HCM) with air backflushing (AB) system and the 19% in the combined coagulation microfiltration (CCM) with intermittent aeration system (Jin et al., 2015; Jin et al., 2016). This higher value was attributed to less effective retention of soluble organics by the DM layer formed on coarse-pore meshes compared with that of the UF/MF membrane used in previous studies of the preconcentration of municipal wastewater. However, the DMF system still collected 51% of organic matter in a recoverable organic concentrate, while 12% of the total influent COD was lost, possibly due to the mineralization of organics through biological degradation and organic foulants attached on supporting mesh surface or other unclear reasons as documented in the literature (Jin et al., 2017). Thus, the addition of particles, such as powdered activated carbon, to enhance the dynamic formation and retention and/or using coagulation to recover a portion of the organic colloids and solutes are recommended to improve the recovery efficiency of organics in the DMF process, which is a subject that requires further investigation.

Table 2 shows the pollutant removal performance of the DMF process during the continuous operation period. It was noted that the removal of nutrients was quite different from that of COD, with removal rates of 22.9%, 8.7%, 14.5% and 5.8% for TN, NH_3-N, TP and PO_4^{3-} respectively. This result can be explained by the fact that soluble components (i.e., NH_3-N and PO_4^{3-}) contribute approximately 80% of the TN and TP. Similar results regarding the composition distribution of various pollutants have been reported by other researchers (van Nieuwenhuijzen et al., 2004; Wang et al., 2007), while the exact components and corresponding contributions varied according to influent quality. Due to the retention of portions of particulate substances, TN and TP in the concentrate showed increases in concentration; however, due to the preferential retention rate of organic matter and nutrients, the COD/TN and COD/TP ratios of the concentrate were substantially enhanced compared with those of the influent.

3.2.4. Bioenergy recovery assessment by BMP assay

The BMP assay of the concentrate was conducted under mesophilic conditions to explore the bioenergy recovery potential of recovered organic matter. The average methane production potential is approximately 0.20 L CH_4/g COD in repeated measurements, as presented in Fig. 5. This result was lower than the theoretical methane yield of 0.35 L CH_4/g COD under standard measurement conditions; however, during anaerobic digestion of real municipal wastewater, the reported methane yields ranged from 0.1 to 0.3 L CH_4/g COD in anaerobic digesters (Ozgun et al., 2013). A previous study of organic preconcentrate processes found a similar methane yield of approximately 0.19–0.27 L CH_4/g COD (Li et al., 2018). The low methane production using the concentrate as a substrate may be due to the following reasons: 1) the retained organics contained large amounts of particulate organic substances, generally composed of slowly-degradable or even non-degradable organic matter; and 2) the accumulation of particles in the membrane filtration systems imposed adverse effects on the metabolic activities of anaerobic microorganisms. Further optimization of the concentrate pretreatment to promote hydrolysis and biodegradability in order to minimize negative influences on sequential AD processes would guide the development of DMF process towards practical application.

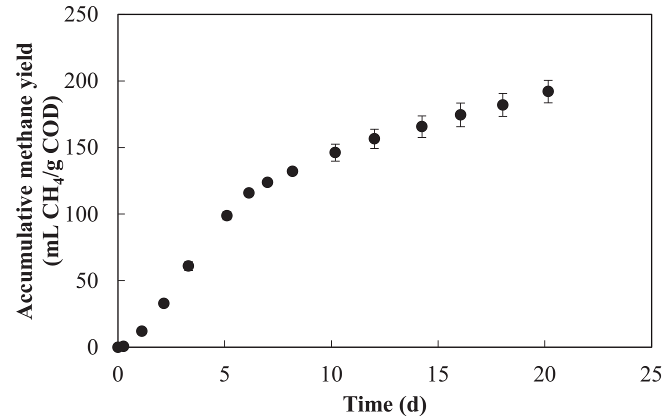

Fig. 5. Accumulative methane yield using organic concentrate as substrate for BMP assay (Average results are depicted based on two replicates).

