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Fouling in membrane bioreactors: the influence of some parameters and the effectiveness of some control strategies

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ABSTRACT

Despite the outstanding performance of membrane bioreactors (MBRs) in producing excellent quality effluent, they can't evade fouling. Fouling control in MBRs is continuously requiring scientific and practical investigations. In this research, an MBR system was run in a currently operating, activated sludge, wastewater treatment plant (WWTP). The influence of hydraulic retention time (HRT), sludge retention time (SRT), and the mixed liquor suspended solids (MLSS) on MBR fouling was studied. The study outlined that increasing MLSS from 5,630 to 8,020 mg/L resulted in flux decline from 12.77 to 10.27 L/m^2·h, while at MLSS between 8,790 and 10,930 mg/L there was no clear relationship between MLSS and flux, furthermore, at MLSS > 10,900 mg/L slow flux decline was noticed. Moreover, the study showed that higher HRTs improved sludge settling and reduced the sludge carryover onto the membrane thus decreasing fouling, while short HRTs increase the likelihood of MBR fouling. Additionally, increasing SRT resulted in flux decline due to the increase of MLSS concentration and viscosity, and reduced hydraulic capacity inside the bioreactor. Backwashing resulted in flux increase from 3.93 to 7.6 L/m^2·h indicating its effectiveness in fouling control, thus it should be kept on when running the MBR system. Aeration intensities of 480, 720, 960, and 1,200 L/h enhanced flux when compared to 240 L/h (biological requirement), their corresponding cumulative flux increase percentages were 9.5%, 22.35%, 40.69%, and 41.35%, respectively. The optimum aeration intensity for this setup was 960 L/h. The effect of membrane-aerator distance was investigated through using four values (5, 10, 17.5 and 25 cm); the results indicated that the distance of 10 cm produced the highest flux. Granular activate carbon (GAC) was added at doses of 1, 1.5, 2, 2.5, 3, 3.5, and 4 g/L. The study concluded that the optimum GAC dose was 2.5 g/L. Running the system at the optimum values of the previously mentioned parameters and at variable aeration intensities revealed that it was possible to reduce the aeration intensity from 1,200 L/h to 720 to get the same flux, thus indicating 40% aeration reduction.

Keywords: Membrane bioreactor; Fouling; Backwashing; Aeration; Granular activated carbon

1. Introduction

The use of a membrane bioreactor (MBR) is regarded as a dependable substitute in wastewater treatment (WWT) sector, it produces excellent-quality effluent. MBR proved its ability to remove organic, inorganic, and biological matters from wastewater [1]. For domestic, municipal, and synthetic wastewaters, the removal efficiency of chemical oxygen demand (COD) varied between 90% and 99%, while for industrial wastewater, it ranged from 63% to 99%. Regarding the total COD removal efficiency of MBRs, approximately 80%–90% of COD removal is attributed to the bioreactor

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primarily through biological degradation, while the membrane accounts for about 10%–20% removal because of its effects on rejection, plugging, and adsorption properties [2,3]. Elevated biomass concentrations in the bioreactor led to enhanced COD removal due to the enhanced bio-degradation. COD removal is affected by various factors, including hydraulic retention time (HRT), sludge retention time (SRT), organic loading rate (OLR) and membrane separation phenomena [4]. Previously, only 65% of suspended solids (SS) removal was possible by means of activated sludge (AS) process [1]. Replacing the secondary clarifier in AS systems by membrane units improved SS removal efficiency up to 100% [5–7].

Despite the outstanding performance of MBRs, they are not able to evade fouling, which limits their widespread use. Fouling remains the primary obstacle that accompanies the widespread and large-scale implementation of membrane processes for WWT, and it continues to be a significant scientific and practical interest. Fouling diminishes membrane permeability, constrains flux, shortens the membrane's operational life, consequently elevating both initial investment costs and operational expenses for the system. Hence, the primary focus of most MBR research revolves around studying fouling mechanisms and developing methods to control or minimize its occurrence [8–19].

Fouling poses a significant challenge for MBR systems, necessitating prevention or mitigation efforts to reduce its detrimental impacts and overcome production losses [20]. According to the International Union of Pure Applied Chemistry (IUPAC), fouling is the process resulting in the loss of performance of a membrane due to the deposition of suspended or dissolved substances on its external surface, at its pore openings or within the pores [21]. Judd [22] defined fouling as: "Process leading to deterioration of flux due to surface or internal blockage of the membrane". Fouling described the phenomenon in which different components available in water or wastewater progressively elevate membrane resistance through by their adsorption or deposition onto the membrane surface, and in some cases by complete blocking of the pores [13]. Controlling fouling is the foremost important step for ensuring the sustainability of membrane operations, and it closely depends on both the quality of the source water and the membrane operation process [23]. Thus, successful MBR operation is primarily dependent on addressing and understanding membrane fouling, which is influenced by multiple factors [24].

In MBRs, transmembrane pressure (TMP) and flux are the two interrelated operational parameters. When operational conditions remain constant, increasing TMP is necessary to achieve a higher flux. Conversely, if TMP is altered, a corresponding change in the flux will result [25,26]. Based on the mode of operation (constant flux or constant pressure), membrane fouling can manifest as either a decline in permeate flux or an increase in TMP, respectively. Put differently, membrane fouling happens when the TMP rises to sustain a particular operational flux or when the permeate flux diminishes while the pressure remains unchanged. Constant pressure operation mode is represented by a quick flux decline at the beginning of operation followed by a more gradual decline until reaching a steady state or a pseudo steady state flux [24].

Generally, fouling can be categorized as either external or internal. External fouling occurs due to the foulants' accumulation on the external membrane's surface. Internal fouling results from the deposition or adsorption of smaller particles in the internal pores. This form of fouling can lead to a decline in membrane performance, even when operating under different dynamic conditions [27]. From a different perspective, fouling can be categorized as reversible, irreversible, or irrecoverable. Reversible fouling happens due to the external deposition of materials, often referred to as cake filtration, and can be remedied using physical techniques such as air scouring, backwashing, or relaxation. Irreversible fouling, on the other hand, pertains to fouling that can only be overcome using chemical methods combined with vigorous physical techniques. Irrecoverable fouling, in contrast, cannot be remedied through any cleaning methods and typically occurs over long periods [11,28].

Sources of fouling (foulants) generally include: colloids, moderately dissolved solids, dissolved organic solvents, micro-organisms, protein molecules, and others [27]. According to the foulant type and its characteristics, foulants can be organic, inorganic, or bio-foulants. Organic fouling is the attachment of organic matter onto the membrane surface. Inorganic fouling results due to the sedimentation of inorganic particles, colloids and crystallization of solids and salts in the membrane pores. Bio-fouling results due to the adhesion and growth of viruses, bacteria, algae and fungi on the membrane surface [27,29–32].

Fouling in MBRs takes place in multiple forms; pore clogging, gel formation and, cake formation. Closure of membrane pores by foulants results in pore clogging [33] and mainly dependent on the particle size and the membrane pore size [34]. This occurs rapidly during the early stage of filtration when the membrane surface is devoid of deposits, allowing incoming particles to directly interact with the membrane pores. Gel formation results due to the consolidation of a layer including high concentration of macromolecules in the immediate proximity of the membrane surface led by concentration polarization [35–38]. Additionally, cake formation occurs due to the continuous deposition of bacteria, bio-polymers and inorganic matters onto the membrane [33]. Cake formation represents the stage during which particles accumulate layer by layer on the outer surface of the membrane, resulting in increased resistance to permeate flow. This is commonly known as cake formation and the increased resistance is denoted as cake resistance [39]. Forms of fouling in MBR are schematically represented in Fig. 1.

Although it's challenging to establish a singular rule for membrane fouling in MBRs, several groups of factors impact the rate at which fouling develops. These factors encompass operational conditions, feed and biomass properties, and membrane characteristics. Within these groups, there are numerous specific factors as outlined in Fig. 2. A detailed description of factors affecting MBR fouling can be found in Qrenawi and Rabah, 2023 [40]. The interplay among these factors will result in many impacts on MBR fouling. Understanding the fouling phenomenon is crucial for implementing effective strategies to diminish, alleviate, and control its consequences [23].

Over decades, strategies of controlling and preventing fouling were extensively investigated to lengthen the

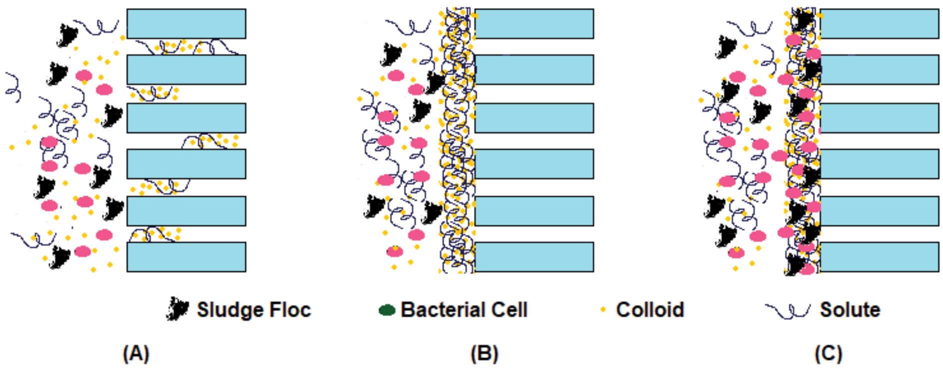

Fig. 1. Forms of MBR fouling: (A) pore clogging, (B) gel layer formation, and (C) cake layer formation [40].

