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Studying the Effect of HRT, SRT, and MLSS on Membrane Bioreactor Performance for Wastewater Treatment

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Abstract

Membrane bioreactors (MBRs) are operated with the same principle of activated sludge (AS) except for solids separation; that it is achieved by filtration through membranes. This article aimed to study the effect of hydraulic retention time (HRT), solids retention time (SRT), and the mixed liquor suspended solids (MLSS) concentration on the performance of a hollow fiber (HF) submerged aerobic MBR with an area of 1.5 m^2. A reactor of 200-liter volume was designed, and operated at HRTs of 4, 6, 8, and 10 hours. For each HRT, five SRT values were selected 5, 10, 15, 20, and 25 days. The MBR's operation cycle was 8 min filtration, 1 min backwashing and 1 min relaxation. Air was supplied continuously to maintain 1.5 – 2.0 mg/l of dissolved oxygen. Results of the experiments showed improvement of the removal efficiency for chemical oxygen demand (COD), total suspended solids (TSS), and ammonia nitrogen with increasing SRT and HRT. The highest removal efficiencies for COD, TSS, and ammonia nitrogen were 97.59%, 99.71%, and 90.54 % respectively, which were achieved at SRT of 25 d and HRT of 10 hrs. The study concluded that at MLSS < 10,000 mg/l, there was no concrete relationship between TSS removal efficiency and MLSS concentrations, but better removal efficiencies of TSS were obtained at MLSS > 10,000 mg/l. The relationship between MLSS and COD removal was clearer than that of TSS; the COD removal efficiency was improved as the MLSS increased; the higher removal efficiencies took place at MLSS > 10,900 mg/l.

***Keywords**:* Activated Sludge; Aerobic; Hollow Fiber; Membrane Bioreactor; Removal Efficiency

1. Introduction

Due to the continuous and increased need for a cleaner water environment, effluent standards are becoming stricter. The main drivers for developing new technologies to have better wastewater treatment processes are the concerns regarding environmental protection, and conformity with strict global wastewater disposal and reuse requirements [1]. Since the effluent of many activated sludge (AS) systems is not able to conform to reuse regulations, it is crucial to treat wastewater sufficiently to meet the requirements of reusing the treated wastewater [2, 3]. Membrane technology is one of the new technologies which can be used to have a better effluent quality [4]. Membrane bioreactor (MBR) is a treatment technique gathering the biological treatment and membrane filtration. Strict regulations on discharging the effluent, and reducing the membrane's capital cost are considered the prime reasons for prevalent usage of MBRs [1]. MBR systems were successfully applied in different wastewater treatment and reuse applications including domestic and industrial wastewaters [5, 6, 7].

MBR refers to the synergy between conventional biological wastewater treatment and membrane

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filtration. Technically, the principle is like AS systems except the separation of solids; it is achieved by filtration through the porous membranes rather than sedimentation in secondary clarifiers [8, 9]. The reactor in MBR systems has a similar function to the aeration tank of AS systems where bacterial activities treat the wastewater. As shown in Fig. 1; MBR pores are sufficiently small to expel AS flocs, bacteria, and sometimes viruses. Thus, MBRs produce higher-quality effluents (equivalent to tertiary treatment) having almost no detectable total suspended solids (TSS). Additionally, MBR process eliminates secondary clarifiers leading to smaller footprints as compared to AS systems [1].

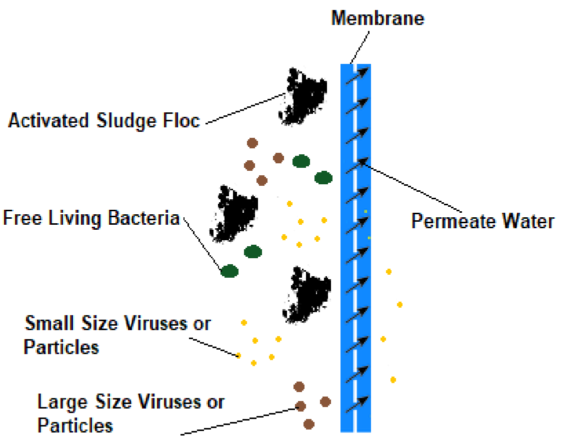

Fig. 1. MBR Schematic Presentation

Capable of producing high-quality effluent, MBR system is almost usually combined with an aerobic reactor. As nearly the whole biomass may be retained in the bioreactor, MBRs can sustainably produce effluent of high quality. Additionally, MBRs could be operated at high sludge retention times (SRTs), that is beneficial for slow growing bacteria [10].

The possibility for operating MBRs at very long SRTs without facing settling problems allows having higher concentrations of the biomass in the aeration tank. Hence, strong wastewater treatment could be achieved, and less sludge production is expected. This results in compact systems when compared to activated sludge (AS) systems and reduces the plant footprint, hence rendering MBRs to be more preferrable for wastewater treatment. MBRs are also capable of treating high molecular weight soluble compounds, this is due to the long SRTs that enhance the possibility of their oxidation. Moreover, under long SRTs and short hydraulic retention times (HRTs) in MBR systems, the biodegradation of refractory organic matter occurs. It is worth mentioning that conventional AS systems can't degrade these compounds [11]. MBRs are also characterized by better control of bacterial activities, rapid operation, and high organic loading rate (OLR). They also overcome operational problems that accompany the settling processes [8, 11, 12].

Both AS processes and MBRs employ the metabolic ability of bacteria in the bioreactor to treat wastewater. Thus, wastewater treatment rate is basically proportionate to active bacteria's concentration in the reactor. However, in AS systems, the possibility of increasing the biomass concentration above a certain value is not applicable, this is because of the limitations of the secondary sedimentation tanks. Secondary sedimentation tanks are usually operated based on the settling characteristics of the AS, which is controlled by the gravitational forces and the interaction between AS particles [1]. Settling obligations increase with increasing concentrations of AS in the secondary clarifier. Approximately, for AS systems, 5000 mg/l of mixed liquor suspended solids (MLSS) in the reactor is considered as the highest value needed to operate the secondary sedimentation tank stably. In MBRs, theoretically, no upper limit for MLSS in the reactor is reported. Optimum levels of MLSS in MBRs can range from 8,000 - 12,000 mg/l, which leads to a reduced footprint needed to treat wastewater to a certain effluent quality or to reach a better quality for the same size of the reactor in comparison to AS systems. The high MLSS-concentration in MBR processes also provides benefits by reducing waste sludge production and thus, reduces the cost associated with wastage activated sludge (WAS) removal. Microorganisms tend to degrade themselves in bioreactors (i.e., endogenous decay). Moreover, MBR is able to deal with nutrient's concentration fluctuations, this is because of the inclusive biological adaptation and detention of dead bacteria [2].