3.3. Applicability of the DMF process coupled with anaerobic digestion

From the technical point of view, the DMF process is a promising technology for the preconcentration of low strength wastewater for the recovery of organics. As seen above, with preliminary optimization of the DM supporting material and structure, the DMF process exhibited satisfactory filtration performance, reflecting a long filtration cycle at low TMP and filtration resistance at minimum operating maintenance; however, the organic preconcentrate efficiency was lower, with a substantial portion of influent organics lost as permeate compared to that of UF/MF process. As in other UF/MF filtration processes (Lateef et al., 2013; Jin et al., 2015; Jin et al., 2017), the organic retention rates ranged from 60%–90% based on whether the process was carried out with or without pretreatment measures, such as coagulation to enhance colloidal and soluble organics recovery (Jin et al., 2017) or frequent air backflushing or chemical backwashing to improve accumulated organics recovery from the cake layer (Lateef et al., 2013; Jin et al., 2015). It should be noted that these methods were initially adopted for membrane fouling control as direct wastewater filtration showed a greater propensity to foul than did activated sludge. The fouling issue was less significant in the DMF system compared with previous UF/MF studies (Lateef et al., 2013; Jin et al., 2015; Gong et al., 2017a; Jin et al., 2017). If proper pretreatment measures, such as coagulation or enhanced DM precoating, are taken into consideration to further improve organics retention rate, the DMF process will be a more competitive method for wastewater treatment and resource recovery.

From the economic point of view, the use of inexpensive meshes as DM supporting materials greatly reduced the cost of the membrane, thus reducing the capital expenditure. During the operation of the DMF process, hydraulic cleaning alone was sufficient to recover DM permeability at the end of one filtration cycle without adopting any other methods, such as membrane relaxation, periodical air/water backflushing, or enhanced chemical cleaning. This minimum maintenance

Table 2
Pollutants removal of the DMF process during continuous operation (Average values are represented together with the standard deviation, which were determined from four replicates).

Parameters	Influent	Effluent	Average removal rate (%)	Concentrate
COD (mg/L)	304.5 ± 29.5	113.0 ± 15.4	62.9	3534.0 ± 308.3
SCOD (mg/L)	119.0 ± 32.5	73.7 ± 18.1	18.7	121.3 ± 14.1
TN (mg/L)	46.8 ± 2.1	36.1 ± 2.4	22.9	85.1 ± 3.7
NH_3-N (mg/L)	36.8 ± 2.3	33.6 ± 2.0	8.7	47.7 ± 1.4
TP (mg/L)	6.2 ± 0.2	5.3 ± 0.4	14.5	15.8 ± 1.4
PO_4^{3-} (mg/L)	5.2 ± 0.3	4.9 ± 0.5	5.8	5.6 ± 0.3

requirement made the maintenance cost extremely low. When a nylon mesh or stainless steel mesh rather than nonwoven material was used as the DM supporting material, the DMs showed good stability and ability to resist the influence of influent wastewater, physical and chemical cleaning during the long-term operation of the DMBRs for the treatment of municipal, simulated industrial wastewater and landfill leachate. The application of DM technology in long-term DMF operations, or in other fields, such as catalytic treatment for wastewater or complex industrial wastewater, has been unexplored so far. In addition, the DMF can be regarded as a short-cut physicochemical treatment rather than a conventional biological treatment process, which can operate at high flux and low HRTs thus giving the system a minimal footprint and requiring low capital expenditure. Raw wastewater can be concentrated as much as 10–50 times, and the high organic concentration was suitable for AD in dealing with high organic loading, thus reducing the required reactor volume of anaerobic digesters for treating organic concentrate.