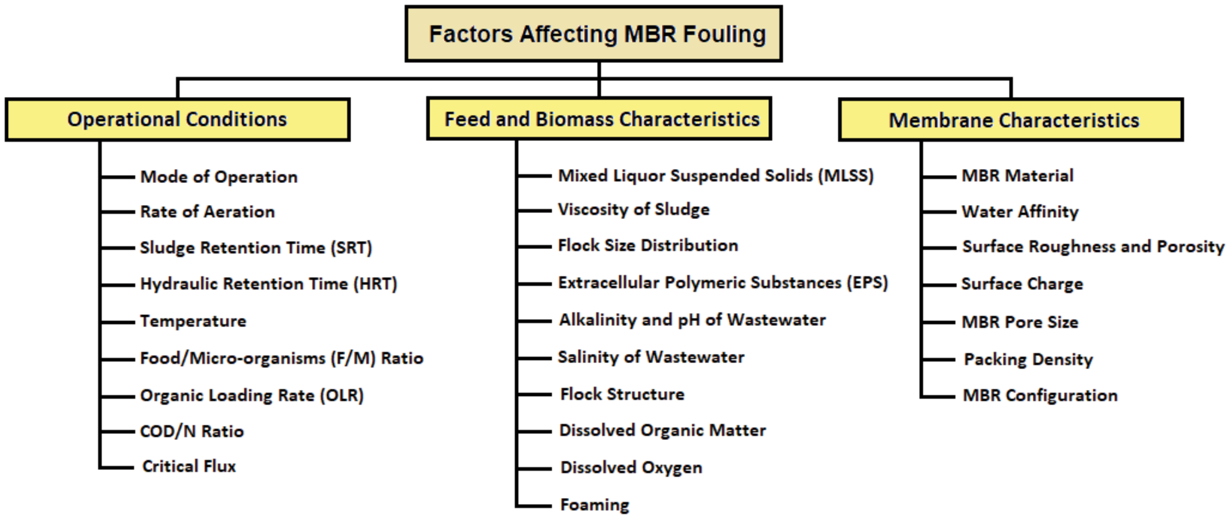

Fig. 2. Factors affecting MBR fouling [40].

lifespan of MBRs with maximum permeate service capacity [41]. In spite of the long period of substantial development for fouling control techniques, there is still a need for further development of many physical and cleaning methods [42]. From a practical point of view, it is possible to proactively prevent fouling by utilizing various techniques [34].

It's not possible to completely eliminate fouling in MBR systems, and one of the key indicators of successful MBR system performance is gauged by the effectiveness of fouling control measures without compromising permeate quality. Various physical cleaning techniques are presently employed in membrane filtration systems, both in pilot and full-scale installations across the globe [19]. Numerous approaches to manage fouling were explored and put into practice in laboratory settings and/or MBR facilities, resulting in a wide array of cleaning alternatives documented in the literature. All methods discussed can be categorized into two groups: membrane cleaning and fouling prevention. Membrane cleanings typically involves the process conducted after the occurrence of membrane fouling, whereas fouling prevention encompasses all measures taken to proactively avoid fouling [23]. From an operational perspective, it is possible to regulate and reduce fouling by implementing various techniques such as aeration, relaxation, backwashing, the introduction of granular materials, and chemical cleaning. Despite the fact that such techniques can't fully prevent fouling, the implementation of effective measures and control systems can enhance the performance of the membranes [19].

Other techniques for fouling mitigation include biological control, electrical control and material modifications (membrane and module modification). Of the novel strategies for membrane modification is the usage of nanocomposite membranes composing inorganic nanomaterials and organic polymers which attracted a wide research area for treating wastewater [43]. Several findings reported that surface modification of membranes using nanomaterials might be a potential approach for improving the membrane efficiency while also making membranes more fouling resistant [44]. This type of membrane could bestow nanomaterial's impressive characteristics presented by their large surface area to volume proportion into the targeted application. Incorporating various kinds of nano particles into polymeric membranes promotes the membrane hydrophilicity and lowers fouling indicating that these membranes become an appealing choice in wastewater treatment. Furthermore, the polymers' mechanical, thermal, and chemical properties are enhanced [45]. Methods applied for fouling mitigation/control are outlined in Fig. 3, while a detailed description of these methods can be found in Qrenawi and Rabah, 2023 [40].

MBR technology is widely acknowledged as a highly competitive and extensively utilized technology for WWT and reuse. Despite the progress and evolution in this technology, it remains crucial to conduct research on the causes, mechanisms, and control strategies of membrane fouling. While some progress has been accomplished for fouling control, there is still ample space for further enhancements [46]. Since a great number of results and conclusions of MBR studies worldwide were based on laboratory scale systems with synthetic wastewater samples, there is a need to conduct further study by applying this technology to a real WWTP. The main objectives of this experimental work are: 1) to study the effect of some parameters including hydraulic retention time (HRT), sludge retention time (SRT), and the mixed liquor suspended solids (MLSS) on MBR fouling, and 2) to investigate the possibility of reducing/controlling MBR fouling tendency by applying different strategies including backwashing, aeration, and use of granular materials with aeration.

2. Methods

2.1. MBR module and equipment

The MBR module used in this research is a hollow fiber submerged MBR manufactured by Neya Water Solutions – India. NEYA MBR module is a skid mounted system containing hollow fiber membrane elements. The MBR module was customized for research purposes with area of 1.5 m^2. MBR's material is Reinforced Polyvinylidene Fluoride (RPVDF) with pore sizes of 0.03 to 0.2 μm. The permeate flux of the MBR is 12–18 L/m^2·h, and the filtration method was from outside to inside through the pores via vacuum pressure. The running cycle was 8 min filtration, 1 min backwashing and 1 min relaxation [47,48]. Figs. 4 and 5 outline the MBR and a schematic cross section of the HF, respectively.

To control the water flow throughout the different modes of MBR operation, two identical solenoid valves (DURAVIS Solenoid Valve, ESV 120.03.050) were connected to the system. The function of the first valve was to control the flow of the permeate water out of the MBR module fibers (outside to inside), while the second valve was used to control the flow of the backwashing water into the MBR module (inside to outside). The two valves were synchronized to each other through a control box to ensure that neither the

Fig. 4. Membrane bioreactor module.

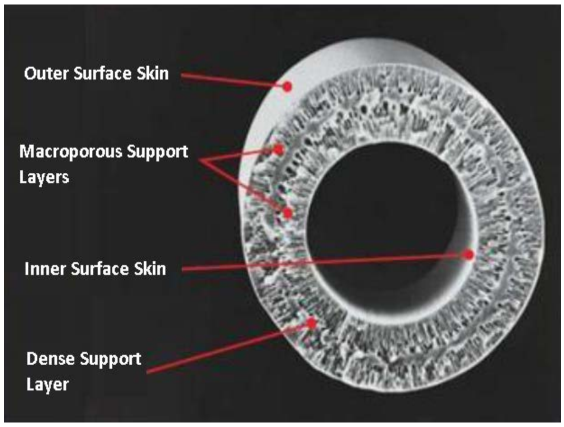

Fig. 5. Cross section of HF MBR [48].

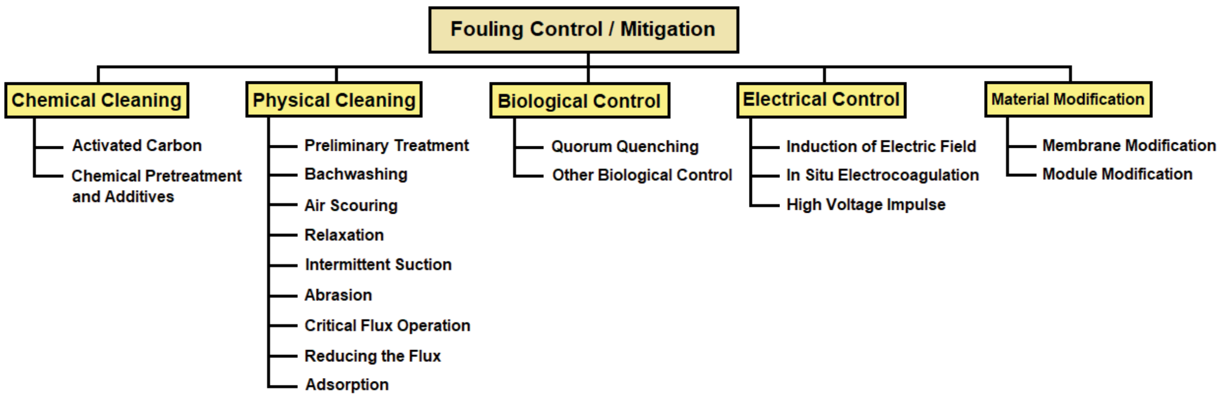

Fig. 3. Methods applied for fouling mitigation/control in MBR systems [40].

permeation mode nor the backwashing mode overlapped during the MBR operation. The permeate flow was measured by a common type of flow meters available in Gaza Strip; Arad water meter, which was suitable for municipal and commercial facilities. The meter was placed horizontally, the dial was positioned face up, washed before operation, and kept full of water all the time. The membrane module was placed inside the aeration basin and operated under vacuum to produce the permeate. According to the manufacturer instructions, the used suction pump was able to suck water with a head of 3–5 m to produce the required flow.

The required aeration for biological activity ranged from 150–200 L/h, while for controlling/mitigation fouling more aeration rates (up to 1,200 L/h) were applied. Air required for both biological process and the fouling control was supplied through air pumps of a suitable capacity. The used air pumps were Aquaruim Air Pump, HX-106; air pumping capacity of each pump was 8 L/min (480 L/h) and it can be operated at 2 modes of operation (240 and 480 L/h).

To control/mitigate fouling in the MBR, backwashing, a common technique, was applied continuously throughout the experimental work. Backwashing was maintained for 1 min after the filtration mode which extended to 8 min. The backwashing head ranged from 1.5–2 bar with a flow of 0.85 L/min.

2.2. Development of experimental matrix

As outlined by Park et al. [23 the range of HRT in MBR systems is 4–9 h, with 6 h is the typical value. In this research, and based on the reported HRTs in literature, four different values of HRT were selected; 4, 6, 8 and 10 h. A bioreactor was designed in a manner that allowed running the experiment at different HRTs in the same bioreactor. The volume of wastewater in the bioreactor was controlled by a floating valve. The bioreactor's plan dimensions were 55 cm × 55 cm, while its height was 85 cm.

SRT values for conventional activated sludge systems ranged from 4 to 10 d, which literally means that the solids reside 4–10 d in the bioreactor, but common MBR plants have longer SRTs. This prolonged SRT obviously leads to a large MLSS (8,000–12,000 mg/L), which in turn lowers F/M ratio and makes the microorganisms in the bioreactor endogenous [23]. It was reported that SRT values for MBR systems could range from 5–20 d [49], 5–30 d [23]. For the case of this research, SRTs of 5, 10, 15, 20 and 25 d were selected. Based on the selected HRT and SRT values; the experimental matrix outlined in Table 1 was developed.