Two MBR types are currently in use; the submerged and the side-stream MBR systems (see Fig. 2). The selection between the two systems became settled, the submerged systems were preferred [8, 13, 14]. Submerged setup reduces the footprint, eliminates the requirements for an additional water tank, lowers power consumption, and reduces fouling [15].

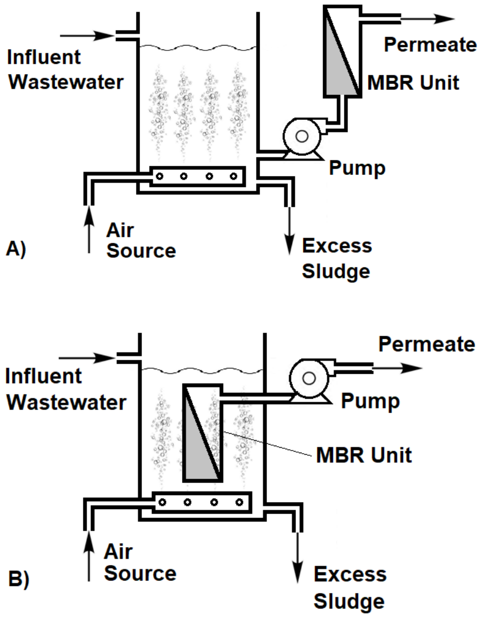

Fig. 2. MBR Types: A) Side-Stream MBR, B) Submerged MBR

Although some achievements regarding the MBR technology have been made, there is room for more improvements in such technology [16]. For the case of this research, the following justifications can be listed: 1) There is a very promising willingness to study the MBR performance in treating wastewater, 2) Since a great number of results and conclusions of MBR studies are based on laboratory scale MBR systems with synthetic wastewater samples worldwide, there is a need to conduct further study by applying this technology to a real wastewater treatment plant (WWTP).

The key goal of the research is to investigate the MBR performance as an efficient and reliable treatment method in producing higher-quality secondary effluent. A hollow fiber (HF) MBR module will be utilized as an alternative to the secondary clarifier in AS system at a WWTP and its performance in removing total suspended solids (TSS), chemical oxygen demand (COD), and ammonia nitrogen through changing some operational parameters including HRT, SRT and MLSS concentration will be studied.

2. Materials and Methods

MBR Module: The MBR module used in this research is a hollow fiber submerged MBR manufactured by Neya Water Solutions - India. The MBR module has an area of 1.5 m^2, and is made of Reinforced Polyvinylidene Fluoride (RPVDF) with pore sizes of 0.03 to 0.2 mm. The MBR height, length and thickness are 405, 480, and 23 mm respectively. The external diameter of the MBR fibers is 1.2 mm while the inner diameter is 0.6 mm. The permeate flux of the MBR ranges from 12 – 18 $l/m^2/hr$. The filtration method will be from outside to inside through the pores via vacuum pressure. The MBR can be run continuously, the running cycle was 8 min filtration, 1 min backwashing and 1 min relaxation [17, 18]. Fig. 3 and Fig. 4 outline the MBR and a schematic cross section of the HF respectively.

Fig. 3. Membrane Bioreactor Module

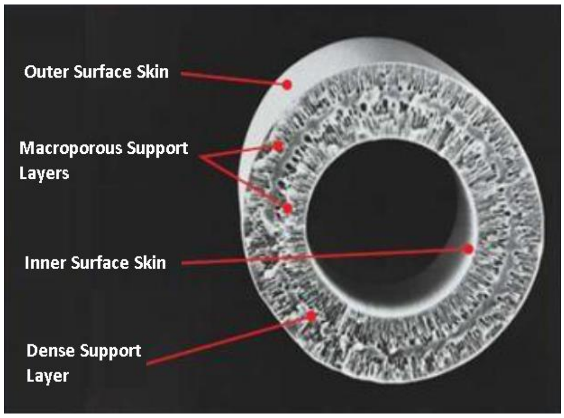

Fig. 4. Cross Section of a HF MBR [18]

Air Pump: To supply the air required for both biological process and the fouling control, a pump with suitable capacity was selected. The air pumping capacity of the pump used in this research was 8 l/min (480 l/hr) and it can be operated at 2 modes (240 l/hr and 480 l/hr).

Solenoid Valves: Solenoid valve is an electromechanical valve used to control fluids’ flow. It is usually utilized as a replacement to manual valves or for controlling systems remotely. They can be found in many uses including water supply, water and sewage treatment, and grey and black water treatment [19, 20, 21]. In the off position, the plunger closes off a small orifice. In the on position, the electric current will generate a magnetic field that creates an upward force, which in turn moves the plunger and allows the orifice to open [21]. To control the water flow throughout the different modes of MBR operation, two identical solenoid valves 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).

Flow meter: To measure the MBR permeate flow, a common type of flow meters available in Gaza Strip was used: Arad water meter. This meter is suitable for municipal and commercial facilities that are provided with water through a public network. The meter should be placed horizontally, and the dial should be positioned face up. It must be washed before operation and should be full of water all the time [22, 23].

Permeate Water Pump: As the submerged MBR is placed inside the aeration basin and generally operated under vacuum to produce the permeate, a suitable suction pump should be selected to run the process. According to the manufacturer instructions, the suction pump should be able to suck water with a head of 3 – 5 m to produce the required flow. A suitable pump in terms of permeate quantity and continuous operation was selected. The specifications of the selected pump were, flow range: 80 – 120 l/hr, suction pressure: 3.2 – 4.5 m, output pressure: 2 – 4 m, inlet and outlet diameter: 8 mm.

Backwashing Pump: Backwashing regime for the MBR was adjusted according to the manufacturer instructions. Backwashing was maintained for 1 minute after the filtration mode which extended to 8 minutes. The backwashing head should range from 1 – 2 bars with a flow of 0.83 to 1.25 liters per minute. To do so, a DIAPHRAGM pump, HF-8367 was utilized and calibrated to reach the optimum operating conditions. After calibrating the pump, the net backwashing head was 1 – 2 bar and the flow rate was 0.85 l/min, which fell within the limits provided by the manufacturer.

