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Review

Gravity-driven membrane filtration for water and wastewater treatment: A review

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ABSTRACT

Gravity-driven membrane (GDM) filtration has been investigated for almost 10 years. The technology is characterized not only by relatively lower transmembrane pressures which can be achieved by gravity (extremely low energy consumption), but also by the phenomenon of flux stabilization: A biofilm is allowed to form on the membrane and a stabilization of flux occurs which is related to biological processes within the biofilm layer on the membrane. This enables stable operation during a year or longer without any cleaning or flushing. Initially, the technology was developed mainly for household drinking water treatment, but in the meantime, the research and application has expanded to the treatment of greywater, rainwater, and wastewater as well as the pretreatment of seawater for desalination. This review covers the field from the rather fundamental research on biofilm morphology and microbial community analysis to the impact of feedwater composition, process parameters and organic removal performance. Not only household applications, but also for community-scale treatment and full-scale applications are discussed. In addition, the application potential is highlighted in comparison to conventional ultrafiltration. Finally, an overall assessment is illustrated and the research and development needs are identified.

Contents

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1. Introduction

For more than half a century, ultrafiltration (UF) has been an established technology featuring membranes with a pore size in the range of 5–100 nm (Mulder, 1996; Baker, 2012b). Whereas first research and development efforts mainly focused on food and medical applications, water treatment gained increasing attention from about 1990, with an initial focus on the removal of turbidity and pathogens for drinking water production (Clark and Heneghan, 1991). The membrane costs were still relatively high at that time, so that high flux values were required to make the process economically feasible. These high flux values were obtained by applying high pressures (around 1 bar or higher), combined with an array of methods to prevent fouling and biofouling (Baker, 2012b). These methods included energy-intensive hydraulically cleaning and chemical cleaning, such as cross-flow, backwash, chemical cleaning, and disinfection (Mulder, 1996). During the last two decades, the membrane price has dropped significantly (Churchhouse, 2000). As a consequence, the membrane flux has become less dominant in the cost calculation and a more significant cost reduction could be achieved by reducing energy and chemicals. The energy consumption can be reduced by applying low operation pressures and applying effective hydraulic fouling control strategies (such as cross-flow), while reduced chemical consumption can be achieved by less frequent chemical cleaning and disinfection. Typical operation pressures are around 0.2–1.0 bar with flux values between 50 and 100 L/m^{2}h (LMH) (Crittenden et al., 2005). However, measures to control fouling and biofouling were considered indispensable for a stable filtration operation until the first publication appeared on the phenomenon of biofilm-controlled flux stabilization (Peter-Varbanets et al., 2010). In this study, it was shown that a dead-end operated (no cross-flow) UF system without any chemical or hydraulic control of fouling and biofouling lead to a stable flux value over an extended period of time, with a biologically active fouling layer playing an essential role for the stabilization of flux. Stable flux values were recorded during months of operation in laboratory studies and during one year in field studies (Peter-Varbanets et al., 2017). While the required Transmembrane Pressure (TMP) was lower (0.04–0.1 bar), also the stable flux value was reported to be considerably lower than in conventional UF (2–10 LMH, depending on the feed water quality). In view of the absence of cleaning strategies and the low flux, the process was considered to be attractive mainly for decentralized surface water treatment applications. The process was first described as gravity-driven membrane (GDM) filtration, but can also be described as "biofilm-controlled ultrafiltration". Because "GDM" is meanwhile a widely and generally accepted term, we will use this in the present review. A description of the principle of GDM filtration with external and submerged membrane configurations is shown in Fig. 1.

Since the first discovery of flux stabilization in GDM processes, much research has been devoted to better understand the morphology and hydraulic resistance of the biofilm layer on the membrane, its biological ecosystem, the parameters influencing the process, the impact of feed water characteristics, the ability of the biofilm in removing dissolved or suspended substances, the influence of pre-treatment, and the application potential in laboratory and field studies. This review will provide an overview of all of these aspects of GDM filtration. Furthermore, a comparison will be made with other UF-based systems, which have been developed to provide low-maintenance or low-energy systems suitable for decentralized application.

2. Characteristics of GDM processes

The phenomenon of flux stabilization in dead-end systems without cleaning and backwashing was first published in 2010 by Peter-Varbanets et al. (2010). In the initial period of filtration, the flux dropped rapidly to reach a stable level after around 5 days of operation. Different types of feedwater were treated at a trans-membrane pressure (TMP) of 0.065 bar (65 mbar) obtained by

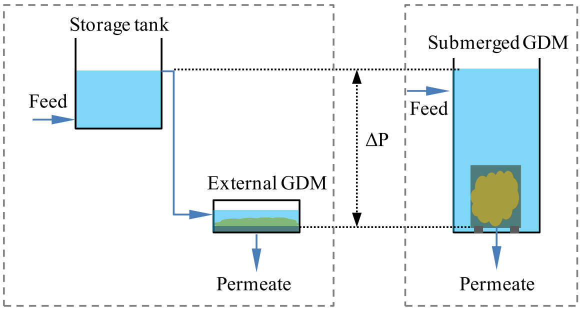

Fig. 1. A schematic diagram to illustrate working principle of external GDM and submerged GDM filtration.

gravity. Depending on the feed water composition, the flux stabilized at a value of 4–10 $L\,m^{-2}\,h^{-1}$ (LMH).

2.1. The stable flux of GDM versus critical or threshold flux concept

The concept of critical flux was introduced by Field et al. (1995) as the flux above which fouling occurs. It assumes that at critical flux the convection of foulants, by flux, is just balanced by back transport. For non-interacting particles, such as latex particles operating below critical flux, this could represent a long-term steady-state providing concentration and cross-flow are unchanged. Since the necessary back transport is caused by tangential shear due to cross-flow, bubbling etc., the classical critical flux concept does not apply to dead-end filtration as used in the GDM process. In addition the application of critical flux to systems with biofouling, such as membrane bioreactors (MBRs), is questionable (Cho and Fane, 2002; Bacchin et al., 2006). To broaden the concept of 'criticality', Field and Pearce (2011) introduced the idea of "Threshold Flux" which is the flux that divides a low fouling region from a high fouling region. The threshold flux can apply to cross-flow or dead-end and any foulants, including biofouling. Based on these considerations it is reasonable to say that the bio-stabilized flux in GDM operation is not a critical flux but a type of "threshold flux".

2.2. Morphology and compositions of biofilm on the membrane

During GDM filtration, the microorganisms, organic aggregated colloidal material, and particulate organic and inorganic material in the feed water can be rejected by the membrane and then accumulated on the membrane surface. These retained substances on the membrane tend to form a biofilm layer, which is considered as "mini ecological system". The characterization of the biofilm in GDM is a complex matter since it includes a range of different fields, such as (1) morphology (3-dimensional structure); (2) biological activity, community composition and their spatial distribution, such as prokaryotes (bacteria), eukaryotes including predators; (3) composition of organic and inorganic constituents and their spatial distribution.

2.2.1. Biofilm morphology

In the first paper describing the phenomenon of flux stabilization in the GDM process, it was found that flux stabilization was associated with the morphology of the biofilm developed on the membrane surface, which was observed by a confocal laser scanning microscopy (CLSM) (Peter-Varbanets et al., 2010). During the first 3 days of operation, a relatively flat and dense biofilm structure was noticed. The first detachment of the biofilm from the membrane surface took place at the 7 day. After that, increased heterogeneity and porosity with the occurrence of large voids between patches of biofilm occurred (Fig. 2).