2.3. Location of the experimental work

The Gaza Central Wastewater Treatment Plant GCWWTP (with an area of 261,300 m^2) is located in the east of Al Bureij at the eastern entrance of Wadi Gaza, 240 m far from the eastern boarders of the Gaza Strip [50]. GCWWTP served Gaza city with the exception of a small area to the north and all of the central communities as far as Deir El Balah in the south. GCWWTP was constructed to contribute towards protecting the groundwater resources and reducing health risks to the population of Gaza city and other neighboring communities [51]. The project also aimed to provide a long term, sustainable solution for the severe environmental deterioration, to establish a new substantial non-conventional water resource by implementing effective treatment for the wastewater generated at Gaza City Central Communities, and to relieve the already overloaded Sheikh Ejleen WWTP and eventually to take it out of service. The WWTP comprised a biological treatment stage with a design capacity of around 600,000 PE based on 0.06 kg BOD_5/(PE × d) [52]. Fig. 6 outlines an aerial photo for GCWWTP.

The treatment plant is a mechanical–biological plant with nitrogen removal and tertiary treatment as well as sludge treatment and is planned to be implemented in two phases [51]. Phase 1 was designed based on "Activated Sludge" technology and on a daily flow of wastewater of 120,000 m^3/d, while phase 2 will cover a treatment capacity of 180,000 m^3/d [50]. Phase 1 consisted of stages 1, 2 and

Table 1
Experimental matrix for organic matter removal

Hydraulic retention time (h)	Sludge retention time (d)				
4	5	10	15	20	25
6	5	10	15	20	25
8	5	10	15	20	25
10	5	10	15	20	25

Fig. 6. Aerial photo for GCWWTP [51].

3. Stage 1 had a capacity of 60,000 m^3/d, to be increased in stages 2 and 3 with extra 30,000 m^3/d to reach the phase 1 capacity of 120,000 m^3/d [52]. AS process of the biological WWT is based on a pressurized aeration system with carbon removal for phase 1, stage 1 and nitrification and denitrification for phase 1, stages 2 and 3 [53].

For stage 1, GCWWTP was designed to receive wastewater with the following characteristics: population equivalent: 600,000 PE, flow rate: 60,000 m^3/d, BOD_{in}: 600 mg/L, COD_{in}: 1,300 mg/L, TSS_{in}: 650 mg/L, $TN\text{-}N_{in}$: 140 mg/L, TP_{in}: 15 mg/L. the effluent standards for the treatment plant: BOD_{out}: 40 mg/L, COD_{out}: 100 mg/L, TSS_{out}: 60 mg/L [52]. The MBR system was placed near the primary clarifiers, as the primary effluent from the WWTP will be considered as the influent to the MBR system.

For the first time, the system was run using freshwater to ensure that the permeate, the backwash were operated as designed. System calibration was performed, and after ensuring the success of the process, the MBR was connected to the primary effluent at GCWWTP.

3. Results and discussion

One of the primary operational challenges in MBRs is fouling, that leads to a reduced flux and increased TMP. Controlling and preventing fouling result in high manpower requirements, increase electrical power consumption, and require chemicals for membrane cleaning [54]. Parameters associated with the design and operation (HRT and SRT) of MBRs, the feed and biomass characteristics, and membrane type influence membrane fouling [55]. The influence of biomass characteristics is very complex because the mixture of AS contains small particulates, solute, colloids, flocs and microorganisms. Many researchers stated that the biological components of AS contributed to membrane fouling [56].

MBR fouling is induced by accumulation or deposition of inorganic, organic, dissolved and particulate matter and microbiological substances on both the membrane surface and within its pores. Therefore, membrane fouling control, membrane lifespan, and membrane cost will be the next area of research interest and needs investigation [4]. In this research, the adopted mode of operation was constant TMP rather than the constant permeate flux. MBR fouling was evidenced as a decline in the permeate flux. In the following sections, the effect of MLSS, HRT, and SRT on MBR fouling will be studied.

3.1. Factors affecting fouling in MBRs

3.1.1. MLSS concentration

As compared to conventional AS systems; MBRs typically operate at higher MLSS concentrations, which, if other factors are kept constant, tends to accelerate membrane fouling [57]. Research findings indicated that increasing the MLSS concentration will result in decreasing membrane permeability [58]. While SS concentrations may initially seem like a reasonable indicator of fouling tendency in MBRs, the relationship between MLSS concentration and the occurrence of fouling is, in fact, intricate. When other biomass characteristics aren't taken into account, the impact of an increase in MLSS on membrane permeability can be either negative [59,60], positive [60,61], or negligible [63,64]. Wu and Huang [65] outlined that running the MBR at MLSS > 10 g/L will dramatically increase the viscosity, which would influence the filterability. They also stated that MLSS had very minor influence on the filterability when it is <10 g/L. Yigit et al. [66] studied the influence of MLSS on fouling in immersed MBRs. Their study revealed that increasing MLSS caused a notable reduction in membrane permeability and increase of fouling rate. This can be mainly attributed to the increase of suspended solids concentration that resulted in a more viscous mixed liquor and to the closure of the membrane pores with solid particles. Also, at high MLSS, wastewater tends to behave like a sticky-gel material that leads to lower permeate flux; a sign of membrane fouling. Thus, membrane fouling control techniques are required at high MLSS values [67–69].

In the literature, there is inconsistency in articles studying the influence of MLSS on membrane fouling in MBR systems. Rosenberger et al. [70] stated that membrane fouling decreased with increasing MLSS concentrations up to 15,000 mg/L. However, beyond this concentration, the trend reversed, and fouling rates began to increase at concentrations > 15,000 mg/L. Other researchers reported that no (or minor) impact of MLSS concentration on MBR fouling including Rosenberger et al. [71], (MLSS = 9,000–14,000 mg/L: no effect), Le-Clech et al. [62] (MLSS = 4,400–11,600 mg/L: no impact between 4,000 and 8,000 mg/L, but slightly lower fouling at 12,000 mg/L), and Brookes et al. [72] (MLSS = 6,000–18,000: similar rate of fouling for flux < 10 L/m^2·h and slightly less fouling rates for higher fluxes). As a result, there is no definitive correlation between MLSS concentration and membrane fouling, suggesting that MLSS concentration alone is an unreliable indicator of fouling tendency [22].

Membrane fouling is not always proportional to the MLSS concentration. Numerous studies have contradicted the notion that membrane fouling is solely dependent on MLSS concentration [23]. It has been noted that, concerning membrane fouling in MBRs, the critical MLSS concentration is approximately 10 g/L. When MLSS > 10 g/L, the amount of AS increases significantly, resulting in a decline in membrane filterability [65].

In this experimental program, flux decline was noticed in the first stage because of pore blockage and closure. After that, a slow (decreasing) flux decline occurred in the second stage because of deposition of membrane foulants, which either deposited from the bulk liquid or produced in biofilms on the membrane surface. This indicated that different MLSS concentrations had a direct influence on the fouling behavior. It can be noticed in Fig. 7 that MBR fouling (indicated by flux decline) increased with increasing MLSS concentration. The flux declined from 12.77 to 10.27 L/m^2·h as MLSS increased from 5,630 to 8,020 mg/L. After that flux fluctuated between 8.43 and 10.39 L/m^2·h as MLSS changed from 8,790 to 10,930 mg/L indicating that there was no concrete relationship between MLSS concentration and flux in this range of MLSS. At higher MLSS concentrations, slow flux decline was noticed indicating that MBR fouling can be correlated to MLSS concentrations >10,900 mg/L. The flux decline at high MLSS values can be attributed to viscosity increase that resulted from high MLSS concentration. The

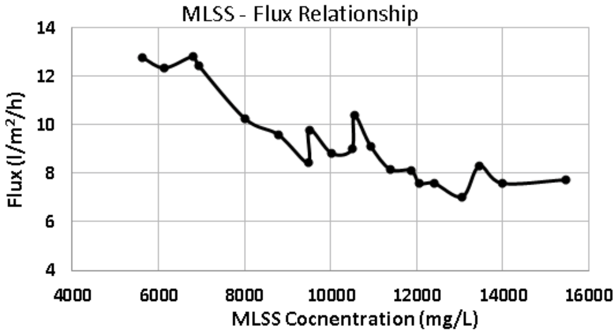

Fig. 7. Effect of MLSS on MBR flux.

increased viscosity can hinder the flow of water through the membrane, making it more challenging to remove solids from the membrane surface, leading to fouling. Flux decline can also be attributed to the increase of SS concentration that increases the likelihood of particles or flocs clogging the pores of the membrane. Additionally, high MLSS concentration can lead to greater deposition of organic and inorganic material on the membrane surface. This accumulation can block the pores of the membrane, reducing permeability and creating a thicker cake layer, further exacerbating fouling. Moreover, at higher MLSS concentrations, the sludge characteristics can change, leading to the formation of more sticky or gel-like substances. These substances can easily adhere to the membrane and promote fouling.

It can be concluded from the previous discussion, that fouling phenomenon in MBRs is complex and the relationship between fouling and MLSS is not always straightforward and can be influenced by several factors beyond just the MLSS concentration. Due to these complexities, predicting fouling solely based on MLSS concentration can be challenging.

3.1.2. Hydraulic retention time

One of the operational parameters influencing fouling in MBRs is HRT. HRT in the MBR is insignificantly different from the AS systems and its range is 1–9 h [63]. However, short HRTs can be applied in MBR processes since MLSS concentrations are much higher than in AS systems. It was reported that higher HRTs were maintained to mitigate fouling tendencies in MBR systems. The majority of research findings indicate that reducing the HRT in MBRs leads to an increase in fouling rates [73,74] because of the increase of sludge viscosity and extracellular polymeric substances (EPS) concentration [9].

A reduction in HRT will trigger releasing EPS from bacteria, leading to a filamentous overgrowth and ultimately resulting in the formation of irregular, larger flocs.