Electrical Control Box: The electrical control box includes: 1) Flasher Relays: They are used at different applications that need double timing control [24], 2) Power Relay: It is compact, reliable, and offers good switching performance, which makes it a popular choice in many industries [25]. For the case of this research, the relay is used to switch the roles for the permeate timer and the backwashing timer to ensure that there is no overlap between them during the process. The control box includes three flasher relays and one power relay. The function for the first flasher relay is to schedule and control the filtration mode. When the flasher status is on, it gives a signal to the permeate water pump to operate. At the same time, the solenoid valve attached to the permeate pump is opened while the solenoid valve attached to the backwashing pump is closed. This ensures that the permeate water will flow only through the MBR fibers (outside to inside flow). When the first flasher status is on, the status of the remaining two flashers is off. After the completion of the filtration mode, the first flasher becomes off while the second flasher becomes on. The function of the second flasher is to give a signal to the backwashing pump to operate. At this stage, the solenoid valve attached to the permeate pump is closed while the solenoid valve attached to the backwashing pump is opened. This ensures that the backwashing water will get into the MBR fibers (inside to outside flow) and will not be mixed with the permeate water. After the completion of the backwashing stage, the relaxation mode will take place. Finally, after the completion of the operation cycle, the third flasher function is to reset the system and enable its start as normal; this ensures the removal of any timing error accumulations.

2.1. Designing the MBR for COD Removal

2.1.1. Selection of HRT

HRT has a fundamental role in design and operation of biological WWTPs. It is a crucial operational parameter, directly affecting the reactor's performance. Decreasing HRT in AS systems will increase the likelihood of biomass being washed out. Thus, it is necessary to keep a proper HRT. Based on the influent properties, normal HRTs in AS systems for municipal wastewater treatment (MWWT) can be 4 – 10 hours. The range of HRT in MBR systems is 4 – 9 h, with 6 h is the typical value. Longer HRTs are needed when wastewater includes recalcitrant molecules, if non-biodegradable matter is introduced to the treatment process, and if biological nutrient removal process is intended [1].

In general, HRT in MBR does not significantly differ from that of AS. Reduced HRT operations are possible in MBR because MBRs are operated at higher MLSS, leading to stable and fast organic matter removal. Nevertheless, MBRs commonly run with comparable HRTs to conventional AS to provide sufficient times for organic matter degradation. Increasing HRT will result in decreasing F/M ratio, leading to significant alterations in the bacterial characteristics. This is due to the strong dependency of the bacterial growth rates on F/M ratio. Consequently, increasing F/M ratio negatively impacts the quality of effluent and worsens solids' settling [1].

For the case of this research and based on the above reported values of HRT in literature, four different values of HRT were selected: 4, 6, 8 and 10 hours. A bioreactor was designed in a manner that allowed running all the experiments at different HRTs. The height of wastewater in the bioreactor (i.e., the volume) was controlled by a floating valve, and the floating valve level could be adjusted to four elevations. The bioreactor's plan dimensions were 55 cm × 55 cm, while its height was 85 cm.

2.1.2. Selection of HRT

SRT is a key operating parameter for operators to control the sludge production rate and to keep a constant biomass concentration in the bioreactor. SRT is directly linked to the MLSS concentration in a bioreactor. Extended SRT operations lead to increased cell residence time, thus increasing the MLSS concentration. Ideally, SRT should be sufficiently extended to maintain the availability of slow growing bacteria accountable for wastewater treatment. Typical SRT values for conventional AS systems are around 4 – 10 days, which literally means that the solids reside 4 – 10 days in the bioreactor and secondary clarifier, 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 [1]. It was reported in literature that SRT values for MBR systems could range from 5 – 20 days [26], 5 – 30 days [1]. For the case of this research, SRTs of 5, 10, 15, 20 and 25 days were selected for the experimental program design.

2.1.3. Experimental Matrix for COD Removal

Based on the selected values for the SRT and HRT; the following experimental matrix, shown in Table 1, was developed.

Table 1

Experimental Matrix for COD Removal

HRT (Hr)	SRT (Days)				
4	5	10	15	20	25
6	5	10	15	20	25
8	5	10	15	20	25
10	5	10	15	20	25

2.1.4. Air Requirements for Biological Activity

In MBRs, aeration is considered the most critical part of the process. Aeration supplies oxygen to the bacterial populations for their metabolic process and for controlling MBR fouling. Fine bubbles with larger surface area facilitate efficient oxygen transfer to the bacteria while coarse aeration with bubbles of bigger size is suitable for effective vibration and cleaning membrane fibers [1]. Air supply enhances the permeation of the membrane by creating fluctuated permeate flux and localized tangential shear forces. Air bubbles also improve HF immersed MBR performance by causing fibers' shaking [27, 28], that generate shear through the relative movements of fibers and the surrounding mixed liquor [14].

In aerobic processes, aerobic bacteria utilize oxygen supplied by aeration as their terminal electron acceptor to oxidize organic and inorganic matter. Moreover, the supplied air mixes the MLSS and generates turbulent flow to clean the membrane. Aeration is the largest energy consumer in biological wastewater treatment. Around 50% of the energy required in conventional AS systems is used for aeration. In MBR, the proportion increases up to 80% due to the surplus of energy consumption by membrane aeration. It is, therefore, important to design the aeration system properly to prevent the overestimation or underestimation of the required aeration, which can result in excess energy consumption or imperfect treatment, respectively. Overestimation of oxygen demand wastes energy costs associated with oxygen supply. However, underestimation of oxygen demand may interfere with complete oxidation of oxidizable pollutants in the wastewater. In practice, oxygen is often provided to the bioreactor through aeration during the operation of MBR [1]. For the case of this research, the required aeration amount for biological activity ranged from 150 – 200 l/hr.

2.1.5. 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 [29]. The geographical area for the GCWWTP covers Gaza City except for a small area to the north and all of the central communities as far as Deir El Balah in the south. To contribute towards protecting the groundwater resources and reducing health risks to the population of the city of Gaza and five other communities, it was proposed to construct the GCWWTP in Al Buriej [30]. 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 overload from the existing Sheikh Ejleen WWTP and eventually to take it out of service. The proposed WWTP comprises a biological treatment stage with a design capacity of around 600,000 PE based on 0.06 kg BOD_5/(PE*d) [31]. Fig. 5 outlines an aerial photo for the Al Buriej WWTP plant.