Recently, optical coherence tomography (OCT) has been widely applied in biofilm structure observation as it provides image acquisition in the range of millimeters (Wagner et al., 2010). Image analysis methods based on Matlab routines have been developed for the analysis of OCT pictures, with the possibility of calculating the surface roughness, porosity, and mean thickness of the biofilm (Derlon et al., 2012; Fortunato et al., 2016; Wang et al., 2017). Therefore, the image acquisition by OCT at the meso-scale can provide details of important "structure/function" relationships (Wagner et al., 2010; Martin et al., 2014; Desmond et al., 2018). Several previous studies (Derlon et al., 2012, 2013; Akhondi et al., 2015; Wu et al., 2016) have employed the OCT technique to *in situ* observe biofilm morphology during GDM filtration. Similarly to CLSM observation results, it was also found that with extended filtration time, the biofouling layer became thicker, more heterogeneous and porous (Fig. 2). The findings from both morphology observation techniques indicate that during GDM filtration, the structures (i.e., roughness and porosity) of the biofilm developed on the membrane surface experienced dynamic changes with filtration time, almost regardless of the feed water type.

In addition, the OCT images also revealed the existence of spatial differences in the biofilm with a more dense layer at the membrane surface. This so called "basal layer" achieved a thickness up to 25 μm (Peter-Varbanets et al., 2011; Derlon et al., 2012). Such a spatial resolution of the biofilm on the membrane provides us valuable information to understand the correlation between the biofilm structure and flux stabilization.

Besides CLSM and OCT, a range of other techniques have been applied in order to reveal the structure of the biofilm. A range of methods for the characterization of fouling layer structure & architecture, fouling composition and biological activity in the GDM process was applied by Fortunato et al. (2016). Besides visualization methods such as OCT, also the chemical composition was analyzed using different methods, including Size Exclusion Chromatography coupled to Organic Carbon Detection (SEC-OCD), Flow Cytometry (FCM), Adenosine Triphosphate (ATP) and Total Organic Carbon (TOC) analysis. Three different Scanning Electron Microscope (SEM) techniques were evaluated, Environmental SEM (ESEM), Cryo-SEM and Freeze-drying SEM, demonstrating that Freeze-drying SEM provided the best preservation of structural characteristics of the biofouling layer.

In addition to the techniques mentioned above, Raman spectroscopy has recently been employed to characterize the composition of biofilms (Desmond et al., 2018). Raman spectroscopy has shown to be a useful tool for "molecular finger printing" of biofilms. Limitations include poor utility for inorganic foulants for which the signal intensity is very weak. Raman spectroscopy enabled 2-D mapping of biofilm showing Raman shift peaks, representative for functional groups relevant for biofilms such as $O{-}P_2^-$ (representative for DNA/RNA), glucoside ring structures (representative for polysaccharides), carboxyl groups (organic acids), and C—C stretch modes (representative for the backbone of a long chain polysaccharide or peptide). Using these techniques, it was shown that the composition of the biofilm alters for different feedwater compositions, including P- and N-limiting conditions (Desmond et al., 2018).

Another technique for determining the composition of biofilm is extraction, followed by TOC analysis, and colorimetric determination. With these technique specific fouling components can be analyzed such as polysaccharides, using the Anthrone method, proteins, using the Bicinchoninic Acid method, and extracellular DNA (eDNA), using PicoGreen staining (Ding et al., 2016b, 2017c; Desmond et al., 2018). A general limitation of these extraction- and colorimetric-based methods is the fact that artefacts can occur by interference by other matrix compounds, thus hindering quantitative interpretation of the data. Besides, Liquid Chromatography coupled to Organic Carbon Detection (SEC-OCD) has been used to characterize the composition of GDM biofilms (Huber et al., 2011; Fortunato et al., 2016). Another technique which can be used to characterize the organic matter in biofilms is 3D-fluorescence Excitation-Emission Matrix analysis (3D-EEM). In GDM biofilms, it was used to identify the occurrence of aromatic proteins, tryptophan containing proteins, and humic-like substances (Tang et al., 2016b; Ding et al., 2017c). A limitation of this technique is however that it only allows for semi-quantitative determination of these compounds. A comparison of visualization and chemical characterization methods for GDM biofilms is provided in Tables 1 and 2.

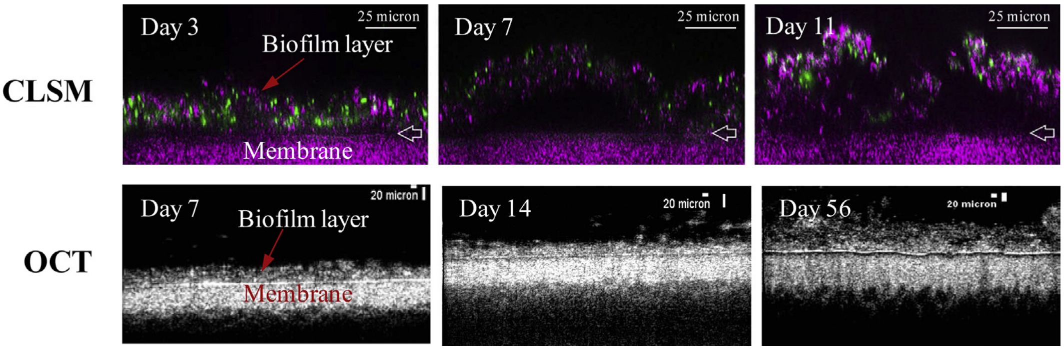

Fig. 2. The CLSM and OCT images showing the morphology of the biofilm on the membranes, which were adopted from Peter-Varbanets et al. (2011) and Akhondi et al. (2015), respectively.

Table 1
Comparison of biofilm visualization techniques.

Method	Resolution[a]	Penetration depth	Sample preparation	In-situ/ex-situ	3-D imaging	Artefacts
CLSM	0.1 μm	+	staining	ex-situ	y	potentially
OCT	10–20 μm	++	–	in-situ	y	no
SEM						
Cryo-SEM	1.1 μm	–	freezing	ex-situ	[b]	potentially
ESEM	1.1 μm	–	–	ex-situ	[b]	potentially
FD-SEM	0.01 μm	–	freeze-drying	ex-situ	[b]	potentially

Abbreviations: OCT: Optical Coherence Tomography; CLSM: Confocal Laser Scanning Microscopy (CLSM); SEM: Scanning Electron Microscopy; ESEM: Environmental Scanning Electron Microscopy; FD-SEM: Freeze-Drying SEM.

[a] Resolution range.

[b] With SEM, a 3-dimensional imaging is possible only of the biofilm surface.

Table 2
Methods for characterization of the composition and biological characteristics of the GDM biofouling layer.

Method	Sample preparation	Invasiveness	Detected compounds	Resolution	Limitations
Composition analysis					
SEC-OCD	filtration	invasive	biopolymers; humic acids; building blocks; low molecular weight organic acids and neutrals	-[a]	compounds must be soluble
3D-EEM	none	non-invasive	aromatic proteins; tryptophan containing proteins; humic-like substances		
Raman Spectroscopy	none	non-invasive	DNA/RNA Polysaccharides Organic acids	2-D	not all functional groups can be distinguished
EPS analysis	EPS extraction	invasive	Polysaccharides Proteins eDNA	-[a]	Interference by matrix compounds
Biological characteristics					
Flow cytometry	ultrasonication	invasive	cell counts	-[a]	ultrasonication can potentially lead to disruption of cells
ATP analysis	none	invasive	biological activity	-[a]	
Pyrosequencing (community analysis)	DNA extraction	invasive	biological community (prokaryotes/eukaryotes)	-[a]	quantification based on relative abundance

[a] Grab samples of the biofilm are used for analysis, no spatial resolution is possible.