Finally, the approximate estimation of energy consumption and production is presented in Table 3 based on the results from the continuous DMF operation and the BMP assay. Energy consumption consists of energy for influent pumping and permeate extraction and is calculated based on methane recovered using the AD process (Kim et al., 2011; Aslam et al., 2017). Using previously reported methods for energy calculations (Kim et al., 2011), the pumping energy required to feed the influent and to achieve effluent permeation was 0.0003 and 0.0082 kWh/m^3, respectively, given the main parameters of flow rate and estimated hydraulic pressure head. For this reason, little electrical energy was expended in the DMF process (0.013 kWh/m^3). On the other hand, the energy produced in terms of electrical energy from methane was evaluated based on an energy efficiency of 33% in the conversion of methane to electricity. Electrical energy production was approximately 0.1014 kWh/m^3, which was found to be sufficient for supporting system operations, with a net energy production of 0.088 kWh/m^3 during wastewater treatment. With further optimization of the DMF-AD combined system, enhancement of the energy production potential can be expected.

Table 3
Gross energy balance of the DMF process coupling with anaerobic digestion.

Parameter[a]	Value
Energy for influent feeding	
Influent flow rate (L/d)	24
Estimated hydraulic pressure head (m)	0.1
Energy requirement (10^{-7} kW)	2.72
Required pumping energy (kWh/m^3)	0.0003
Energy for permeation	
Average effluent flow rate (L/d)	24.0
Estimated hydraulic pressure head (m)	3.0
Energy requirement (10^{-6} kW)	8.17
Required pumping energy (kWh/m^3)	0.0082
Total pumping energy (influent feeding and permeation) (kWh/m^3)	0.0085
Total electrical energy required for pumps (influent feeding and permeation) (kWh/m^3)[b]	0.013
Electrical energy production potential from methane	
Average influent COD (mg/L)	300
COD recovery efficiency (%)	51
Biomethane production potential (L CH_4/g COD)	0.2
Methane production potential (mol/m^3 wastewater)	1.38
Methane energy content (kWh/m^3)	0.3072
Electrical energy production from methane (kWh/m^3)[c]	0.1014
Net electrical energy production (kWh/m^3)	0.0884

[a] Calculation method and default parameters are according to the references. Energy requirement = QγE/1000, where Q (m^3/s) is the flow rate, γ = 9800 N/m^3 and E (m H_2O) is head loss (Kim et al., 2011; Aslam et al., 2017).
[b] Assumed energy transfer efficiency of 65% in conversion of electrical energy to pump energy (Yoo et al., 2012).
[c] Assumed energy conversion efficiency of 21% in conversion of methane to applicable electricity and energy available from methane combustion is 0.222 kW h/mol (Kim et al., 2011).

4. Conclusions

The dynamic membrane filtration (DMF) based preconcentration process was developed for recovering organic matter from domestic wastewater to enhance net energy production. Through a process of optimization, a DM module with a 25 μm stainless steel mesh with a three-layer structure was selected for rapid DM layer formation. The DMF process showed a high flux of 30–60 L/m^2 h at a low TMP. During 192 h of continuous operations, COD in the concentrate reached 2000–2500 mg/L during one filtration cycle with an influent COD of 200–300 mg/L. COD mass balance analysis indicated that more than 50% of influent COD was retained in the concentrate. Air back-flushing can effective regenerate the DM layer for permeability recovery, but the accumulation of irremovable fouling should be considered during long-term stable operation. The BMP assay supported the idea that the DMF concentrate could be used for a downstream anaerobic digestion (AD) process, with a methane production potential of 0.20 L CH_4/g COD; however the exact effects of DMF operation on the BMP of the organic concentrate needs further investigation. The applicability analysis indicates that, with further optimization, DMF-AD coupled processes make energy-positive wastewater treatment possible.

Declaration of Competing Interest

None.

Acknowledgments

This study was jointly supported by the Natural Science Foundation of Shaanxi Province (grant no. 2018JQ5054), the Special Scientific Project of Education Department of Shaanxi Province (grant no. 17JK0462), the National Natural Science Foundation of China (grant no. 51508450), and the Program for Innovative Research Team in Shaanxi (grant no. IRT2013KCT-13).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2019.05.080.