Fig.5 Photo for GCWWTP [31]

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 [30]. 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 [29]. Phase 1 consisted of Stage 1, 2 and 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 [31]. The AS process of the biological wastewater treatment is based on a pressurized aeration system with carbon removal for Phase 1, Stage 1 and nitrification and denitrification for Phase 1, Stage 2 and 3 [32].

For the Phase 1, stage 1; the plant 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}: 1300 mg/l, TSS_{in}: 650 mg/l, TN-N_{in}: 140 mg/l, TP_{in}: 15 mg/l. the effluent standads for the treatment plant: BOD_{out}: 40 mg/l, COD_{out}: 100 mg/l, TSS_{out}: 60 mg/l [31]. The MBR system was placed near to the primary clarifiers, as the primary effluent from the WWTP will be considered as the influent to the MBR system.

2.2. System Calibration and Operation

The NEYA MBR operates with three interrelated processes including the permeate, the backwash, and the cleaning processes. In the permeate process, clean water gets collected in the hollow fiber cavity, leaving the biomass outside. Backwash is regularly applied to prevent clogging (fouling) of hollow fiber membrane. Through the cleaning process, normally NaClO is used to clean the MBRs, as clogging is mainly taking place because of the organic substances. Acids should be used whenever needed to remove the inorganic matter from the MBR [33].

For the first time, the system was run using freshwater to ensure that the previously mentioned three processes were operated as designed. System calibration in terms of checking of permeate flow rate, the backwashing pump and the aeration system was performed. After ensuring the success of the process, the MBR was run to treat wastewater at GCWWTP.

3. Results and Discussion

MBR performance is mainly dependent on the biological degradation in bioreactor and rejection capacity of membrane. The biodegradation of organic matter, suspended solids, and nutrients depended on the process type whether aerobic, anoxic, or anaerobic. The rejection of MBR is commonly expressed as the ratio of the concentration of a certain parameter in the influent and the effluent [34]. The primary goal of MBR process is to minimize the organic matter in the influent before being discharged or reused. To evaluate the attainment of this goal, researchers used to measure the organic matter in the influent and the effluent to determine the removal efficiency [35]. It was stated that out of the MBR's COD removal efficiency, the bioreactor accounted for 80-90 % it because of the bacterial activity. On the other hand, the membrane accounted for 10-20 % through different mechanisms such as rejection, plugging, and adsorption [36, 37]. Depending on the wastewater treated in MBRs, removal efficiencies for COD ranged from 76% [38] to 99% [39, 40].

MBR system is considered as a reliable alternative for wastewater treatment that can provide permeate of superior quality. The removal efficiency COD ranged from 90 to 99 % for municipal wastewater and synthetic wastewater, and from 63 to 99 % for industrial wastewaters. High MLSS concentration in MBRs achieved remarkable increase in COD removal because of the enhanced biodegradation. Various parameters contribute to COD removal include HRT, SRT, OLR and membrane filtration [2]. In the past, only 65 % of TSS removal was possible by means of AS process [8]. Using membranes as alternative to final clarifiers in AS processes improved TSS removal efficiency up to 100 % [41, 42, 43]. Many studies on MBRs found that the membrane bioreactor made the wastewater effluent free from TSS irrespective of membrane configuration and type of wastewater [2]. From a practical point of view, very high values for TSS removal efficiencies were reported; in particular, higher than 99% [44, 45].

For the case of this research, organic matter removal from municipal wastewater was studied. Throughout the experimental work, the pH of influent wastewater, effluent wastewater and the bioreactor was measured. There were no remarkable variations in the pH values that ranged from: 7.2 to 7.6 for the influent, 7.1 to 7.7 for the effluent, 7.3 to 7.8 for the bioreactor. The dissolved oxygen was 1.5 - 2 mg/l inside the bioreactor. During the experimental program, the range of wastewater temperature was 18.3 - 25.3 ◦C for the bioreactor, 18.3 - 25.1 ◦C for the effluent, and 20.1 -26.1 ◦C for the influent. The total dissolved solids (TDS) were also measured; they ranged from: 2510 - 2990 mg/l for the influent, 2540 - 2880 mg/l for the effluent, and 2550 - 2880 mg/l for the bioreactor. No remarkable improvement in TDS concentration between influent and effluent was recorded. The aeration intensity was maintained according to the biological requirements of the system.

From the factors influencing TSS, COD, and ammonia nitrogen removal in membrane bioreactors; HRT, SRT, and MLSS concentration will be investigated in this work. In the following sections, the influence of HRT, SRT and MLSS on MBR performance in removing TSS, COD, and ammonia nitrogen will be discussed.

3.1. Effect of HRT on MBR Performance

Lower HRTs lead to high organic loading rate (OLR), resulting in a reduced reactor volume needed to reach a specific treatment efficiency. Long RHTs will enhance the bacterial growth and provide more time for microorganisms to metabolize and degrade pollutants (more favorable conditions for microbial growth are provided), leading to improved removal efficiency. Additionally, a longer HRT allows for increased contact time between the wastewater and the bacteria, thus enhancing the biological treatment processes. High HRTs are suitable for treatment of wastewater that contains high concentration of COD and/or BOD or for slowly biodegradable compounds [46]. It is essential to select a suitable value for the HRT in MBR processes to avoid the washout of the active bacteria and to control the volume of the aeration basin. The type and quality of both influent and effluent wastewater also affect the selection of HRT in MBR processes. As compared to conventional AS process, the selection of HRT in MBR is more flexible as the MLSS is much greater. In general, the biodegradation of the organic matter is more stable and the removal efficiency for both the COD and TSS is higher at longer HRTs [1].

In this research, the selected HRT values were 4, 6m 8 and 10 hours. The removal efficiencies for COD and TSS at each HRT were determined. For each selected HRT value, five values for the SRT were selected: specifically, 5, 10, 15, 20 and 25 days. For each SRT value, influent and effluent samples were collected and sent to the laboratory for COD and TSS testing. MLSS and MLVSS for the bioreactor were also measured. The removal efficiencies for TSS were presented in Fig. 6. By referring to Fig. 6, it can be generally concluded that the TSS removal efficiencies were improved at high HRT values as compared with low HRT values for a given SRT value. The highest removal efficiencies for the TSS were obtained at HRTs of 10 and 8 hours. However, at HRT values of 4 and 6 hours; the removal efficiencies for TSS were lower. The TSS lowest removal efficiencies were reported when operating the system at HRT of 6 hours while the highest TSS removal efficiencies took place when operating the system at HRT of 10 hours.