2.2.2. Biological composition and function

The biological parameters, such as amounts of live/dead cells, microbial community compositions, and predation behaviors are relevant to the characteristics of the membrane biofilm in GDM processes. Several methods have been employed to reveal the amounts of live and dead cells the GDM biofilms, including ATP analysis (Peter-Varbanets et al., 2010), flow cytometry, and CLSM live/dead staining (Akhondi et al., 2015). The analytical results in the previous studies revealed that the biofilm layer formed on the membranes displayed a high viability. The viable cells were found to be related to the heterogeneity of the biofilm layer, i.e., leading to the formation of cavities and channels inside of the biofilm (Peter-Varbanets et al., 2010).

Further identification of microbial community compositions in the GDM biofilm were generally performed by suing pyrosequencing technique. Several previous studies (Akhondi et al., 2015) have revealed that the bacterial community attached to the membrane was highly diversified. The significant differences in prokaryotic and eukaryotic communities existed between the GDM systems with different configurations provide useful information to explain the difference in permeability of those systems (Wu et al., 2017b).

Importantly, the presence of the predators could impact the microbial community distribution and biofilm morphology (Klein et al., 2016). When metazoans were spiked to GDM systems operated with river water, a substantial improvement of stable flux could be achieved (Klein et al., 2016). In presence of oligochaetes, the stable flux at 61.5 mbar value increased to 9.2–12.5 LMH, in the presence of nematodes, the stable flux increased to 14.0–20.8 LMH, while the stable flux in the control systems was 5.7–8.8 LMH. This indicates that the activity of metazoans, particularly nematodes, resulted in major changes of biofilm morphology: oligochaetes and nematodes transformed relatively smooth and dense biofilms into highly porous and heterogeneous structures, while the basal layer was practically completely removed by nematodes (Klein et al., 2016), resulting in a marked increase in flux. Similarly, Böhme showed that protists can influence the basal layer structure, with different basal layer thicknesses for different protists (Böhme et al., 2009). Previous work on GDM filtration of seawater has demonstrated that the permeate flux can be maintained at about 20 LMH (at an equivalent hydraulic pressure of 40 mbar) for over almost a year without using any flushing or cleaning. This is attributed to the movement and predation behaviors of *Stichotrichia*, *Copepoda*, and *Pterygota*, which were predominant eukaryotes at genus level in the GDM (Wu et al., 2017b). On basis of these results, the increase of flux was associated with an increased heterogeneity (roughness) of the basal layer on the membrane surface, which was attributed to the activity of the predators. It remains partly unclear how the bacterial and eukaryotic population of the biofilm is by the water composition and operation conditions. More research will be required in order to reveal such mechanisms.

2.2.3. *Organic/inorganic substance composition*

Organic/inorganic substances accumulated in the biofilm layer perform several roles: (1) they are considered as nutrients for bacterial growth; (2) they could cause membrane organic/inorganic fouling to influence permeate water productivity; (3) their presence could influence the morphology of biofilm matrix.

A range of methods, such as extracellular polymeric substances (EPS) extraction and analysis (Ding et al., 2016b, 2017c; Desmond et al., 2018), size exclusion chromatography coupled to organic carbon detection (SEC-OCD) (Peter-Varbanets et al., 2010, 2011; Chomiak et al., 2015; Fortunato et al., 2016; Ding et al., 2017a), 3D-fluorescence excitation-emission matrix technique (3D-EEM) (Tang et al., 2016b; Ding et al., 2017c), Raman spectroscopy (Desmond et al., 2018) have been applied for the characterization of organic compositions in the biofilm layer on the membrane surface in the GDM systems. Although these GDM systems were fed with different types of water with dissimilar characteristics, it was found that (1) microbial products (protein and polysaccharides derived products) and slowly-biodegraded products were majorly present in the biofilm matrixes; (2) lower organic substances present in the biofilm matrix led to higher permeate flux.

Furthermore, the accumulated organic/inorganic substances in the biofilm layer could affect the biofilm morphology structure. For example, the presence of small kaolin particles (3.6 μm) in the feedwater was shown to lead to more compact fouling layer structures with an increased hydraulic resistance (Chomiak et al., 2014). The presence of large particles (18.1 μm, diatomaceous earth mixed with kaolin) on the other hand did not increase the hydraulic resistance in comparison to a GDM system without addition of kaolin.

3. The parameters influencing stable flux and biofilm cake properties

3.1. *Feed water*

GDM systems have been reported to be applied in treating river water for decentralized potable use, rain water and greywater for decentralized non-potable use, wastewater for safe discharge, and pre-treating seawater for desalination. As shown in Table 3, the stabilized flux levels in the GDM systems are related to the types of feed water. Generally, the feed water containing higher organic substances appears to result in forming biofilm with higher resistance, leading to permeate flux in a sequence as follows: (diluted)

Table 3
Overview of membrane filtration performance in the reported GDM systems fed with different types of water.

Water source	Stable flux (LMH) (range)	Membrane Pore size	Membrane module type*	Applied pressure (mbar)	Hydraulic resistance (10^{11} m^{-1})			Ref.
					membrane	total	Biofilm	
River water	10	PES 100 kD	FS	65	3.0	23.4	20.4	Peter-Varbanets et al. (2010)
Dil. wastewater 12.5 mgTOC/L	4			65	3.0	58.4	55.4	
River water treated by sand filtration	11.1	PES 100 kD	FS	65	3.0	21.0	18.0	Peter-Varbanets et al. (2011)
River water	8.0	PES 100 kD	FS	40	3.0	18.0	15.0	Derlon et al. (2012)
Pond/tap water		PVDF 40 nm	HF-OI					Oka et al. (2017)
No fouling control	**			**	33.1	157.7	124.6	
Air sparging	**			**	33.1	82.8	49.7	
Backwashing	**			**	28.0	57.1	29.1	
Dil. wastewater		PES 20 kD	FS	45	5.4			Wang et al. (2017)
7.5 mgCOD/L	4					40.4	35.0	
15 mgCOD/L	2					80.8	75.4	
Greywater	1.0	PVDF 0.2 μm	HF-OI	30	3.1	107.8	104.7	Jabornig and Podmirseg (2015)
	2.0					53.9	50.8	
Synthetic greywater	2.0	PES 150 kD	FS	50	3.0	89.8	86.8	Ding et al. (2016b)
Rainwater	6.0	PES 150 kD	FS	50	3.0	29.9	26.9	Ding et al. (2017a)
Seawater	18.6	PVDF 80 nm	FS	40	0.8	7.7	6.9	(Wu et al., 2017b)
River water (with addition of nematodes)	18–20	HPS 100 kD	FS	61.5	5.7	11.1–13.2	5.4–7.5	Klein et al. (2016)

*Module types: FS: flat sheet; HF-IO: hollow fiber in-out; HF-OI: hollow fiber out-in; **Membrane systems operated at constant flux instead of constant pressure; Abbreviations: PES = Polyethersulfone; PVDF = Polyvinylidene fluoride; HPS = Hydrophylized Polysulfone.

wastewater/greywater < rainwater < river water/seawater. This trend was further confirmed by the facts that (1) the addition of wastewater to river water resulted in a lower stable flux value (Peter-Varbanets et al., 2011). (2) The average flux in treating low organics containing lake water was ~5 LMH and decreased to ~2 LMH in treating high organics containing lake water (due to algal growth) (Lee et al., 2017).

Possibly, higher organic substances in the feed water could cause (1) more organic accumulation in the biofilm matrix. This could be due to the organic amounts deposited on the membrane surface were sufficient and beyond microbial utilization capability; and (2) limited oxygen levels in the GDM systems. Such oxygen conditions may be unfavorable to the growth and predation activity of the eukaryotes derived from the feed water.