Furthermore, a decrease in HRT will lead to an increase in MLSS concentration and sludge viscosity, both of which are primary factors affecting the hydrodynamic conditions within MBR systems [73,75]. Isma et al. [56] studied the effect of changing HRT and SRT on membrane fouling using synthetic wastewater. In their research, SRTs of 4, 15 and 30 d at HRTs of 4, 8 and 12 h, were used, respectively. They found at the longest SRT (30 d) and longest HRT (12 h) will reduce membrane fouling and slow rise in TMP was noticed. Similarly, study on the impact of microbial activity and fouling propensity in submerged anaerobic MBRs run at HRTs of 14, 16, and 20 d showed that reducing the HRT from 20 to 14 d resulted in more EPS release, and therefore excessive fouling [76]. Visvanathan et al. [77] outlined that TMP values didn't increase at higher HRTs, because of the fast formation of compact layer on the membrane surface at longer HRTs. This indicated that fouling in MBRs decreased as HRT increased. Chang and Lee stated that membrane fouling was more pronounced when microorganisms were in the exponential growth phase than in biomass in the endogenous phase, indicating that HRT indirectly affected MBR fouling as it influenced sludge characteristics [73,74].

When investigating the influence of HRT on membrane fouling, Du et al. [46] demonstrated that shorter HRT can produce higher OLR and F/M. Consequently, this influences the metabolic activities of microorganisms and microbial metabolites, and leads to an increase in sludge particle size, ultimately causing severe membrane fouling. Despite that the fouling mechanism and its mitigation techniques are complex and influenced by various factors, many researchers reported that decreasing HRT tended to increase fouling rate in MBRs because of the higher EPS concentration and sludge viscosity [73,74].

Fig. 8 shows flux decline in MBR at different SRTs when changing HRT values. By referring to Fig. 5 it can be concluded that fouling rate is higher at shorter HRTs regardless of the SRT value. It can be also noticed from Fig. 8 that after 10 h of MBR operation rapid flux decline was obtained. This can be attributed to the increased MLSS concentration and the closure of membrane pores with suspended solids particulates. The high MLSS concentration was noticed in samples collected from the bioreactor at all SRTs and HRTs. Higher HRTs tend to improve sludge settling and at the same time to reduce the sludge carryover onto the membrane surface, thus decreasing fouling. On the other side, short HRTs slow down the degradation of organic matter, increase the OLR on the MBR surface, and limit the opportunity of biological flocks to form; leading to higher concentrations of SS, thus increase the likelihood of MBR fouling.

To better understand the influence of HRT on MBR fouling, analysis was conducted based on the average values of daily flux of the MBR. According to the meter readings taken over 2 d of system operation, Fig. 9 was developed. By referring to Fig. 9, it can be concluded that flux decline rate (fouling) is declined with increasing HRT from 4 to 10 h for a given SRT value. Worth to mention that the influence of HRT on MBR fouling can be system-specific and may vary depending on the operating conditions, membrane type, wastewater characteristics, and overall system design. Thus, it is necessary to maintain a suitable HRT value throughout proper monitoring, control, and maintenance of the MBR system. Selecting an ideal HRT value will lead to a controlled biomass concentration that will minimize fouling while still achieving effective wastewater treatment (balancing the treatment performance and controlling fouling in MBRs).

3.1.3. Sludge retention time

SRT is a highly impactful factor that greatly affects fouling in MBR systems, because it influences many other parameters

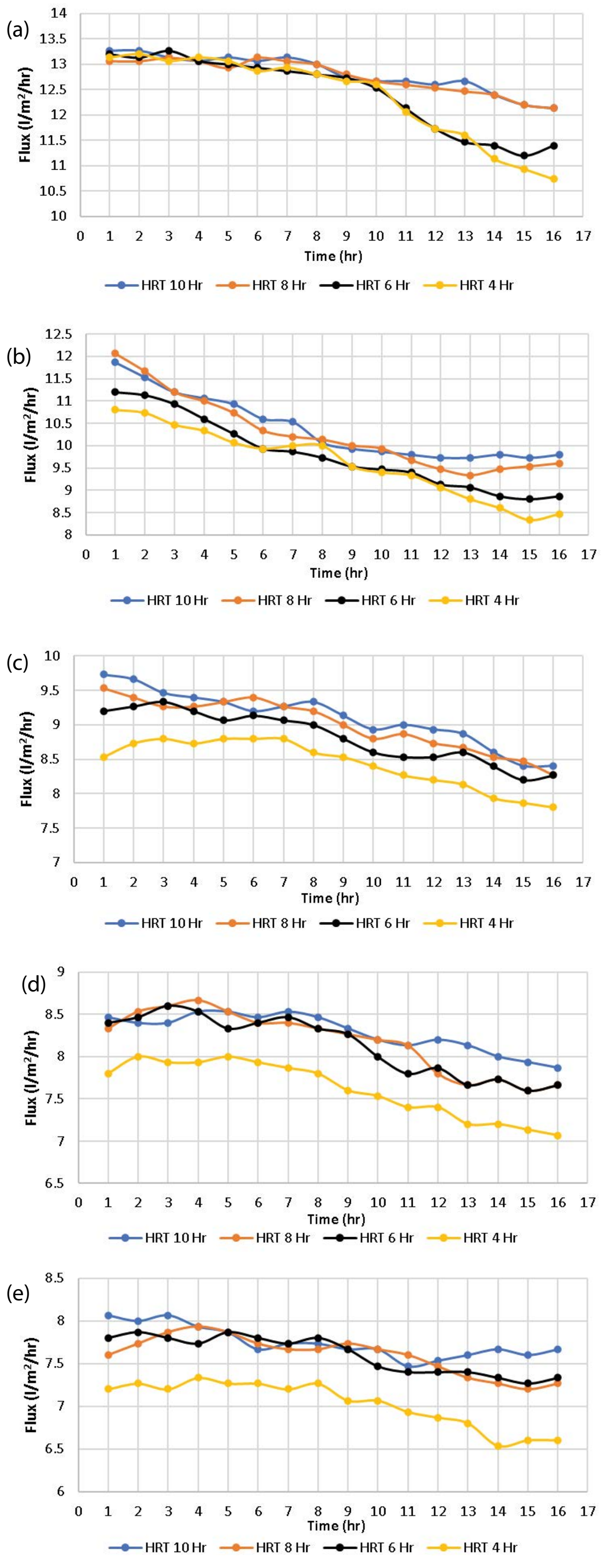

Fig. 8. Effect of HRT on flux decline at different SRT values. (a) SRT 5 d, (b) SRT 10 d, (c) SRT 15 d, (d) SRT 20 d, and (e) SRT 25 d.

including EPS, MLSS concentration and viscosity, and F/M ratio [78]. Several studies pointed out that higher SRT led to a reduction in EPS concentrations because the biomass remains in the bioreactor for a longer duration, conversely, lowering the SRT was shown to increase the concentration of EPS [79,82]. Long SRT values create conditions of starvation within the biological reactor, resulting in an environment that is conducive to limited EPS formation, reduced sludge production and nitrification [22,83]. Nonetheless, an excessively high SRT is not preferred, as it can lead to heightened membrane fouling due to the accumulation of MLSS and an increase in sludge viscosity [81]. It was also reported that increasing SRT resulted in an exhibit decrease of fouling rate [84]. Lower membrane fouling tendency is noticed at high SRT values because the free EPS level decreased as SRT increased. This can be due to the fact that most of the substrates are consumed for the maintenance needs of microorganisms. On the other hand, MLSS concentration increases as the SRT increases, leading to increased viscosity of the mixed liquor. This situation deteriorates membrane fouling; moreover, it requires excessive aeration. Therefore, optimum SRT selection is needed to control membrane fouling properly [5,23]. In MBRs, the application of high or even unlimited SRTs can be tailored according to wastewater characteristics. However, for the purpose of mitigating membrane fouling, it has been recommended to maintain the optimum range of SRT; which is between 20 and 50 d [9]. It was observed that extremely short SRTs of approximately 2 d resulted in an almost tenfold increase in fouling rates compared to those measured at 10 d, with a slight increase in MLSS from 1.2 to 1.5 g/L [85]. This can be explained by the elevated EPS concentrations at these short SRTs [9].

In an experimental study to investigate the effect of SRT on membrane fouling in MBR, Van den Broeck et al. [86] observed that SRTs of 30 and 50 d resulted in lower rates of membrane fouling in comparison to a 10-d SRT. Thay also noted that higher SRT enhanced AS bio-flocculation and consequently lowered fouling rate within the tested SRT range (10–50 d). However, contradictory results have been reported elsewhere, indicating that membrane fouling is not determined by one or two factors. It has been observed that operating MBRs at SRTs >50 d will increase fouling [78]. Chang and Lee [87] showed that fouling rate in MBRs decreased as SRT increased from 3 to 33 d.

In this experimental work and by referring to Fig. 10 it was clear that with increasing the SRT; flux reduction was obtained, this conclusion was valid for all values of HRTs. This can generally be linked to the increase of MLSS concentration and viscosity, and reduced hydraulic capacity due to excessive solids accumulation; which in turn increased MBR fouling and thus reduced the flux. It can also be noticed (from the slope of the flux decline curves) that flux decline rate (fouling rate) increased as the SRT increased from 5 to 10 d and reached its maximum value at SRT of 10 d for all HRTs. However, at SRTs > 10 d, the fouling rate decreased and reached its minimum value at SRT of 25 d for all HRT values. Fig. 11 also supports these conclusions. This can be revealed to many reasons including:

- Better biomass settling due to the development and formation of bigger flocks that are more likely to settle