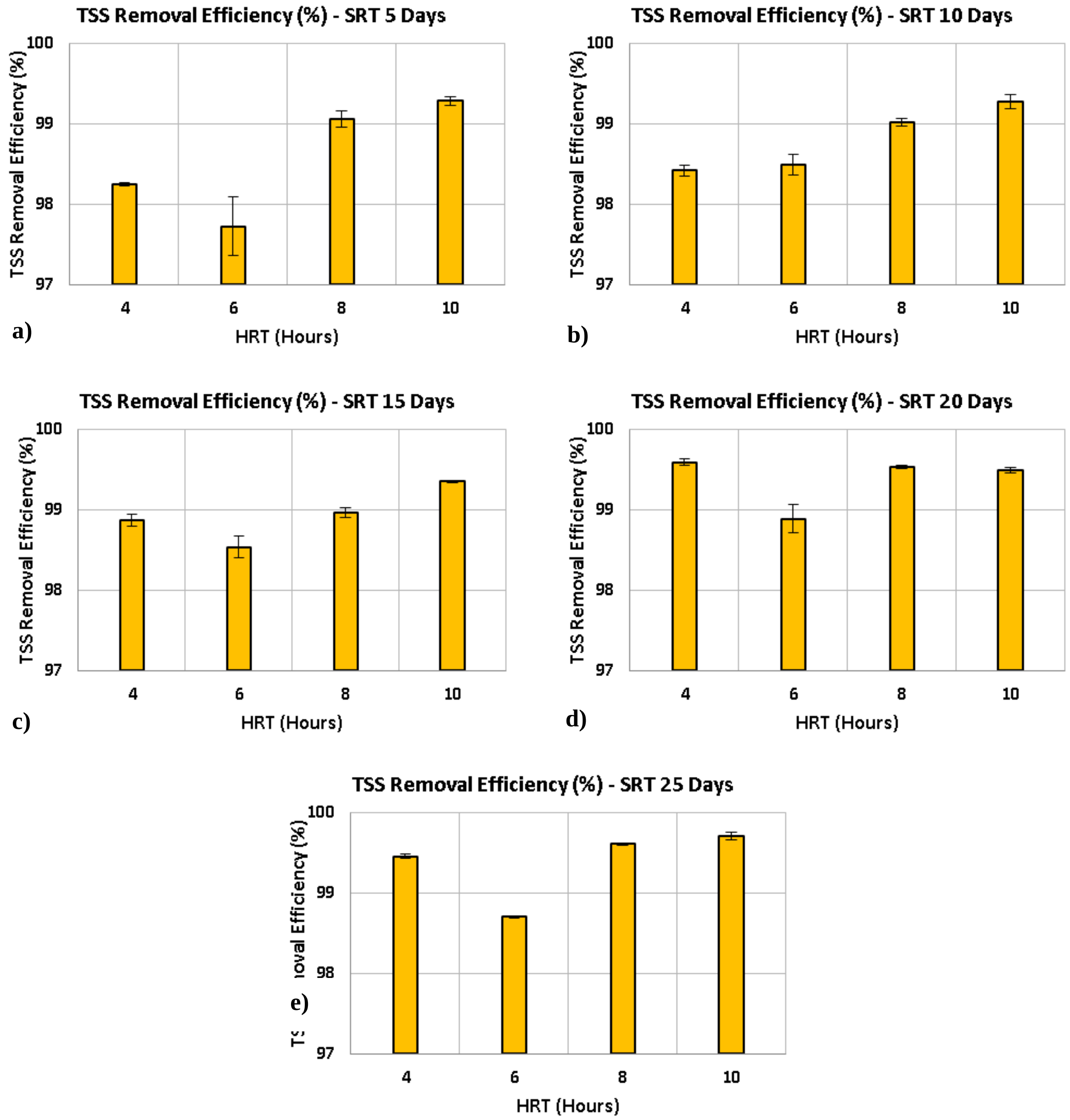

Fig. 6. TSS Removal Efficiency at SRTs of: a) 5 d, b) 10 d, c) 15 d, d) 20 d, e) 25 d

For the case of COD removal and by referring to Fig. 7; the same trend found for TSS removal was applicable for COD, i.e., the removal efficiencies were improved as the HRT increased from 4 to 10 hours for a given SRT value. The highest removal efficiencies for COD were reported at HRTs of 10, 8 and 6 hours respectively, while the lowest one was obtained at HRT of 4 hours. The COD highest removal efficiency took place when operating the system at HRT of 10 hours.