3.2. *Operation pressure*

In conventional MF/UF membrane processes with effective fouling control strategies, an increased driving pressure generally leads to almost linearly increase of the permeate flux. In the GDM system, however, the variation of TMP did not result in a significant difference in stable flux, illustrated in several studies (Peter-Varbanets et al., 2010; Kus et al., 2013a; Akhondi et al., 2015; Derlon et al., 2016; Tang et al., 2016a). This means, the total resistance of the fouled membrane increased with the increase of pressure during membrane filtration. This effect was attributed to compression of the fouling layer at higher pressures, leading to a lower porosity and higher resistance of the fouling layer (Peter-Varbanets et al., 2010; Derlon et al., 2016).

For example, Tang et al. (2016a) operated out the GDM system under different operation pressures (60, 120 and 200 mbar) for reservoir water treatment. The flux stabilized around 8.6 LMH at a TMP of 200 mbar, which was only slightly higher than at the lowest pressure (60 mbar), with a stable flux of 6.6 LMH. Kus et al. (2013a) also reported that flux was independent of the water head in the GDM system which was varied in the range of 0.15–2.0 m, corresponding to 15–200 mbar. This implies that the total resistance varied between 11×10^{11}–1.4×10^{14} m^{-1}. Therefore, it is suggested that lower pressure (40–60 mbar) is more favorable for this type of passive membrane filtration process due to the reduced energy consumption.

3.3. *Temperature*

In the GDM systems, temperature is an important parameter (1) relating to the permeate water viscosity, which determines the water permeate flux based on the Darcy's law, and (2) influencing microbial growth and activity. Thus, the GDM performance could be influenced by operating temperature. Akhondi et al. (2015) found that when the operating temperature varied from 21 ± 1 °C to 29 ± 1 °C, the fouling resistance was reduced by 25% at 40 mbar of driving force and 21% at 100 mbar of driving force. Meanwhile, at a higher temperature (29 ± 1 °C), it was noticed that the biovolume reduced and porosity increased with the filtration time. This may be associated with a higher predation activity of the grazers.

3.4. *Intermittent operation*

As GDM or gravity-driven membrane bioreactor (GDMBR) systems have been considered as suitable decentralized water or wastewater treatment technique, it is likely their operation is carried out on a discontinuous base. The impact of intermittent operation and forward-flushing on the flux stabilization during dead-end ultrafiltration of drinking water was investigated (Derlon et al., 2012). The results revealed that a standstill period resulted in fouling layer relaxation and consequently temporary flux increase, followed by a flux decrease towards the stable flux value. Furthermore, it was shown that flushing after a standstill period further intensifies this process. Flux decline and recovery during intermittent operation with or without flushing were reversible. Additionally, they found that particles deposited in the fouling layer form larger aggregates during standstill periods. Thus, in addition to back-diffusion, aggregation processes also play an important role during standstill and flux recovery. Moreover, the impact of intermittent operation can be predicted depending on the duration of the standstill and operating periods.

In addition, combined intermittent air sparging (a few minutes per day) and intermittent relaxation (several hours per day) was also attempted to be applied for the GDM system in treating a mixture of pond and tap water (Oka et al., 2017). By optimizing the intermittent air sparging conditions, a stable permeability was achieved amounting for 40% of the initial permeability, while without air sparging the stable permeability was 21% of the initial permeability. Furthermore, intermittent relaxation resulted in a 40–60% increase in stable flux, depending on the time of relaxation (1–8 h per day).

Although increasing the permeation standstill period could increase the flux level, this may decrease the average permeate water production rate (L/d). Tang et al. (2016a) found that when the standstill period was as high as 12 h, the water production rate was lower than the control (although the flux during operation was higher than the control).

3.5. *Shear conditions*

In conventional membrane filtration processes, shear force was generally applied to alleviate membrane fouling. In the GDM systems, shear force was also proposed to improve permeate flux. However, Ding et al. (2016a) found in the GDM system for grey water treatment, the permeate flux did not stabilize in the shear reactor and decreased down to 0.5 LMH at the end of the test period, which was much lower than the non-shear GDM system with the stable value of 2 LMH. It was attributed to the fact that the shear stress resulted in a thinner but denser bio-fouling layer with higher EPS content (proteins and polysaccharides). The shear conditions might select for the strongly binding micro-organisms, while the higher EPS content was related to this binding capacity and the high resistance of the fouling layer. Additionally, the hydraulically reversible resistance and irreversible resistance were higher, which indicates that strong shear stress would increase the cleaning frequency. It has also been reported that shear stress produced at the membrane surface might cause cell damage, with subsequent release of intracellular dissolved organic matters and signs of membrane fouling behavior (Chow et al., 1999; Campinas and Rosa, 2010).

While, a combination of shear force with permeation relaxation could improve permeate flux in the GDM systems. For example, after a standstill time of 2–7 days, the biofilm was expanded, and could easily be removed by gentle shaking (sloughing off), resulting in about 50% flux recovery (Peter-Varbanets et al., 2011).

3.6. *DO concentration*

It is well-known that oxygen is necessary for the metabolism of microorganisms. In MBR systems, it was found that the DO concentration not only influences the growth of the bacteria on the membrane during the filtration, but also the properties of the suspended biomass in submerged membrane systems, such as the floc structure, particle size distribution and the content of EPS in a MBR system as well as the permeate flux (Wilén and Balmér, 1999;

Yoon Kim et al., 2006; Yun et al., 2006). However, dissimilar conclusions were generally drawn because of complexity of MBRs.

In the GDM systems, the effect of DO concentration on membrane performance was also examined and it appears that high DO levels benefited to membrane performance. Peter-Varbanets et al. (2011) prepared feed water containing different fractions of wastewater for GDM filtration, and the DO concentration ranged from 0.1 to 7.9 mg/L. Results showed that the flux stabilized with all feed waters, but that a high DO (7.9 mg/L) resulted in a considerably higher permeate flux (8.9 LMH) compared with the low DO (0.1 mg/L) which achieved a stable value of 0.8 LMH. A similar observation was also noticed by Ding et al. (2017a) that low DO (0.4–0.6 mg/L) increased the hydraulically reversible resistance and cake layer resistance compared with high DO (6.0–6.5 mg/L) in a GDMBR system for grey water treatment. This phenomenon was attributed to the fact that the bio-fouling layer grown under low DO condition exhibited a lower biological activity, was thicker and had a lower surface roughness, as well as contained higher EPS contents (including proteins and polysaccharides).

3.7. Membrane and membrane module configuration

In the GDM systems, the biofilm layer performs a predominant role in controlling the permeate flux, while the membrane resistance has less contribution to the GDM performance (Table 3). However, it still needs to be further clarified whether the properties of membrane and membrane module configurations influence the biofilm development, which may lead to an impact on the GDM performance.

Frechen et al. (2011) compared the performance of the membranes with a pore size of 100 nm and 20 nm (flat sheet membrane) in the GDM system treating river water. Although initial flux values were quite different, stable flux values were similar, around 4–5 LMH. In the GDM systems for seawater pretreatment, several types of microfiltration (MF) and UF polymeric flat sheet membranes were used (Wu et al., 2016, 2017a). As shown in Table 4, a wide range of clean water permeate flux values (27–795 LMH) was noticed, depending on the membrane pore size and materials. However, their stabilized flux was comparable, within a range of 2.7–8.4 LMH in the dead-end filtration cell systems (shorter HRT) or 16.3–18.6 LMH in the submerged GDM reactors (longer HRT). Lee et al. (2017) tested three UF membranes (PES-100 kDa, PVDF-120 kDa, and PVDF-100 kDa) and one MF membrane (PTFE-0.3 μm) in the GDM systems for treating lake water. The flux variations were quite similar for the four membranes during the entire GDM filtration. These observations indicated that membrane property has little effect on the flux.