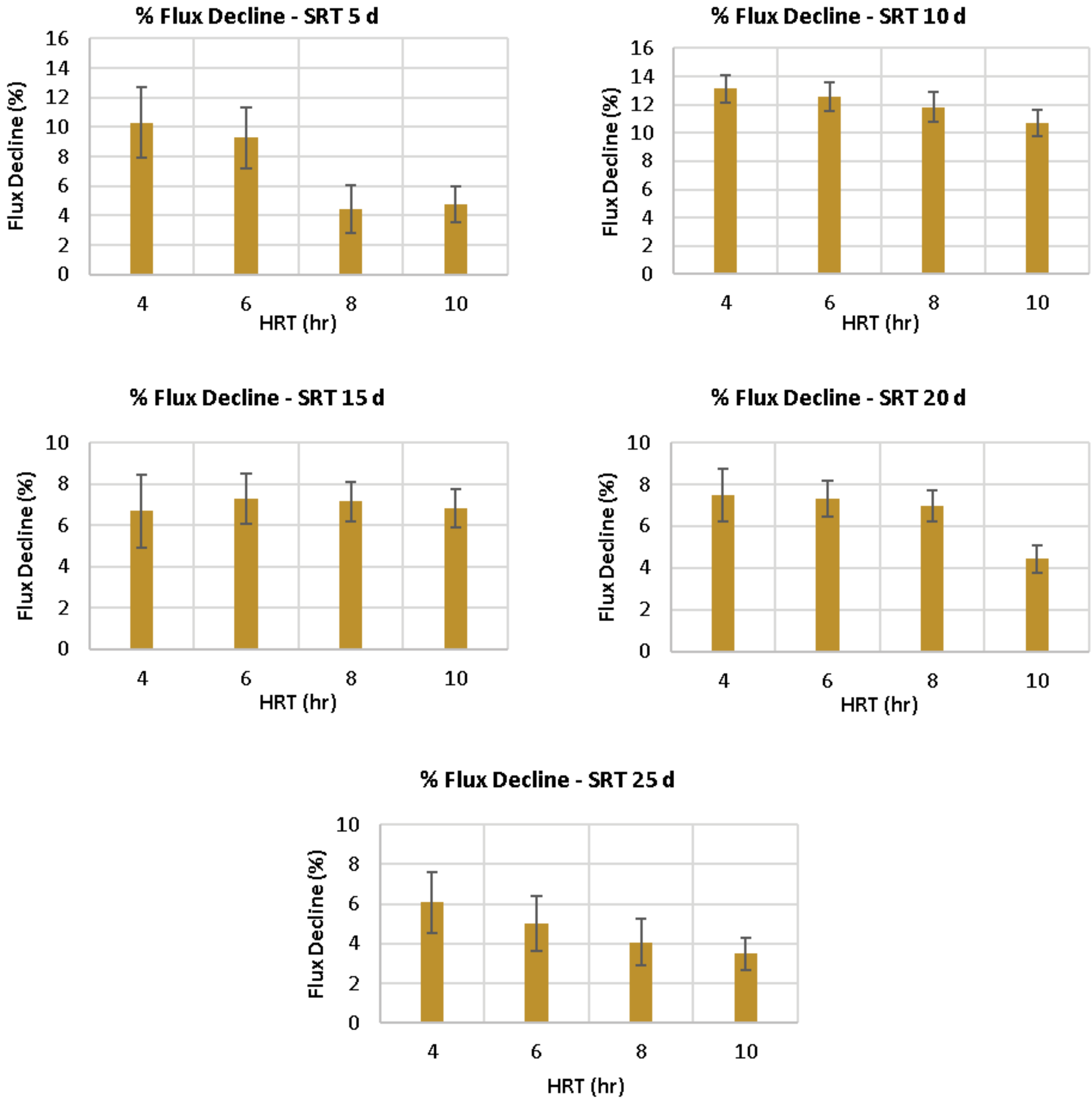

Fig. 9. Effect of HRT on percentage flux decline.

than being carried over to the MBR surface, thus lowering the chance of MBR fouling.

- Stronger and integrated flock formation by bacteria that reduces the presence of loose biomass particles which can contribute to MBR fouling.
- EPS reduction due to the more stable and mature microbial community. High EPS production can lead to biofilm formation on the MBR surface; contributing to fouling.
- Balanced growth and controlled concentration of microorganisms which can lead to a more efficient breakdown of organic matter and nutrients, thus reducing fouling.

Worth to mention that while a longer SRT generally reduces fouling rates, there is an optimal range for SRT. Achieving the right balance between SRT and other operational parameters is crucial for effective MBR operation and minimizing fouling.

3.2. Fouling control/mitigation strategies

There many strategies for fouling mitigation/control in MBRs, including backwashing, relaxation, surface scouring using air, membrane scouring using granular materials, chemical cleaning, and any combination thereof [54]. However, in this research backwashing, aeration, and usage of granular materials techniques for fouling control will be investigated.

3.2.1. Backwashing (physical cleaning)

Physical cleaning generally aims to produce shear force on the membrane surface to loosen fouling cakes on the

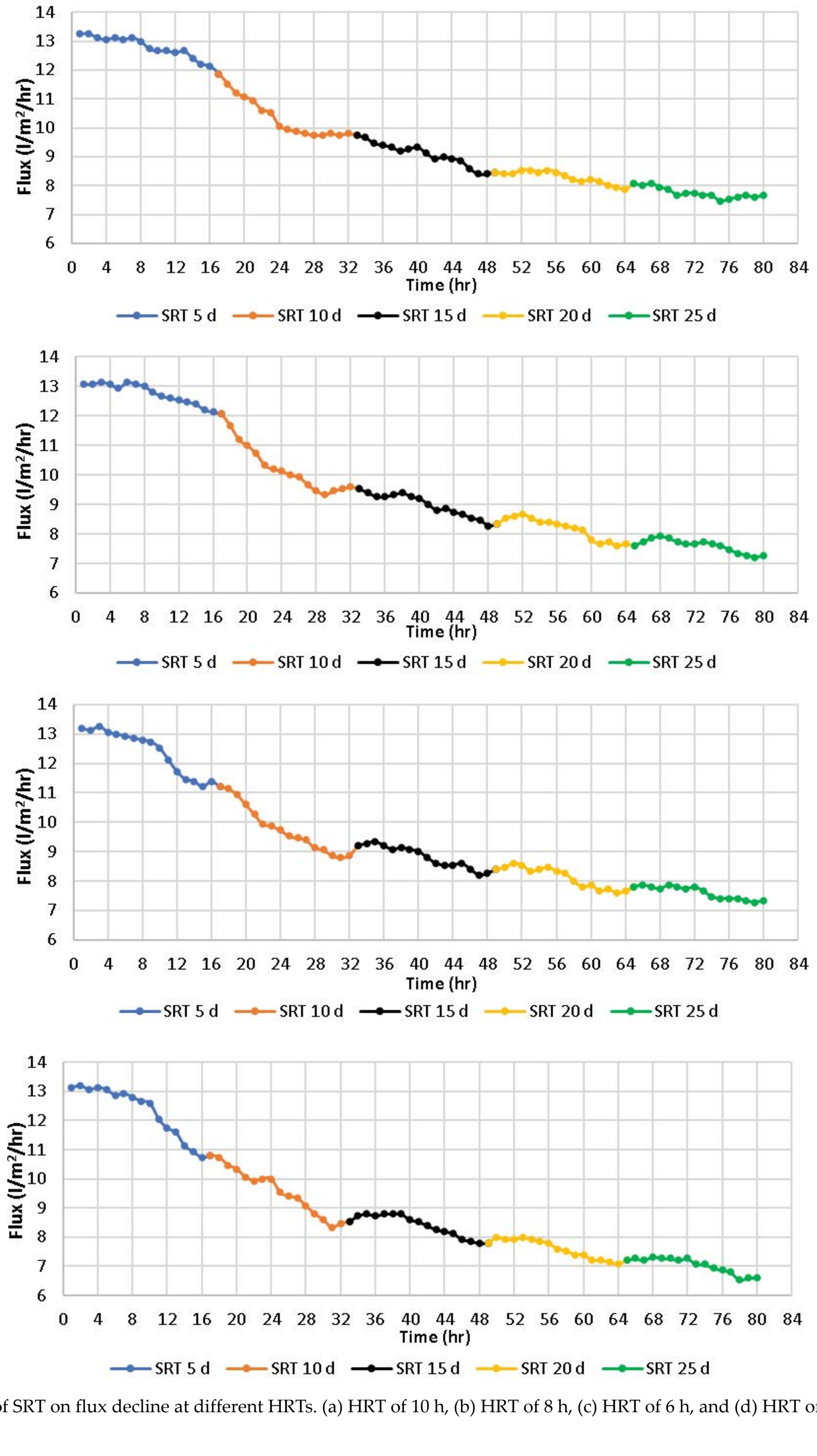

Fig. 10. Effect of SRT on flux decline at different HRTs. (a) HRT of 10 h, (b) HRT of 8 h, (c) HRT of 6 h, and (d) HRT of 4 h.

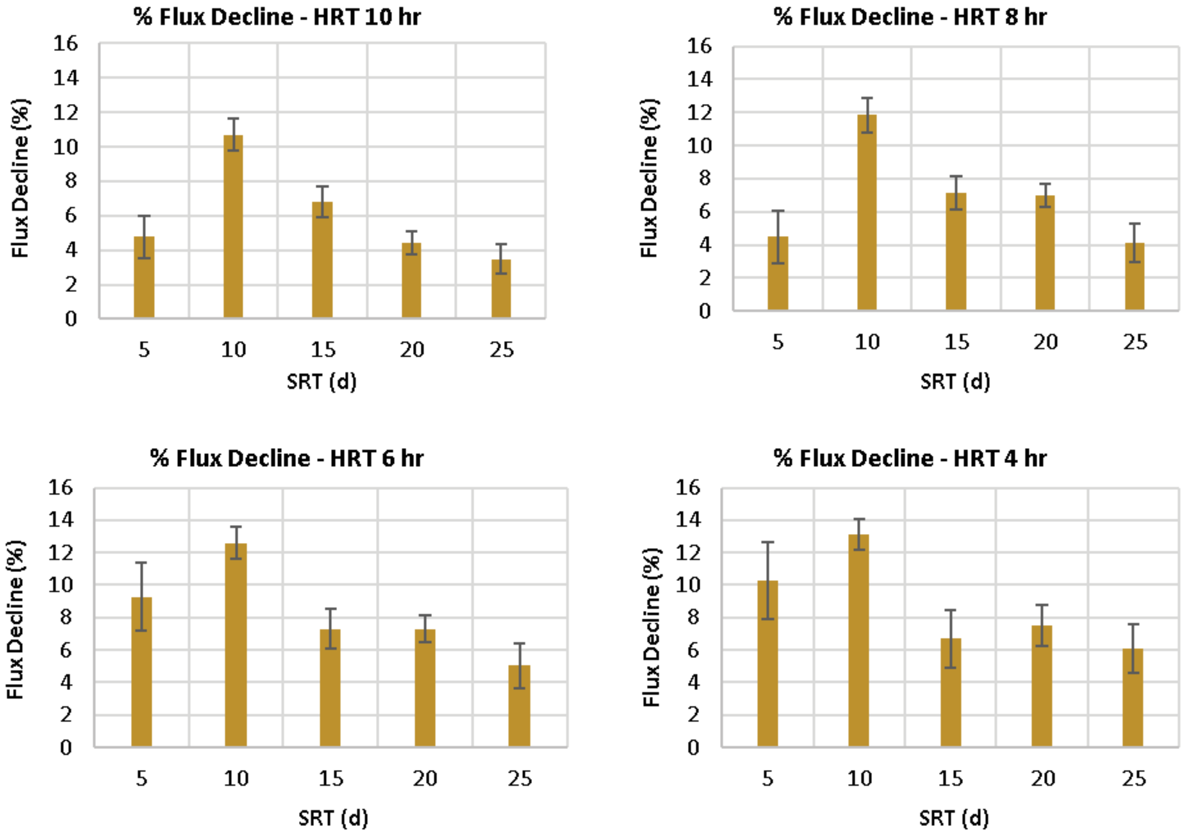

Fig. 11. Percentage flux decline at different HRTs and SRTs.