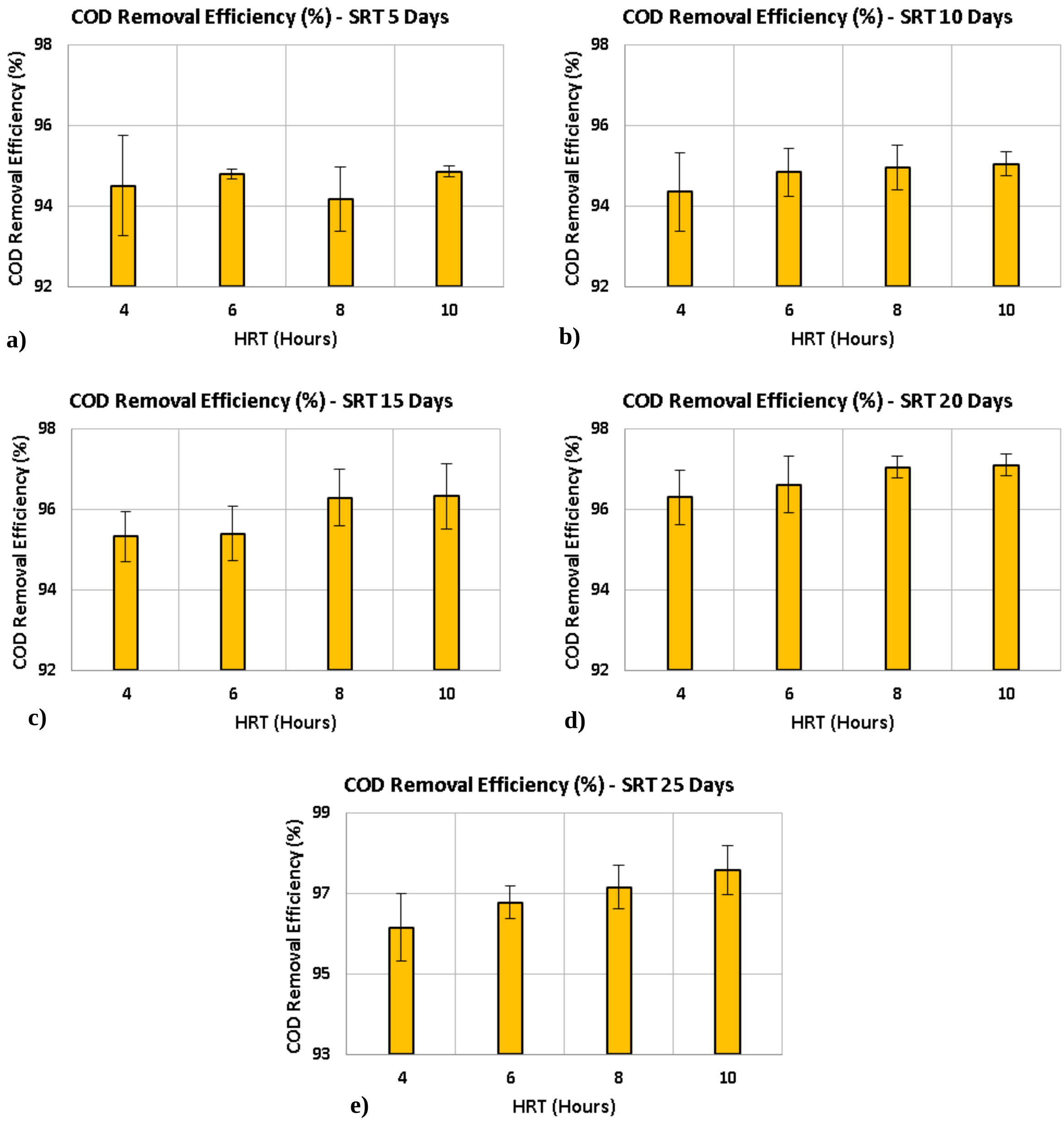

Fig. 7. COD Removal Efficiency at SRTs of: a) 5 d, b) 10 d, c) 15 d, d) 20 d, e) 25 d

3.2. Effect of SRT on MBR Performance

Wastewater treatment operators aim to run their systems at short HRTs and long SRTs while maintaining the process efficiency. More influents can be treated as HRT shortens and SRT increases; however, this situation is a challenging goal to attain in AS operations because of the incomplete separation capability of secondary clarifier. Longer SRTs in AS is not readily achievable because of losing microorganisms in secondary clarifiers. Additionally, in MBRs it is possible to decouple HRT and SRT because the membranes can achieve perfect separation of the microorganisms [47]. Longer SRT values enable better wastewater treatment and produce less wastage sludge than AS systems. Considering that the costs for further sanitary treatments of the excess sludge have increased and the regulation for sludge disposal is stricter than before, the long SRT operation seems to provide many benefits [1]. Higher SRTs enable MBRs to operate at higher OLR and lower (F/M) ratios; such condition makes MBR process more compact, in comparison to AS [48]. Nevertheless, the complete detention of bacteria in MBR systems leads to longer

SRTs. If sludge isn't wasted from the bioreactor, the SRT of MBR could potentially become infinite. This is impractical in AS because the effluent from the secondary clarifier contains at least several mg/l of TSS due to the limitation of settling tanks within the common retention time 2–4 h [1].

In this research the selected values for SRT were 5, 10, 15, 20, and 25 days respectively. By referring to Fig. 8, it can be generally concluded that removal efficiencies for the TSS were improved as the SRT increased at a given value for the HRT. The highest removal efficiencies for the TSS were obtained at SRTs of 25, 20, 15, 10 and 5 days respectively; with 25 and 20 days were the highest at all experiments. The TSS lowest removal efficiency was reported when operating the system at SRT of 5 days, while the highest TSS removal efficiency took place when operating the system at SRT of 25 days.

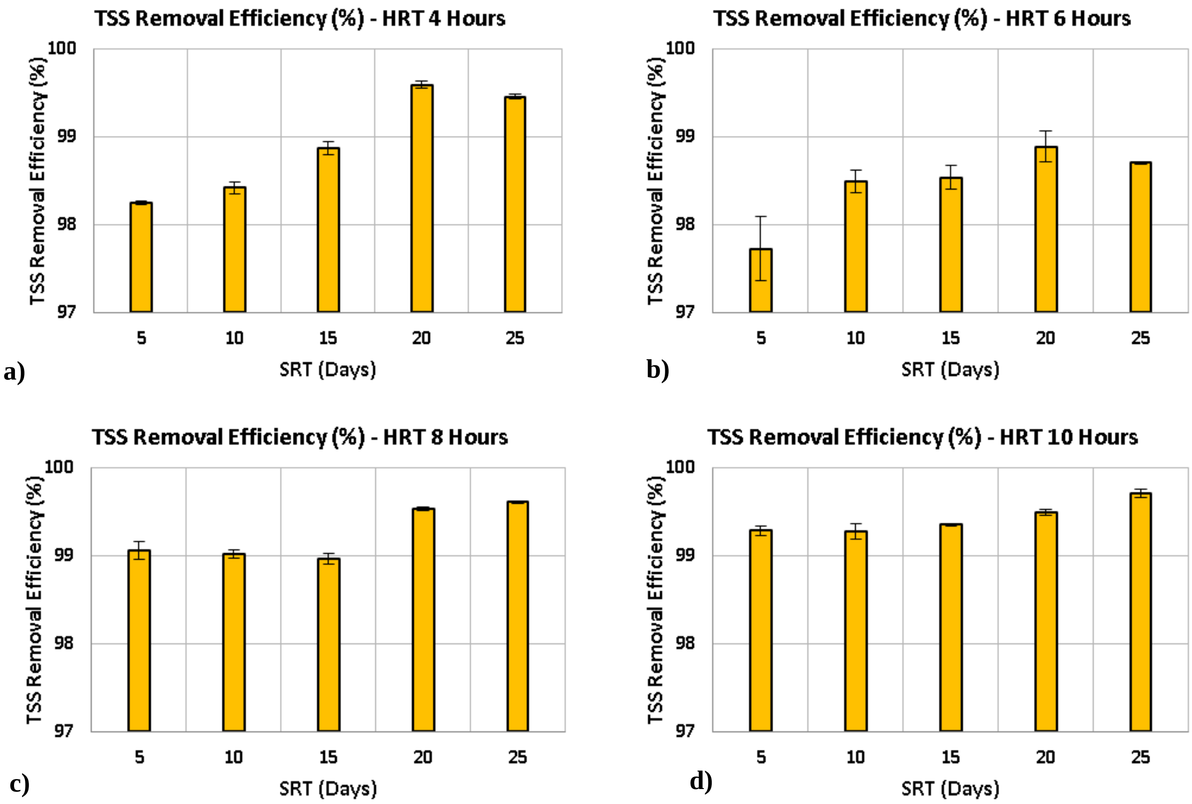

Fig. 8. TSS Removal Efficiency (%) at HRTs of: a) 4 Hrs, b) 6 Hrs, c) 8 Hrs, d) 10 Hrs