Furthermore, Chawla et al. made a comparison of hollow fiber (outside-in) and flat-sheet membrane modules for the treatment of river water (Chawla et al., 2017). Monitoring the flux during around 1 month, it appears that the flux stabilized in the flat-sheet system at around 2 LMH (corresponding to a hydraulic resistance of around $2.0 \times 10^{13}\ \mathrm{m}^{-1}$), but it cannot be concluded with certainty if the flux stabilized in the hollow fiber system since still some flux decrease could be observed in the last days of operation. Higher flux values were monitored with decreasing duration of filtration and increasing frequency of standstill. In the submerged GDM systems treating seawater (Table 4), it was found that the flat sheet membrane modules had a higher permeate flux than the hollow fibre membrane modules. However, the hollow fibre membrane modules offer greater productivity per footprint. Furthermore, compared to the tested flat sheet membrane modules, the tested hollow fibre membrane modules displayed less cake layer fouling potential, possibly because hollow fibre configuration led to more effective detachment of such fouling layers from the membrane.

In addition, for the hollow fibre membrane module, the fibre packing density is another crucial parameter impacting GDM performance. Less packing density tends to provide more space for the eukaryotes to move and predate the bacteria attached on the membrane, which benefits to flux improvement. While, once the available space is enough for the movement of the eukaryotes, further expanding the space could not benefit to further increase permeate flux (Table 5). When the reactor space is limited, the hollow fibre membrane module with higher packing density can be a suitable choice due to greater productivity per footprint. Therefore, the hollow fibre membrane with less membrane resistance, reduced irreversible fouling potential, greater packing density (i.e., smaller hollow fibre diameter), and a degree of looseness can be the optimal membrane for the GDM system in order to achieve economically comparable to conventional UF processes. Overall, the results from these studies imply that membrane properties have limited influence on the GDM performance, but membrane module and reactor configurations could have significant effects on the GDM performance.

3.8. Integration with other processes

To improve GDM performance in terms of membrane permeate flux and organic removal, the GDM system was proposed to be combined with other processes, such as biofilm reactor, adsorption process, coagulation process etc. The purposes of additional processes are expected to reduce organic substances in the GDM by enhancing biodegradation or by physical removal. However, whether the additional processes benefit to GDM performance appears case by case.

Wu et al. (2016) integrated biofilm reactor with the submerged GDM system to extend the organic retention time and promote biomass. The hybrid biofilm-submerged GDM reactor displayed a higher permeate flux (~5.7–8.6 LMH) than that of single GDM filtration cell (~4.5 LMH). In addition, an increased hydraulic retention time was beneficial to improve the removal of the dissolved organic substances during GDM filtration, leading to improved permeate quality.

Ding et al., 2018a, 2018b added a granular activated carbon (GAC) layer or powered activated carbon (PAC) layer, or sand layer on the membrane surface in the GDM system treating rainwater. It

Table 4
Impact of membrane properties on the membrane performance in a dead-end GDM filtration cell for seawater pretreatment (Wu et al., 2016, 2017a).

	Flat sheet membrane				Hollow fibre membrane
Materials	PES	PVDF	PVDF	PVDF	PVDF
Brand	Microdyn-Nadir	Millipore	Millipore	–	GE
Pore size	100 kD	0.22 μm	0.45 μm	0.08 μm	0.1 μm
Membrane area (m^2)	0.0023	0.0023	0.0023	0.0023	0.0011
Contact angle (°)	81 ± 3	77 ± 1	74 ± 2	–	76 ± 2
Clean water flux at 40 mbar (L/m^2 h)	27.3 ± 0.4	227.1 ± 1.5	679.2 ± 46.2	182.0 ± 1.0	795.0 ± 18.3
Stabilized seawater flux at 40 mbar (L/m^2 h)	4.5 ± 0.1	8.4 ± 0.1	7.3 ± 0.4	2.7 ± 0.6	3.6 ± 0.3

Table 5
Impact of membrane properties on the membrane performance in a submerged GDM reactor for seawater pretreatment (Wu et al., 2017a).

	Flat sheet membrane			Hollow fibre membrane			
Materials	PVDF	PVDF		PVDF			
Brand	Millipore	–		GE			
Pore size	0.22 μm	0.08 μm		0.1 μm			
Reactor configuration and size	Lab-scale	Lab-scale	Pilot-scale	Lab-scale			Pilot-scale
Membrane area (m^2)	0.0198	0.0198	0.9	0.02 (898)[a]	0.02 (1139)	0.028 (2151)	0.87
HRT (h)	13.0	13.0	21.6	11.1	11.1	11.1	21.6
Clean water flux at 40 mbar (L/m^2 h)	227.1 ± 1.5	182.0 ± 1.0		795.0 ± 18.3			
Stabilized seawater flux at 40 mbar (L/m^2 h)	17.2 ± 0.8	16.3 ± 0.2	18.6 ± 1.4	12.7 ± 1.4	13.1 ± 1.2	8.5 ± 0.9	15.2 ± 1.7
Productivity (m^3/day) per membrane module (m^3 in volume)	89	–	–	128	274	436	359

[a] The number in the bracket represents the packing density (m^2/m^3), which was calculated by dividing the membrane module area (m^2) with the membrane module volume (m^3).

was found that improved 20–25% removal efficiency of organics because GAC or PAC layer could effectively adsorb florescent compounds (e.g., aromatic proteins, tryptophan proteins and humics). However, compared to the GDM system without GAC or PAC layer (4.5 LMH), the presence of GAC layer decreased the level of stable flux (3.0–3.2 LMH) due to a denser bio-fouling layer with higher amount of biomass and extracellular polymeric substances contents. However, the sand layer assisted system did not show any improvement in organic removal and led to a lower permeate flux compared to the control system.

Ding et al. (2017b) combined *in situ* coagulation or pre-coagulation with the GDMBR system for treating synthetic sewage. The results showed that *in situ* coagulation and pre-coagulation increased more than two-fold and one-fold of permeability respectively, compared to the control system (without coagulation). This is due to the presence of the dosed aluminum preventing formation of microbial metabolites and helping avoid membrane pore blocking.

4. Contribution of biofilm cake layer to organic removal in GDM processes

In the GDM process, the membrane is expected to reject greater-sized particles or colloidal and the biofilm developed on the membrane is expected to enhance dissolved organic substances as the biofilm can either act as a secondary membrane (separation role) or perform biodegradation of organic substances.

In order to illustrate the biofilm role in the GDM system, detailed analysis of organic removal effectiveness by the GDM process was emphasized in previous studies (Table 6). Using SEC-OCD to analyze the organic fractions of DOC in feed and permeate, it was shown that around 5%–40% of the humic acids and 70%–90% of the biopolymers in river water are removed by the GDM system (Peter-Varbanets et al., 2011; Chawla et al., 2017). While the removal of biopolymers by UF membranes is expected because of their size, the removal of humic compounds is supposed to be due to the biofilm acting as a secondary membrane, since the molecular weight of the humic acids (<1000 Da) is much smaller than the MWCO of the UF membrane (Peter-Varbanets et al., 2011). In order to confirm this hypothesis, Ding et al. compared the removal of organics in the GDM process with the removal by a virgin membrane (Ding et al., 2017a). The results showed that the removal of several NOM fractions in the GDM process was significantly higher than that by the pristine UF membrane: The UF membrane rejected biopolymers by 44–47.7%, while the rejections in the GDM systems were around 93.9–95.9%. Furthermore, the UF membrane rejected humic substances by 31.2–38.1%, while the rejections in the GDM systems were 48.1–51.6%. Since humic acids are considered to be a relatively stable end product of degradation processes, their increased rejection can be attributed to the GDM fouling layer acting as a secondary membrane. The increased rejection of biopolymers can be attributed to either biological activity, the action of a secondary membrane, or a combination of both.