References

Angelidaki, I., Alves, M., Bolzonella, D., Borzacconi, L., Campos, J.L., Guwy, A.J., Kalyuzhnyi, S., Jenicek, P., van Lier, J.B., 2009. Defining the biomethane potential (BMP) of solid organic wastes and energy crops: a proposed protocol for batch assays. Water Sci. Technol. 59, 927–934.
Aslam, M., McCarty, P.L., Shin, C., Bae, J., Kim, J., 2017. Low energy single-staged anaerobic fluidized bed ceramic membrane bioreactor (AFCMBR) for wastewater treatment. Bioresour. Technol. 240, 33–41.
Boehnke, B., Schulze-Rettmer, M.R., Zuckut, S.W., 1998. Cost-effective reduction of high-strength waste water by adsorption-based activated sludge technology. Water Eng. Manag. 145, 31–34.
Chen, R., Nie, Y., Kato, H., Wu, J., Utashiro, T., Lu, J., Yue, S., Jiang, H., Zhang, L., Li, Y.-Y., 2017. Methanogenic degradation of toilet-paper cellulose upon sewage treatment in an anaerobic membrane bioreactor at room temperature. Bioresour. Technol. 228, 69–76.
Chinese NEPA, 2002. Water and Wastewater Monitoring Methods. 4th ed. Chinese Environmental Science Publishing House, Beijing, China.
Ersahin, M.E., Ozgun, H., Dereli, R.K., Ozurk, L., Roest, K., Van Lier, J.B., 2012. A review on dynamic membrane filtration: materials, applications and future perspectives. Bioresour. Technol. 122, 196–206.
Fan, B., Huang, X., 2002. Characteristics of a self-forming dynamic membrane coupled with a bioreactor for municipal wastewater treatment. Environ. Sci. Technol. 36, 5245–5251.
Faust, L., Temmink, H., Zwijnenburg, A., Kemperman, A.J.B., Rijnaarts, H.H.M., 2014. High loaded MBRs for organic matter recovery from sewage: effect of solids retention time on bioflocculation and on the role of extracellular polymers. Water Res. 56, 258–266.
Gong, H., Wang, X., Zheng, M., Jin, Z., Wang, K., 2014. Direct sewage filtration for concentration of organic matters by dynamic membrane. Water Sci. Technol. 70, 1434–1440.
Gong, H., Jin, Z., Wang, Q., Zuo, J., Wu, J., Wang, K., 2017a. Effects of adsorbent cake layer on membrane fouling during hybrid coagulation/adsorption microfiltration for sewage organic recovery. Chem. Eng. J. 317, 751–757.