For the case of COD removal and by referring to Fig. 9; better COD removals were got as the SRT increased from 5 to 25 d. The highest removal efficiencies for COD were got at HRTs of 10, 8 and 6 hours respectively, while the lowest one was got reported at HRT of 4 hours. The COD highest removal efficiencies took place when operating the MBR at SRTs of 25 and 20d.

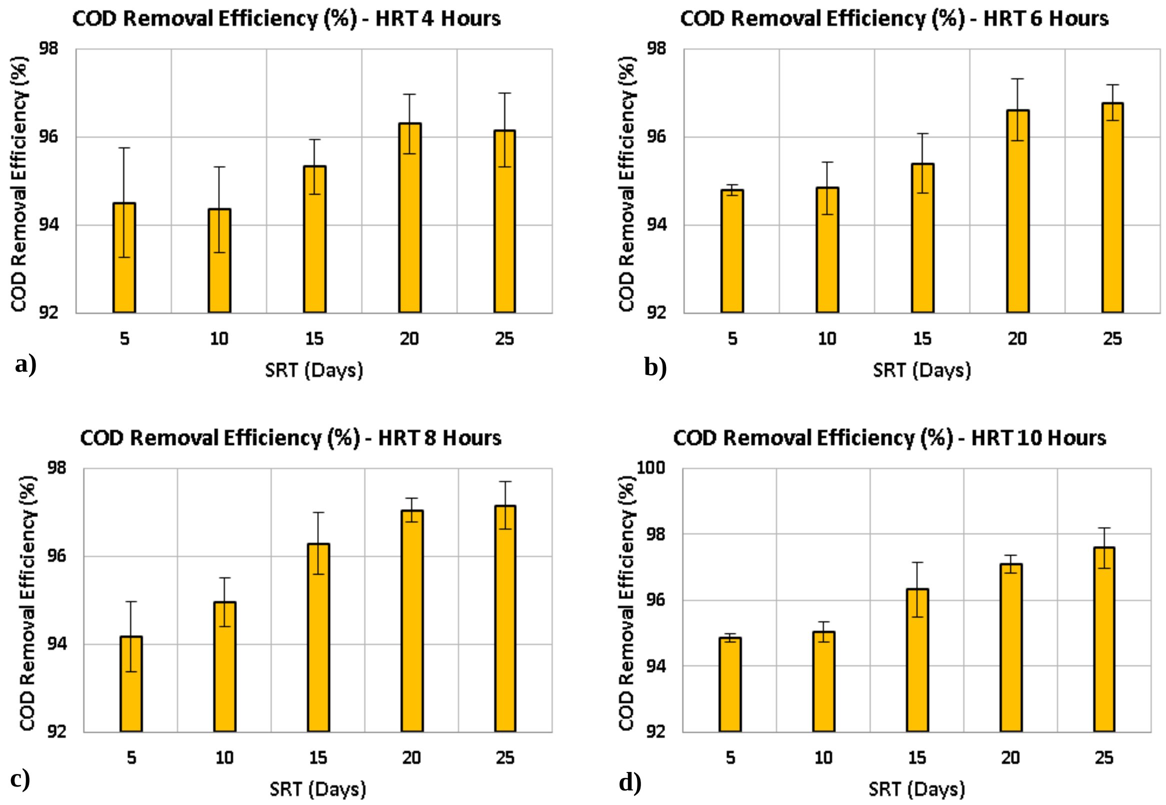

Fig. 9. COD Removal Efficiency (%) at HRTs of: a) 4 Hrs, b) 6 Hrs, c) 8 Hrs, d) 10 Hrs

For the combined effect of both SRT and HRT on removal efficiency for both TSS and COD, it was concluded from Figs. 7 – 10 that the best removal efficiencies for TSS and COD were 99.71% and 97.59% respectively which took place at SRT of 25 d and HRT of 10 hr. The corresponding effluent concentrations for TSS and COD were 0.36 mg/l and 10 mg/l, respectively. The second highest efficiency for TSS and COD were 99.61% and 97.15% respectively which took place at SRT of 25 d and HRT of 8 hrs. The corresponding effluent concentrations for TSS and COD were 0.45 mg/l and 8.3 mg/l, respectively.

3.3. Effect of MLSS on MBR Performance

As mentioned before, MBRs can be operated at MLSS values greater than those of the AS systems. High MLSS-concentration of MBR processes provides benefits by reducing waste sludge production. As the MLSS in the MBR reactor increased, it is expected to have larger populations of microorganisms available for organic matter removal, such microorganisms have the tendency to biodegrade themselves in bioreactor. High MLSS concentrations can also be linked to the increased sludge age or SRT, which provides longer contact time between the bacterial populations and the wastewater, allowing for improved degradation of complex organic compounds. Consequently, achieving high and stable COD removal in MBRs is possible with high MLSS as compared to AS systems [49]. In this current work, MLSS ranged from 5630 to 15460 mg/l, which was expected to result in better COD removal, and the TSS removal efficiency was also investigated.

By referring to Fig. 10, there was no concrete conclusion that the TSS removal efficiency was improved by increasing MLSS concentrations, but it can be noted that better removal efficiencies of TSS could be achieved for MLSS concentrations > 10,000 mg/l. The same conclusion was also applicable for the TSS effluent concentration (better effluent quality at MLSS > 10,000 mg/l), see Fig. 11. This can be related to the built-up of a more porous and cake-like layer on the MBR because of MLSS increase, which improved the filtration and enhanced the TSS removal.