Also, in case of diluted wastewater treated by the GDM system, a substantial reduction of DOC was observed by comparing the organic compositions of the feed and permeate, with significant reduction of biopolymers (from 539 to 64–74 mg/L), humic substances (738–55–155 mg/L) and building blocks (157–41–63 mg/L) (Wang et al., 2017). A complete rejection of proteins was reported in the final stage of operation. It is elucidated that the high removal of humic substances was attributed to retention by the fouling layer acting as a secondary membrane.

An improved permeate quality due to the presence of the

Table 6
Removal efficiency for organic compounds by GDM systems in treating different water matrices.

Compound	Removal in GDM	Removal by pristine membrane	Removal mechanism	Time span	Water matrix	Reference
Humic acids	10–40%	44–47.7%			river water	(1)
	79–93%				diluted wastewater	(2)
	93.9–95.9%				greywater	(3)
Biopolymers	70–90%	31.2–38.1%	Microbial degradation		river water	(1)
	86–88%				diluted wastewater	(2)
	48.1–51.6				greywater	(3)
Building blocks	60–74%				diluted wastewater	(2)
Proteins	100%				diluted wastewater	(2)
Dextrane (1 kDa)	30–100%	“low”	Microbial degradation	after “few days”	synthetic water	(4)
AOC	>80%	<10%	Microbial degradation		acetate as C-source	(5)
	60–80%			0–2 months	river water	(5)
	10–60%			>2 months		
	>50%				sea water	(6)
Microcystins	“near 100%”		Microbial degradation	>15 days	lake water	(7)

1: (Peter-Varbanets et al., 2011); 2: (Wang et al., 2017); 3: (Ding et al., 2017a); 4: (Chomiak et al., 2015); 5: (Derlon et al., 2014); 6: (Wu et al., 2017a); 7: (Kohler et al., 2014).

biofilm in GDM was also observed in GDM systems operated with synthetic water spiked with organic substances (dextran) (Chomiak et al., 2015): It was reported that the removal of low molecular weight dextran (1 kDa) progressively increased to almost 30% after a few days of operation and finally reached nearly 100%, which was attributed to biological activity in the biofilm. High-molecular weight dextran molecules (150 and 2000 kDa) were initially retained due to their size, but hydrolysis combined with biological degradation occurred with extending operation time (>7 days).

As assimilable organic carbon (AOC) has been identified as an advanced indicator for assessment of biofilm regrowth, the AOC removal efficiency by the GDM system has paid more attentions. It is worth noting that the removal of AOC in the GDM system is a more complex process. In a system with acetate as carbon source, the presence of the biofilm on the membrane was found to increase the removal of AOC, with >80% of AOC removed in the GDM system compared to <10% removed by the virgin membrane (Derlon et al., 2014). In case of natural river water, the AOC removal ranged between 60 and 80% during the first 2 months of operation, with relatively stable AOC concentrations in the permeate. Upon longer operation, the AOC concentration in the permeate increase, and the removal ranged between 10 and 60%. It was suggested that the decrease in AOC during longer operation times might be caused by increasing accumulation of organic matter on the membrane in combination with hydrolysis and release of low-MW material which is detected as AOC. In the GDM pilot system pre-treating seawater, more than 50% of AOC removal was also observed (Wu et al., 2017a). This increased AOC removal resulted in an improved performance of the subsequent RO system: The TMP in the RO did not increase with GDM pretreatment, while a steady increase was observed with a conventional UF pretreatment (Wu et al., 2017b).

Besides organic related parameters, the removal of specific compounds has been investigated in GDM systems. For example, Microcystins are cyanobacterial toxins, as excreted substances derived from *Microcystis aeruginosa*, which can incur a problem for drinking water safety. Kohler et al. (2014) found that the biofilm on the membrane in the GDM system could successfully reduce the amount of microcystins to below the critical threshold concentration of 1 μg/L. This could be related to the activity of microcystin degrading bacteria developing within the biofilm after exposure to microcystins. The removal of different classes of compounds is summarized in Table 6.

5. Implementation aspects of field and pilot GDM processes

Initially GDM systems are expected to be applied as decentralized drinking water treatment facility. Several pilot GDM systems have been reported to be installed in the areas without available drinking water facility and successfully operated. With plenty of fundamental research works carried on the GDM systems, the optimized optimization conditions of the GDM systems have been achieved and the GDM systems have been also scaled-up for other applications.

Case 1. A gravity-driven hollow fiber ultrafiltration with periodical backwashing was designed to treat microbiological water. With periodic cleaning and backwashing, the system can produce ~9 L/h of clean water for household use. The cost per liter treated is estimated at ~ US$0.001/L (Clasen et al., 2009).

Case 2. A gravity-driven water treatment on a smaller scale (membrane area of 6 and 11 m^2), termed as “water backpack”, intended for emergency relief such as earth quakes or tsunamis (Frechen et al., 2011). A flux of around 5 LMH could be maintained over two months of operation without any flushing or cleaning, treating surface water with turbidity values of up to 70 NTU.

Case 3. A community-scale pilot study using GDM filtration was reported by Boulestreau (Boulestreau et al., 2012), treating river water in South Africa (Ogunjini region) for decentralized drinking water production, with a capacity of 5 m^3/day. The pilot consisted of a submerged flat sheet membrane module of 40 m^2 installed in a marine container for ease of transportation. The membrane tank was regularly drained (on a day to week basis) in order to remove debris. During about 3 months of operation, the turbidity of the feedwater was most of the time around 10–50 NTU, but regular peaks occurred with turbidity raising up to 605 NTU. It was concluded that the stable flux remained high (5–7 LMH) when the turbidity remained in a reasonable range (<160 NTU), while extremely high peaks of turbidity (>600 NTU) led to a decrease in flux to about 2–4 LMH.

Case 4. Three GDM pilot systems were operated at schools in Uganda during an extended period of time (Peter-Varbanets et al., 2017), treating lake Victoria water at different locations (Busime, Bulwande, Lugala). The lake water was pumped with a pipe line to a storage tank which fed the GDM system and another storage tank was used for the purified water. Monthly maintenance included draining the GDM tank as well as shock-chlorination of the clean water tank and network. After almost one year of operation, the flux was 2.95 LMH in Bulwande and 5.2 LMH in Lugala, while the clean water flux of the membrane was 11.6 LMH at the applied pressure of 75–100 mbar. The highest flux was achieved in Busima (10.7 LMH), although this system was not yet stable. Each system had a membrane area of 75 m^2, so that the water treatment capacity of the systems was between 5.3 and 19.3 m^3 per day.

Case 5. The pilot GDM system has been used to pre-treat seawater for reverse osmosis desalination (Wu et al., 2017b). A stable flux of 18.6 ± 1.4 LMH could be maintained at a gravitational pressure of 40 mbar during an operating time of more than one year. This corresponds to a total resistance of $7.7 \times 10^{11}\ m^{-1}$ which in fact is only slightly higher than many virgin UF membranes, and in fact is the lowest resistance value observed for the reported GDM systems in treating different types of water. This may be associated with relatively low organic contents and the abundance of eukaryotes in raw seawater, contributing to form more heterogeneous cake layers on the membranes. It was shown that the GDM pretreatment had a beneficial effect in comparison to a conventional UF: the TMP of the subsequent reverse osmosis system did not increase when GDM pretreated seawater was fed, while a steady TMP increase of the subsequent reverse osmosis system was observed with UF pretreated seawater (Wu et al., 2017b).