MBR external side and dislodge the deposits from MBR pores. One of the physical cleaning methods is reversing TMP, for example, backwashing [88]. It involves reversing the permeate flow through the membrane, and it is the most commonly employed technique to maintain a consistent flow in MBRs because of its straightforwardness and easy control. It efficiently eliminates a substantial portion of the cake layer on the membrane's surface, but its use is typically restricted to hollow fiber or tubular membrane systems [17]. Hence, backwashing was regarded as a fundamental tool for managing fouling in the majority of MBR facilities. In essence, backwashing is made using permeate, pure water, air, and other means capable of eliminating fouling. The frequency of backwashing and the level of pressure applied (according to the membrane manufacturer's recommendations) vary based on the membrane type and system design [23].

Backwashing implementation can only be successful once considering factors such as the backwash flux intensity, the momentary flux, the ratio of permeate to backwash, and the used backwashing agent. Establishing an optimal backwashing schedule is often determined through a process of trial and error, relying on the experience of operators [19]. The application of a backwashing mechanism was discovered to be more effective than aeration alone. However, this mechanism demonstrated its highest efficiency when combined with aeration [89].

Backwashing frequency can be either (a) less frequent with a longer backwash or (b) frequent with a shorter backwash duration [14]. Less frequent, longer backwash (10 min filtration/0.75 min backwash) was found to be more effective than more frequent but shorter backwash (3.3 min filtration/0.25 min backflush) [90]. In practice, backwashing processes tend to follow manufacturers' recommendations to avoid any membrane damages. For HF systems, backwashing, if used, is typically applied and often complements rather than displaces relaxation [22].

In this experimental work, the MBR system was run according to the manufacturer recommendation (8 min filtration, 1 min backwashing, 1 min relaxation). The backwashing head ranged from 1.5 to 2 bar with a flow of 0.85 L/min. The backwash was conducted using freshwater available at the experiment location. After running the MBR at HRT of 10 h and SRT of 25 d and reaching the steady state flux, the backwashing pump was stopped to investigate the effect of backwashing on flux decline (fouling). The flux decline was outlined in Fig. 12; it can be noticed from the figure that the flux decline curve can be divided into two phases: (1) the rapidly declining phase characterized by a sharp flux decline rate (0.50 L/m^2·h) that continued for 7 h, and (2) the steady state phase that was characterized by minor flux decline rate (0.034 L/m^2·h) and continued for 8 h. In the rapidly declining phase, the flux declined from 7.67 to 4.20 L/m^2·h, while in the steady state phase it declined from 4.20 to 3.93 L/m^2·h. To have better understanding about the effect of backwashing on MBR flux, the backwash pump was run again and the flux was monitored. As outlined in Fig. 12, it can be noted that MBR flux was improved

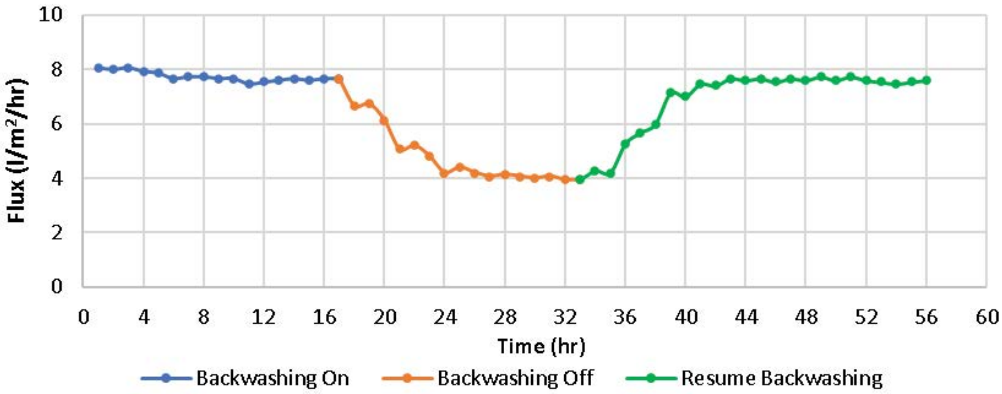

Fig. 12. Effect of backwashing on MBR flux.

and the improvement curve can also be divided into two phases: (1) the rising curve starting from a flux of 3.93 to 7.46 L/m^2·h in 8 h (rate of flux increase was 0.44 L/m^2·h), and (2) the steady state phase with almost constant flux value (average value of 7.6 L/m^2·h). This gave an indication about the importance of backwashing when operating the MBR system. Thus, as indicated by the manufacturer that backwashing is a must when running the MBR system.

3.2.2. Aeration

Aeration is one of the most efficient cleaning techniques in MBRs due to its effective scrubbing between liquid and gas [23]. It is one of the common adopted strategies when fouling control in MBR systems is being implemented [91]. It has a dual function in MBRs as it provides oxygen for the biological process (biodegradation process and biomass cell synthesis) and serves as a method of displacing the cake layer accumulated on the membrane surface [92]. Basically, aerators are installed beneath the membrane modules to scour the solids from the membrane's surface. Aeration importantly improves filtration performance because flux tends to increase by increasing the aeration intensity (m^3/h/m^2) to a certain extent. Providing the proper amount of aeration is essential to minimize the energy cost as well as to reduce membrane fouling [23]. Research showed that increasing the aeration rate in MBRs led to less fouling propensity [58,93]. Aeration can disrupt the cake layer formed near the membrane, and researchers have established correlations between the aeration intensity and the permeate flux [94,95].

Generally, augmenting the aeration rate promotes the mitigation of fouling because it introduces higher shear onto the membrane surface, facilitating the more effective removal of deposited microbial bio-flocs. The impact of aeration on cake removal and TMP pressure was investigated using a pilot-scale immersed MBR, and the study concluded that aeration played a vital role in controlling filtration conditions [63]. An elevated aeration rates can indeed diminish sludge adherence to the membranes, but it also exerts a substantial impact on biomass characteristics. Excessive aeration intensities can result in the disintegration of sludge flocs and the generation of soluble microbial products (SMPs). By increasing aeration intensities, colloids and solutes tend to be the primary culprits for membrane fouling, as the resistance they pose cannot be effectively mitigated by elevating shear stress [96]. Increasing aeration intensity by more than a factor of ten doesn't always yield a commensurate flux increase. Therefore, optimization of aeration intensity allowing sufficient shear force to reduce the cake layer is needed [23]. On the other hand, some unbeneficial impacts on microorganisms due to coarse aeration are reported. For example, deflocculation by coarse aeration is the most commonly reported problem. Floc size reduction by deflocculation leads to severe membrane fouling, so extensive and excessive coarse aeration should be restrained. The success of submerged MBR plants depends on how the fouling control strategy is implemented. If coarse aeration is too extensive, the operating costs will increase and deflocculation would be anticipated. On the other hand, if coarse aeration is not sufficient, membrane fouling will also become severe [23].

Prior research indicated that the effectiveness of cake removal through aeration didn't rise proportionally with the aeration rate's increase. Instead, there was an optimal aeration rate that maximized cake removal efficiency [97]. Excess aeration is discovered to be ineffectual in fouling control, as it surpasses a critical threshold. Beyond this point, it doesn't provide any additional benefits in fouling control but does increase the cost of aeration [19]. Hence, achieving a balance between these issues necessitates finding the optimal aeration intensity. Deviating significantly from this critical aeration intensity was shown to cause increased membrane fouling, as the increased shear force tends to disintegrate the large flocs [98].

The amount of aeration required for controlling fouling in MBRs depends on the installed membrane area. Aeration rate can be quantified by specific air demand (SAD) per membrane area (SAD_m) or per permeate volume (SAD_p). For the majority of membrane modules, SAD_m ranged from 0.3 to 0.8 N m^3/(h·m^2), while SAD_p ranged from 10 to 90 m^3·air/m^3 permeate [23]. Other researchers stated that air scouring rates can range from 3 to 12 L·air/min/m^2 [99].

For the case of this research, the air demand for the biological activity and fouling control are summarized in Table 2. To provide air for fouling control, three identical air pumps were used with a capacity of 480 L/min for each. The utilized pumps had two modes of operation that can provide either 240 or 480 L/min of air.

The system was run with the same MBR immediately after resuming the backwash process. Air supply was increased gradually to the system starting from 240 L/min until reaching 1,200 L/min. The flux (L/h·m^2) readings were monitored on an hourly basis as outlined in Fig. 13. As shown in Fig. 13, it can be noted that the flux was improved as the aeration intensity increased. Considering the flux at aeration intensity of 240 L/h as a baseline, the cumulative percentages increase of flux were 9.5%, 22.35%, 40.69%, and 41.35% at aeration intensities of 480, 720, 960, and 1,200 L/h, respectively. The percentages of flux increase for each aeration intensity were 9.5%, 12.85%, 18.34%, and 0.66% at aeration intensities of 480, 720, 960, and 1,200 L/h, respectively; and the corresponding flux values were 7.59, 8.31, 9.28, 10.69, and 10.73 L/m^2·h, respectively. There was no remarkable increase in flux when increasing the aeration intensity from 960 to 1,200 L/h. It can be concluded from the previous discussion that the optimum aeration intensity for the MBR system was 960 L/h. Fig. 14 outlines the ratio (in %) between the flux at different aeration rates and the design flux (13.76 L/m^2·h).