Gong, H., Wang, Z., Zhang, X., Jin, Z., Wang, C., Zhang, L., Wang, K., 2017b. Organics and nitrogen recovery from sewage via membrane based pre-concentration combined with ion exchange process. Chem. Eng. J. 311, 13–19.
Hu, Y., Wang, X.C., Tian, W., Ngo, H.H., Chen, R., 2016. Towards stable operation of a dynamic membrane bioreactor (DMBR): operational process, behavior and retention effect of dynamic membrane. J. Membr. Sci. 498, 20–29.
Hu, Y., Yang, Y., Wang, X.C., Ngo, H.H., Sun, Q., Li, S., Tang, J., Yu, Z., 2017a. Effects of powdered activated carbon addition on filtration performance and dynamic membrane layer properties in a hybrid DMBR process. Chem. Eng. J. 327, 39–50.
Hu, Y., Wang, X.C., Sun, Q., Ngo, H.H., Yu, Z., Tang, J., Zhang, Q., 2017b. Characterization of a hybrid powdered activated carbon-dynamic membrane bioreactor (PAC-DMBR) process with high flux by gravity flow: operational performance and sludge properties. Bioresour. Technol. 223, 65–73.
Hu, Y., Wang, X.C., Ngo, H.H., Sun, Q., Yang, Y., 2018a. Anaerobic dynamic membrane bioreactor (AnDMBR) for wastewater treatment: a review. Bioresour. Technol. 247, 1107–1118.
Hu, Y., Yang, Y., Yu, S., Wang, X.C., Tang, J., 2018b. Psychrophilic anaerobic dynamic membrane bioreactor for domestic wastewater treatment: effects of organic loading and sludge recycling. Bioresour. Technol. 270, 62–69.
Jin, Z., Gong, H., Wang, K., 2015. Application of hybrid coagulation microfiltration with air backflushing to direct sewage concentration for organic matter recovery. J. Hazard. Mater. 283, 824–831.
Jin, Z., Gong, H., Temmink, H., Nie, H., Wu, J., Zuo, J., Wang, K., 2016. Efficient sewage pre-concentration with combined coagulation microfiltration for organic matter recovery. Chem. Eng. J. 292, 130–138.
Jin, Z., Meng, F., Gong, H., Wang, C., Wang, K., 2017. Improved low carbon-consuming fouling control in long-term membrane based sewage pre-concentration: the role of enhanced coagulation process and air backflushing in sustainable sewage treatment. J. Membr. Sci. 529, 252–262.
Kim, J., Kim, K., Ye, H., Lee, E., Shin, C., McCarty, P.L., Bae, J., 2011. Anaerobic fluidized bed membrane bioreactor for wastewater treatment. Environ. Sci. Technol. 45, 576–581.
Kimura, K., Honoki, D., Sato, T., 2017. 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, 37–43.
Lateef, S.K., Soh, B.Z., Kimura, K., 2013. Direct membrane filtration of municipal wastewater with chemically enhanced backwash for recovery of organic matter. Bioresour. Technol. 150, 149–155.
Li, S., Yang, Y., Hu, Y., Tang, J., Wang, X.C., 2017. Development of a novel two-stage powdered activated carbon-dynamic membrane filtration (PAC-DMF) system for direct physicochemical wastewater treatment. Desalin. Water Treat. 99, 299–308.
Li, S., Hu, Y., Yang, Y., Wang, X.C., 2018. Potentials of organics and bioenergy recovery by applying a novel two-stage powdered activated carbon and dynamic membrane filtration (PAC/DMF) process. China Water & Wastewater 34, 18–22 (In Chinese).
McCarty, P.L., Bae, J., Kim, J., 2011. Domestic wastewater treatment as a net energy producer – can this be achieved? Environ. Sci. Technol. 45, 7100–7106.
Metclaf & Eddy, 2001. Wastewater Engineering: Treatment and Reuse. fourth ed. McGraw-Hill, New York.
Mezohegyi, G., Bilad, M.R., Vankelecom, I.F., 2012. Direct sewage up-concentration by submerged aerated and vibrated membranes. Bioresour. Technol. 118, 1–7.
Ozgun, H., Dereli, R.K., Ersahin, M.E., Kinaci, C., Spanjers, H., van Lier, J.B., 2013. A review of anaerobic membrane bioreactors for municipal wastewater treatment: integration options, limitations and expectations. Sep. Purif. Technol. 118, 89–104.
Saleem, M., Alibardi, L., Cossu, R., Lavagnolo, M.C., Spagni, A., 2017. Analysis of fouling development under dynamic membrane filtration operation. Chem. Eng. J. 312, 136–143.
van Nieuwenhuijzen, A.F., van der Graaf, J.H.J.M., Kampschreur, M.J., Mels, A.R., 2004. Particle related fractionation and characterisation of municipal wastewater. Water Sci. Technol. 50, 125–132.
Verstraete, W., Van de Caveye, P., Diamantis, V., 2009. Maximum use of resources present in domestic "used water". Bioresour. Technol. 100, 5537–5545.
Wang, X., Jin, P., Zhao, H., Meng, L., 2007. Classification of contaminants and treatability evaluation of domestic wastewater. Front. Environ. Sci. Eng. 1, 57–62.
Wu, H., Gao, J., Yang, D., Zhou, Q., Liu, W., 2010. Alkaline fermentation of primary sludge for short-chain fatty acids accumulation and mechanism. Chem. Eng. J. 160, 1–7.
Yoo, R., Kim, J., McCarty, P.L., Bae, J., 2012. Anaerobic treatment of municipal wastewater with a staged anaerobic fluidized membrane bioreactor (SAF-MBR) system. Bioresour. Technol. 120, 133–139.