Case 6. Rainwater was treated by GDM combined with GAC in a pilot study by Kus et al. (Kus et al., 2013b, a). A hollow fiber polysulfone membrane with a pore size of 100 nm was operated in a submerged manner (outside-in). A stable flux of 0.47 LMH was maintained during 60 days of operation.

6. Economic assessment of GDM processes

Due to gravity-driven nature, GDM systems are energy efficient processes. In the comparison of GDM with other technologies, the decreased energy consumption or complete absence of external energy has been mentioned often as an advantage. Indeed, in household water treatment systems, the system is usually operated manually so no external energy is required. However, in larger-scale gravity driven systems for drinking water production, a pumping system is required to transport the feed water up to the inlet of the system. It is reported that the GDM system that was developed as an autonomous water treatment system for emergency relief had a membrane area of 11 m^2 at an estimated price of 700 Euro (around 860 US$) and consumed only 0.02–0.04 kWh/m^3, which is substantially less than for normal MBRs (Frechen et al., 2011). In addition, in a GDM pilot plant in South Africa, treating river water with a capacity of 5 m^3/day, the energy demand consisted only of the pump energy required to transport to the inlet, which amounted to 0.006 kWh/m^3 (Boulestreau et al., 2012).

In gravity-driven systems for wastewater or greywater treatment, aeration is required which increases the energy consumption. A so called gravity-driven MBR (GDMBR) consumed 0.040 kWh/m^3 for the treatment of grey water. For comparison, a low energy MBR without cleaning/flushing in a moving bed biofilm membrane reactor (MBBMR) consumed less than 1.3 kWh/m^3 (Jabornig and Favero, 2013). For conventional MBRs, the energy consumption is in the range of 0.3–6.1 kWh/m^3, with 4.9–6.1 (kWh/m^3) reported by Gil et al. (2010), 0.64 (kWh/m^3) by Fenu et al. (2010), 1.1–2.53 (kWh/m^3) by Komesli et al. (2015) and 0.3–0.4 (kWh/m^3) by Van Dijk et al. (vanDijk and Ronckren, 1997).

Obviously, the decreased energy consumption in the GDMBR goes to the expense of flux: the flux in the GDMBR was in the range of 1–2 LMH, while conventional MBRs are operated at a flux of 8–25 LMH. Also for drinking water treatment by GDM systems, reported stable flux values of 4–20 LMH are considerably smaller than those in UF plants with flushing and cleaning, which are in the range of 50–100 LMH (Mulder, 1996; Baker, 2012a; Crittenden et al., 2012). It is obvious that a cost comparison between GDM and UF is dependent on case-specific parameters (e.g. local electricity tariff and labor costs) and therefore, a cost comparison cannot be made on a quantitative basis. Thus, we will make a cost assessment and comparison between GDM and conventional UF on a qualitative basis.

The integral costs of a membrane plant are considered to be the sum the capital expenditure (CAPEX) and operating expenditure (OPEX) (Judd, 2017). CAPEX includes all equipment, land and installation services costs whereas OPEX is primarily determined by the chemical and energy costs, membrane replacement costs, labor and other items such as water supply and wastewater discharge costs, whereby both OPEX and CAPEX are expressed as costs per m^3 of water produced. This means that in order to calculate CAPEX, the investment costs are depreciated over a certain period of time. Comparing the costs of GDM versus conventional UF technology, it should be noticed that the cost balance will depend strongly on the scale. The CAPEX is mainly determined by (1) the membrane investment costs and (2) auxiliary equipment, such as pumps, vessels, and process control. Because membranes are packed in modules, the investment costs increase almost linearly with the plant capacity. Thus, the membrane investment costs for GDM are higher than for conventional UF, as schematically shown in Fig. 3a. Obviously, the relative position of these lines depends on the level of stable flux in GDM and the average flux value in conventional UF. On the other hand, the costs for auxiliary equipment, such as pumps and process control will be higher for conventional UF. In contrary to the membrane costs, which increase almost linearly in view of the modular concept, the rule of scale applies for auxiliary equipment, which means that these costs increase less than linear with scale. Usually, exponential functions are applied to describe the costs depending on production scale with typical exponents in the order of 0.6 (Westney, 1997). A schematic, qualitative presentation of the costs of auxiliary costs as a function of production capacity is shown in Fig. 3b. The sum of membrane and equipment costs is schematically shown in Fig. 3c. The graphs show a break-even point, at which the investment costs for both processes are the same (arrow in Fig. 3c). The CAPEX however is expressed not as investment costs, but as investment costs per m^3

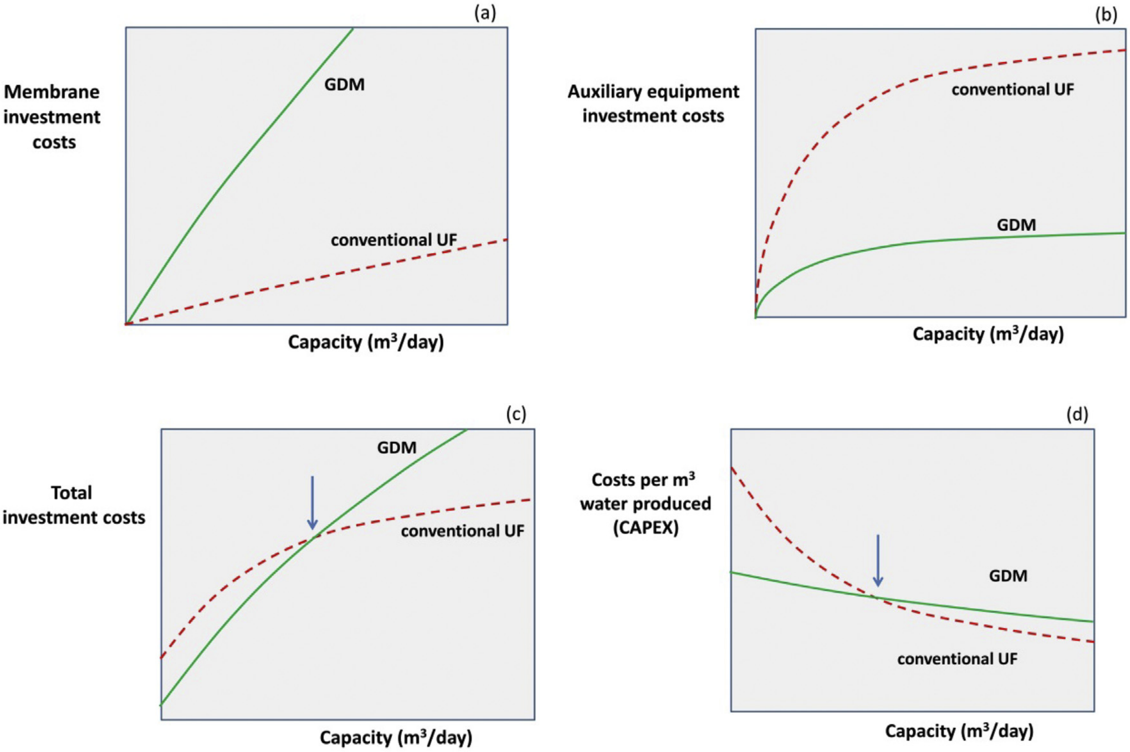

Fig. 3. Schematic (qualitative) presentation of investment costs of GDM and conventional UF as a function of production capacity.

Table 7
Qualitative comparison of costs of GDM in comparison to conventional UF for different scales of application.