3.2.3. Membrane-aerator distance

Unlike other factors that influence fouling in MBRs, studies addressing the impact of the membrane-aerator distance on MBR fouling are limited. A study examining MBR configurations found that the optimal distance between the membrane and aeration tubes for inducing the highest shear stress was 250 mm [100]. In another study, experiments were conducted by altering the aeration pipes-membrane distance from 0 to 300 mm. The membrane surface shear stress increased with the extension of distance, but this will cause the decline of erosion uniformity. The shear effect on the membrane surface quickly increased as the distance increased from 0 to 75 mm. But when the distance was furtherly extended to 150 and 300 mm, the shear stress growth was not significant. Additionally, with distance increase, the needed aeration head increased accordingly, which would result in higher power consumption. Therefore, it was recommended that the membrane-aerator distance should range from 75 to 100 mm [101]. Decreasing the membrane-aerator distance showed lower TMP at which the suction pressure stabilizes. This can be explained by the increased effectiveness of air scouring at the membrane surface with the decrease in the membrane-aerator distance. The less the membrane-aerator distance; the lower membrane fouling would be obtained [102].

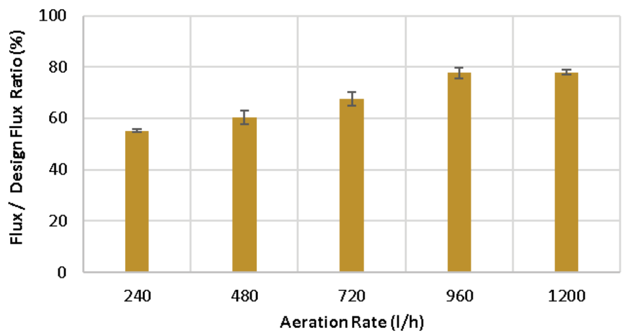

Fig. 14. Flux/design flux ratio at different aeration intensities.

Table 2
Air demand requirements for biological activity and fouling control

	Biological requirement	Fouling control requirement		
		SAD_p (m^3·air/m^3·p)	SAD_m (m^3/m^2·h)	l air/min/m^2
Range	–	5–100	0.3–0.8	3–12
Air demand (L/h)	152–200	30–1,300	450–1,200	270–1,080
Applied air (L/h)	240	240, 480, 720, 960, and 1,200		

According to the meter readings, permeate range: 6.53–13.27 L/m^2·h.
Area of membrane: 1.5 m^2.

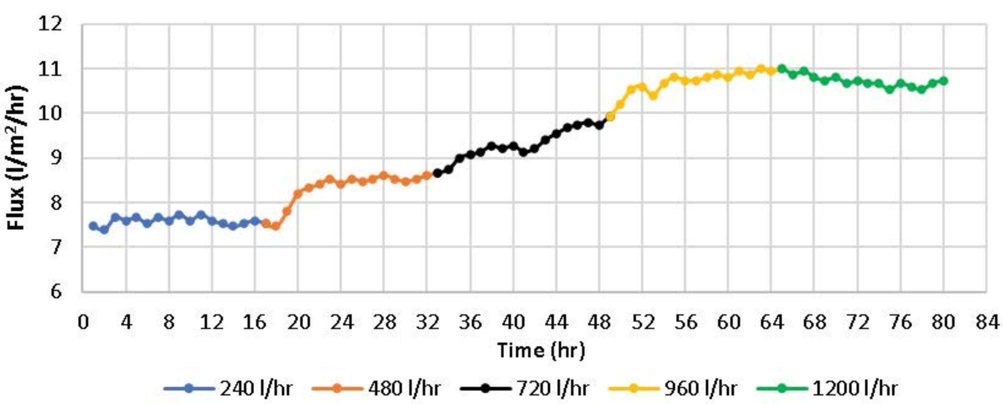

Fig. 13. Effect of aeration intensity on flux.

The membrane-aerator distance may indeed influence fouling, therefore it will be studied in this research. In this experimental work, the influence of the membrane-aerator distance on flux was investigated. For this sake, four values of the distance were used (5, 10, 17.5 and 25 cm); the system was run at an aeration rate of 240 L/h. Flux readings were recorded at an hourly basis as outlined in Fig. 15.

According to the results shown in Fig. 15 it can be noticed that the optimum distance between the membrane and the aerator was 10 cm. The flux was increased from 7.55 to 8.11 L/m^2·h (7.39% flux increase) as the distance increased by from 5 to 10 cm, respectively. When increasing the distance from 10 to 17.5 cm, the flux declined to 8.03 L/m^2·h (1.08% reduction as compared to the distance of 10 cm), while at 25 cm distance the flux furtherly declined and reached 7.79 L/m^2·h (2.91% reduction as compared to the distance of 17 cm). Fig. 16 outlines the ratio between the flux at different membrane-aerator distances and the design flux (13.76 L/m^2·h). The results revealed that the distance between the aerator and the membrane can impact the fouling phenomenon, this can be attributed to the mixing hydrodynamics inside the bioreactor. It is known that proper aeration will prevent stagnant zones where solids can settle and accumulate on the MBR surface. An appropriate membrane-aerator distance can help maintaining a well-mixed environment, even distribution of air and solids, and hinder the buildup of solids on the membrane surface. Moreover, as the aerator-membrane distance is increased, the shear effect might not effectively reach the membrane surface and this leads to increased fouling. Additionally, the distance can influence the size and distribution of bubbles reaching the membrane surface. While aeration can help prevent fouling, excessive agitation caused by the proximity of the aerator might lead to mechanical damage to the membrane surface. Thus, finding the suitable balance between effective mixing and avoiding direct physical damage to the membrane is crucial.

3.2.4. Addition of granular activated carbon and aeration

Energy consumption during operating MBR system is double that of the CAS systems because of the aeration utilized for controlling fouling [104,105]. Aeration is responsible for about 65% of the total power requirements in MBRs [106,107]. Hence, it is crucial to explore alternative fouling control approaches to decrease power requirements when operating the MBR. The use of scouring materials in MBRs garnered significant interest as an energy-efficient strategy for mitigating fouling. The inclusion of scouring agents became prominent research subject due to its ability to combine the efficiency of membrane cleaning with reduced power requirements [42]. To improve the detachment of foulants from the membrane surface, researchers turned their attention to the use of granular materials in combination with aeration, aiming to deliver effective and continuous membrane cleaning [108]. Addition of granular materials within the bioreactor can frictionally interact with the membrane surface, assisting in the detachment of cake layers from the membrane, thereby enhancing permeability [23].

Some researchers stated that incorporating granular materials into submerged MBRs can reduce membrane fouling due to their mechanical cleaning [54,109,110]. Powdered activated carbon (PAC), granular activated carbon (GAC), and zeolites are the most common materials used in this case [111]. Utilizing granular materials yields several benefits on MBR, including improved membrane permeability even at high flux rates of up to 35 L/(m^2·h), reduced cleaning demands for MBRs, significant flux enhancements, stable effluent quality, compliance with biomass separation requirements, and no adverse effects on membrane functionality [54].

Incorporating adsorbents into the bioreactor can lead to a reduced in solutes and colloids, improve flocculation capability, and create mechanical cleaning, thus reducing

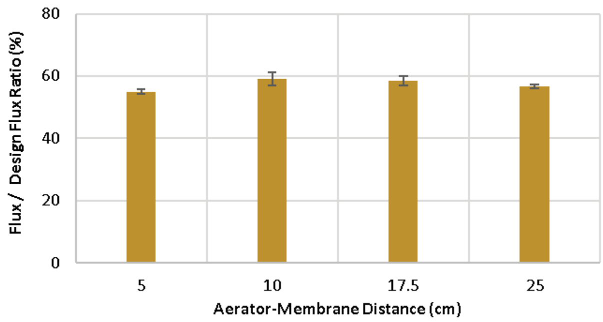

Fig. 16. Flux/design flux ratio at different aerator-membrane distances.

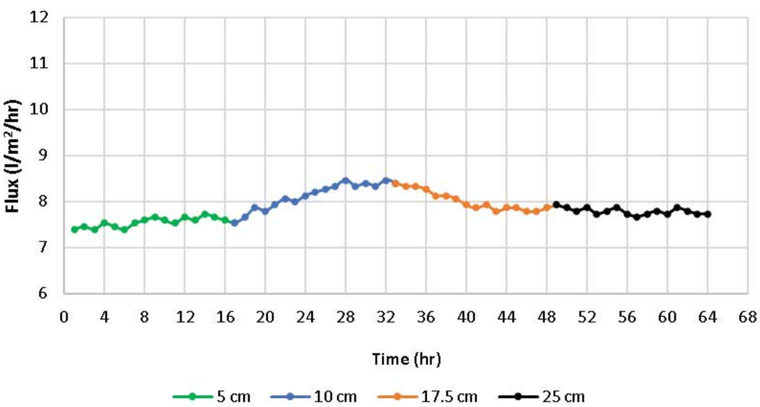

Fig. 15. Effect of aerator-membrane distance on flux.

fouling in MBRs [9]. Moreover, GAC particles can effectively manage membrane fouling through their continuous scouring action on the membrane during its operation, without requiring replacement or the addition of more GAC [112–114]. Fouling control becomes efficient when the media size is about 3 mm or bigger. Smaller media is ineffective in preventing the deposition of foulants on the membrane. Furthermore, the utilization of small scouring media may elevate fouling resistance due to their propensity to accumulate on the membrane [115,116].