	Household scale		Community scale		Full-scale	
	GDM	UF	GDM	UF	GDM	UF
CAPEX	++		±	±		+
Chemical costs	+		+		+	
Energy costs	+		+		+	
Membrane replacement costs	±	±	±	±	±	±
Operation & Maintenance	+		+		+	

++: large cost benefit; +: medium cost benefit; ± costs depend on conditions.

of water produced and the result of this conversion is shown in Fig. 3d.

As mentioned above, the operating costs (OPEX) are determined mainly by (i) chemical consumption, (ii) energy consumption, (iii) membrane replacement costs and (iv) labor costs.

(i) No chemical membrane cleaning is applied in GDM, although in some cases intermittent disinfection of the feed lines or storage vessels was applied (Peter-Varbanets et al., 2017). However, in comparable treatment plants, the chemical consumption is expected to be lower than in conventional UF.
(ii) In view of the absence of flushing and the lower TMP, the energy consumption of GDM is considerably lower than for conventional UF or conventional MBR's.
(iii) The membrane replacement costs will be higher due to the higher membrane area of GDM. On the other hand, the membrane lifetime expectance is considerably larger than for conventional UF since GDM is operated without chemicals which is considered to be the main lifetime limiting factor of polymeric membranes (Baker, 2012b; Peter-Varbanets et al., 2017)
(iv) Since the GDM does not need supervision, no skilled personnel is required. The operation & maintenance (labor) costs are therefore are expected to be lower than in conventional UF.

Based on the assessments above, a (qualitative) comparison of costs was made for GDM versus conventional UF on 3 different scales: (1) household scale with a capacity of 20–50 L/day; (2) treatment for small communities, with a capacity of 1–10 m^3/day. (3) Full scale, with a capacity of more than 100 m^3/day. The cost trends concerning both CAPEX and OPEX are summarized in Table 7.

As already mentioned, the cost balance will depend on many factors which are locally determined. For example, the energy price and the costs of labor will have a large impact, while also the comparative levels of flux in GDM and UF are important factors. Thus, the feasibility of GDM should be calculated for each situation specifically. However, the above considerations show that the niche for application is for small to mid-scale plant sizes.

7. Perspectives for research and potential applications of GDM processes

7.1. Stabilization of flux

The literature describes high flux values (10–20 LMH) to be associated mainly with the occurrence of higher organisms (metazoans), while low flux values (<5 LMH) seem to be associated with water sources with a high fouling potential, such as greywater. The question is how high flux values can be achieved for a broad range of water types and conditions. The growth of metazoans in the biofilm seems to be a rather erratic process since (1) the occurrence in the feed water is dependent on the water source and seasonal conditions, and (2) the growth and sustainability of these organisms in the biofilm is hard to control on basis of the existing knowledge on their ecology. Therefore, cultivation and dosing of specific types of metazoans has been discussed as a possible measure to sustain a constant level of organisms in the system (Klein et al., 2016). However, it is questionable if this measure is economically and technically feasible. At least for a small scale application, this does not seem to be the case. For large scale applications, the implementation of such a measure is worthwhile to investigate, since it could reduce the required membrane area by a factor 2 or higher in comparison to GDM without metazoan control. The relatively low flux obtained in the case of greywater (Kunzle et al., 2015; Ding et al., 2016b) appears to be associated with the high general fouling potential of this type of water. Pretreatment of the feedwater by GAC adsorption has been shown effective to increase the stable flux in GDM (Tang et al., 2017), from 2 to 6 LMH. This effect was associated with the removal of foulants and the improvement of growth conditions for higher organisms. While the above study was carried out for river water, the same technology could be studied for greywater.

7.2. Improvement of permeate quality

As discussed, the presence of a biofilm in the GDM process can result in higher rejections of a range of compounds, including humic acids, polysaccharides, proteins, AOC and microcystins. Although it was speculated that both straining effects (the biofilm acting as a secondary membrane) and biological degradation processes within the biofilm can play a role in this improved removal, the exact mechanisms still remain unclear. In order to obtain a better understanding of these mechanisms, dedicated experiments could be designed for example using radioactively labelled compounds to trace the fate of specific compounds. Also, it would be worthwhile to investigate the fate of other compounds in GDM as compared to conventional UF. Specifically, the fate of organic and inorganic micropollutants should be investigated since they occur in many drinking water resources and are relevant for human health. With regard to the removal of AOC, it was observed that removal takes place by fresh biofilms, but leaching occurs in more mature biofilms, presumably due to hydrolysis and release from the biofilm itself (Chomiak et al., 2015). In order to sustain a high AOC removal during longer operation periods, it could be considered if it is possible to intermittently remove the biofilm from the membrane, for example using flushing or aeration strategies.

7.3. Potentials of application

Table 7 gives a qualitative overview of different cost factors of GDM in comparison to conventional UF for different scales of application. In order to make a quantification of costs, a specific case study should be selected where experience is available on the process parameters for GDM and UF. This means that long-term optimization studies are required for both technologies. A first step in this direction was made by pilot experiments with different membrane module configuration for seawater treatment (Wu et al., 2017a) but also in this case, the experiments were carried out on a small scale which may not be representative for a full-scale treatment plant. In such studies, also the required operation and maintenance for GDM (if any) should be studied and the membrane life time should be estimated.

Table 7 identifies household-scale water treatment systems as a clear niche for application of GDM, which is also proven by the commercialization for emergency relief in the so called “water backpack” (Frechen et al., 2011). Application on community scale is being investigated for water kiosks at schools in Uganda (Peter-Varbanets et al., 2017). The benefits of the GDM technology compared to UF for this specific setting including the reduced need for operation and maintenance, no moving parts and process control, as well as independence from grid electricity. For other settings on community scale, e.g. for community-scale rainwater treatment in industrialized countries, the benefits of GDM may be less clear. Long-term studies are required also here to provide a more quantitative basis for comparison.

For large-scale application, it remains unclear if GDM technology can ever compete with conventional UF. In order to investigate this option, not only long-term pilot studies are needed, but also a collaboration with commercial partners is required in order to make an assessment of all relevant cost factors.

8. Conclusions

- Different types of water resources, including river and pond water, greywater, sea water and diluted wastewater can be treated by ultrafiltration at a stable flux without cleaning or flushing. A higher transmembrane pressures results in increased hydraulic resistance and therefore, the process is mostly operated at low pressures (below 0.1 bar), which can be obtained by gravity (less than 1 m of water head).
- The flux stabilization in the GDM process is related to the formation of a biofouling layer. A range of visualization methods and analytical techniques has been applied to characterize the biofouling layer. This has revealed that different types of organisms contribute to the formation of a heterogeneous fouling layer, containing with a stable hydraulic resistance.
- The available publications show a correlation between stable flux and water composition, with lower stable fluxes reported for waters with a higher content of TOC. In addition, the composition of the microbial community composition and the content of extracellular polymeric substances (EPS) in the fouling layer have been reported to correlate to the stable flux value.
- The presence of the biofouling layer was found to contribute to the improvement of the water quality, improving the removal of a range of compounds including humic acids, biopolymers, AOC and algal toxins
- The presence of specific types of predators was reported to result in an increase in fouling layer heterogeneity and a higher permeability. Thus, process and membrane module configurations which allowed the proliferation of higher organisms (predators) lead to an increased productivity.
- After standstill periods a flux recovery was reported by several authors. This feature can be used to optimize productivity in decentralized operation, which are characterized by a varying water demand.
- In comparison to conventional UF, the costs of the GDM process show a stronger correlation with treatment capacity. Therefore, the GDM process is typically more favorable than conventional UF at low capacities. In remote settings and situations where the process operators and electricity is not always available, the GDM process provides additional advantages in terms of process robustness.

Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

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