Although the incorporation of GAC helps alleviate fouling in MBRs, additional research is required to determine its optimum dosage [117]. Experimental findings indicated that increasing the GAC dosage has a limited impact on mitigating fouling beyond a critical threshold [42]. Running the MBR beyond the optimal dosage may give counter results; it may raise the apparent viscosity of sludge, exacerbate fouling due to de-flocculation, diminish mass transfer, and impede sludge dewaterability [117]. In an experiment executed by Johir et al. [118] it was shown that adding GAC with a particle size ranging from 0.3 to 0.6 mm and a concentration of 0.5–2 g/L led to a significant and abrupt reduction in filtration resistance with about 60%. According to Siembida et al. [54] introducing granular materials led to substantial reduction in cake layer formation on the membranes due to abrasion. Furthermore, the study revealed that addition of granular materials facilitated successful long-term operation without the need for membrane chemical cleaning. Incorporating granular materials enabled MBR operation at higher flux rates, exceeding that of conventional MBRs by more than 20%. Likewise, Kurita et al. [119] discovered that adding granular materials to submerged MBRs raised the critical flux by over 40%. This enabled stable MBR operation even with a 50% reduction in aeration which significantly reduced the cost of operation and maintenance. Nonetheless, granular materials may negatively affect the membrane itself, therefore, additional research is essential to determine the optimal aeration intensity and identify suitable granular materials that don't harm the membranes [120]. In an attempt to highlight an alternative MBR design in which a composite sponge-granular activated carbon-sponge (SGS) layer is covered around the membrane module; Alsalhy et al. [121] designed a new sponge-GAC-sponge membrane module for use in a membrane bioreactor. Results of their study revealed that membrane fouling is controlled in the SGS-MBR by decreasing the cake layer thickness on the membrane surface by about 96%. The flux recovery efficiency of the membranes was highly improved in the SGS-MBR because microorganisms are not directly attached to the membrane. Yang et al. [110] reported that a sponge-MBR system was proficient at controlling membrane fouling, and especially the cake layer on the membrane. The result was an 86% reduction in cake resistance and a 20% flux increase compared to the MBR alone. The sponge-GAC acts as a pre-filter and prevents accumulation of too much biomass on the membrane during its operation. It is clear that this pre-filtration will be beneficial as it will absorb too much biomass and protect the polymeric membrane from fouling [121].

In this experimental work, the addition of GAC as a fouling mitigation technique was adopted. The used GAC was the commercially available one in Gaza Strip, its density was 0.75 kg/l. The grain size distribution for GAC is outlined in Fig. 17. It is clear from Fig. 17 that more than 96% of the sample ranged from 1.25 to 4.75 mm. The effective size of GAC (D_{10}) was 1.3 mm, the uniformity coefficient (C_u) was 2.12, while the coefficient of gradation (C_c) was 0.81.

The experiment was run at HRT 10 h, SRT 25 d, aeration rate 240 L/h, backwashing mode was on, and the distance between air source and the membrane was 5 cm. The system was firstly operated without the addition of GAC until reaching the steady state condition, after that GAC was added at doses of 1, 1.5, 2, 2.5, 3, 3.5, and 4 g/L. The flux was monitored throughout the experiment, its variation is outlined in Fig. 18.

It is clear from Fig. 18 that flux increased with increasing GAC dose until reaching a certain dose, after that flux increase ceased. The flux values were 7.76, 7.97, 8.58, 8.88, 9.52, 9.54, 9.63, and 9.63 L/m²·h at GAC doses of 0, 1, 1.5, 2, 2.5, 3, 3.5, and 4 g/L, respectively. The corresponding percentage flux increase values with respect to the original flux (without GAC addition, that is, 7.76 L/m²·h) were 2.69%, 10.43%, 13.92%, 21.10%, 21.32%, 22.19%, and 22.28%, respectively. It was concluded that GAC doses above 2.5 g/L had minor effect on flux improvement which can be neglected; indicating that the optimum dose of GAC for this experimental work was 2.5 g/L. Fig. 19 outlines the ratio between the flux and the design flux at different doses of GAC.

To investigate the influence of all the previously mentioned factors on fouling control, a final experiment was run at the optimum values of aerator-membrane distance (10 cm), GAC dose (2.5 g/L), and continuous backwash mode while changing the aeration rate. The aeration rates were set at 240, 480, 720, 960, and 1,200 L/h. The corresponding flux values were 8.21, 9.38, 10.6, 12.05, and 12.18 L/m²·h, respectively. The results of this experiment represented as a ratio between the flux and the design flux (13.76 L/m²·h) were summarized in Fig. 20. The results revealed that operating the system at the optimum values of GAC dose (2.5 g/L), aerator-membrane distance (10 cm), continuous backwash mode, and at aeration intensity of 720 L/h will yield a permeate flux of 10.81 L/m²·h. Operating the system at aeration intensity of 1,200 L/h, aerator-membrane distance (5 cm), and no addition of GAC yielded flux of 10.73 L/m²·h. This indicated that running the MBR system at the optimum conditions while reducing the aeration intensity by 40% gave the same flux value. Under the same optimum conditions, when

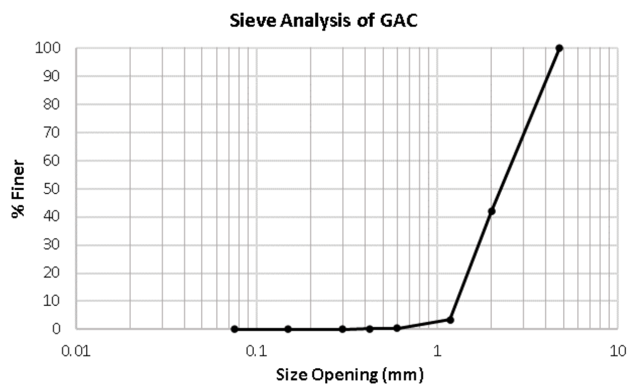

Fig. 17. Gran size distribution of GAC.

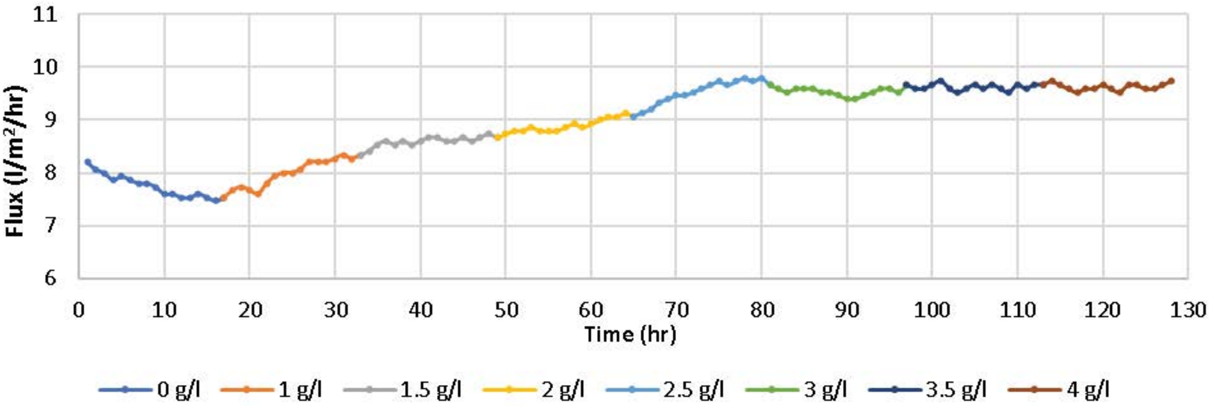

Fig. 18. Effect of GAC dose on flux variation.

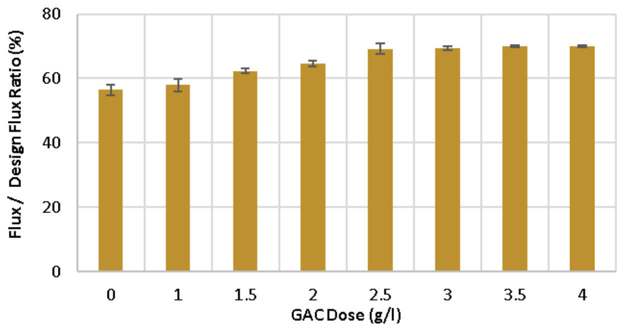

Fig. 19. Flux/design flux ratio at different GAC doses.

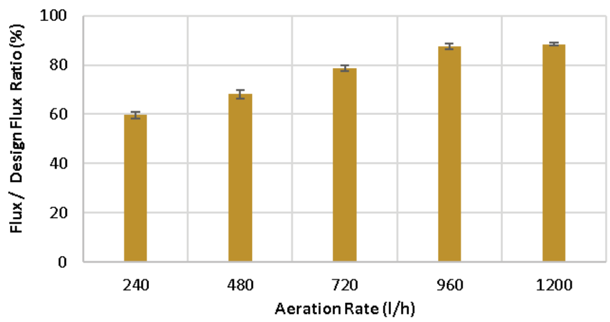

Fig. 20. Flux/design flux ratio at optimum parameters and different aeration intensities.

the aeration intensity was increased to 960 and 1,200 L/h; the corresponding flux values were 12.05 and 12.18 L/m^2·h, respectively. These flux values represented 87.57% and 88.52% from the design flux, respectively.

4. Conclusions and recommendations

The results of this work revealed that fouling in MBR systems can be correlated with MLSS only at certain concentrations, indicating that fouling in MBRs was complicated and the relationship between fouling and MLSS concentration was not always clear. The influence of HRT on fouling on MBR can be attributed to the fact that HRT influenced the sludge characteristics in the system. Generally speaking, increasing HRT will result in better flux and reduced membrane fouling. SRT tended to increase fouling as a result of increasing MLSS concentration and the viscosity of the mixed liquor. On the other hand, the rate of fouling increase appeared to decrease with increasing SRT.

Applying backwashing as a strategy for fouling mitigation was beneficial, indicating that backwashing must be conducted at all MBR systems; which was in-line with the manufacturer's instructions. Additionally, aeration was considered as an effective means for fouling control, and it is necessary to set an optimum aeration intensity to achieve the balance between operational cost, and fouling control requirements. In this work, aeration intensity of 960 L/h was the optimum among all the investigated intensities. The aerator-membrane distance can impact fouling in MBRs, with 10 cm was the optimum distance that resulted in the highest permeate, and this can be attributed to its influence on the mixing hydrodynamics within the bioreactor. The experiments also concluded that the use of GAC enhanced the permeate flux if the proper dosage was used. The optimum dosage of GAC in this experimental work was 2.5 g/L. Operating the system with the optimum values of all the previously mentioned parameters; backwashing mode was on, membrane-distance aerator 10 cm, GAC dosage 2.5 g/L, and with changing the aeration intensity, revealed that it was possible to reduce aeration by 40% as compared to running the system under other conditions.

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