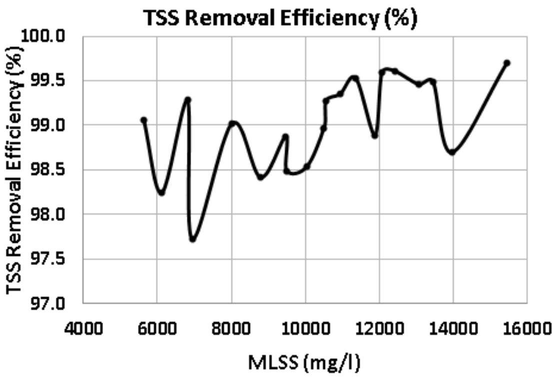

Fig. 10. Effect of MLSS on TSS Removal Efficiency

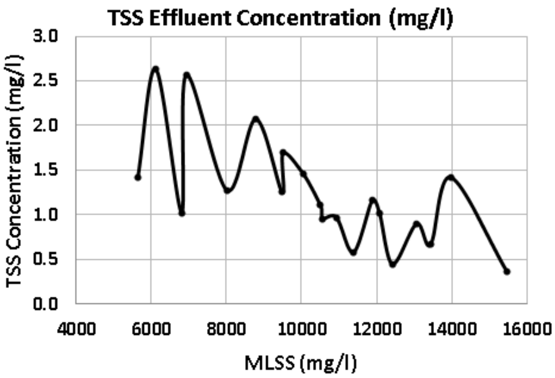

Fig. 11. Effect of MLSS on TSS Effluent

For the case of COD, the relation between MLSS and removal efficiency was more obvious than that of the TSS; this was supported by the results outlined in Fig. 12 and Fig. 12. Fig. 12, showed that the removal efficiency improved as the MLSS increased; the higher removal efficiencies took place at MLSS > 10,900 mg/l. This was also supported by the COD effluent concentrations shown in Fig. 13. This better removal efficiency can be related to the higher biomass concentration associated with high MLSS that can enhance the biodegradation process, leading to better COD removal.

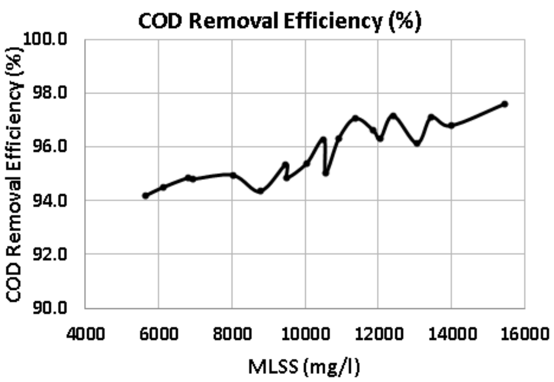

Fig. 12. Effect of MLSS on COD Removal Efficiency

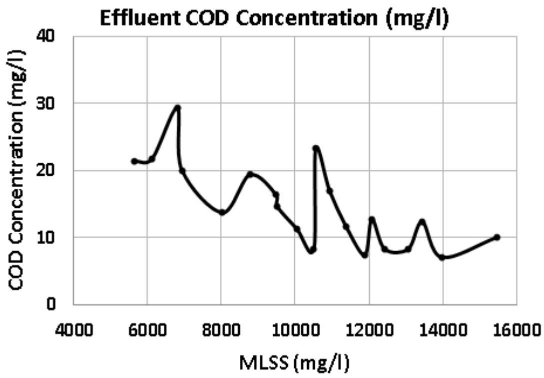

Fig. 13. Effect of MLSS on Effluent COD (mg/l)

Worth mentioning that during all the experimental work, MLVSS concentrations were measured. The values of MLVSS/MLSS ranged from 0.775 to 0.820 with an average of 0.803. This provided information about the composition of the biomass in the MBR. The higher MLVSS/MLSS informed higher proportion of volatile solids in the mixed liquor, implying a larger population of active and biodegrading microorganisms thus more microbial activity and better biodegradation capacity of the MBR.

3.4. MBR Performance for Nitrogen Removal

Although the system was designed for COD removal; ammonia concentrations in both the influent and the effluent were measured at SRT of 25 days for each HRT value. The removal efficiency ranged from 83.33% to 90.54%; the highest removal efficiency (90.54%) took place at HRT of 10 hours and SRT of 25 days while the second highest removal efficiency (85.90%) took place at HRT of 8 hours and SRT of 25 days. Influent and effluent ammonia concentrations at SRT of 25 days and different HRTs were as follows: 68 mg/ and 10 mg/l at HRT of 4 h, 66 mg/l and 11 mg/l at HRT of 6 h, 78 mg/l and 11 mg/l at HRT of 8 h, and 74 mg/l and 7 mg/l at HR of 10 h, respectively. Fig. 14 outlined the removal efficiency of ammonia at SRT of 25 days and different HRTs.

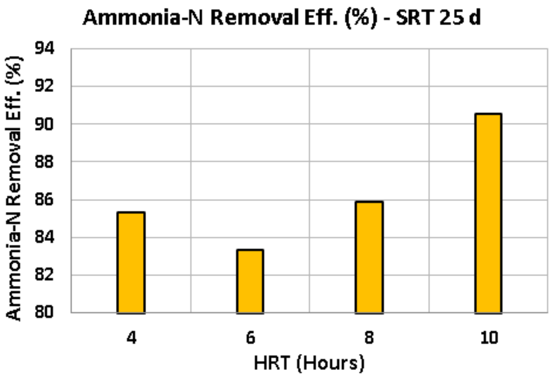

Fig. 14. Ammonia Removal efficiency at SRT of 25 days and different HRTs

3.5. Comparing MBR performance with that of GCWWTP

A comparison between the MBR performance and the GCWWTP in terms of COD and TSS effluent was made. As shown in Fig. 15, the TSS effluent concentration for the MBR ranged from 0.36 mg/l to 2.63 mg/l with an average of 1.25 mg/l, on the other hand the TSS effluent concentration for the GCWWTP ranged from 16 mg/l to 88 mg/l with an average of 43.8 mg/l. By referring to Fig. 16, it can be noticed that the COD effluent concentration for the MBR ranged from 7 mg/l to 29.33 mg/l with an average value of 14.7 mg/l, on the other hand the COD effluent concentration for the GCWWTP ranged from 50 mg/l to 123 mg/l with an average value of 77.2 mg/l. From the previous discussion, it can be generally concluded that the MBR gave more stable effluent concentrations for both the TSS and COD as compared to the GCWWTP.

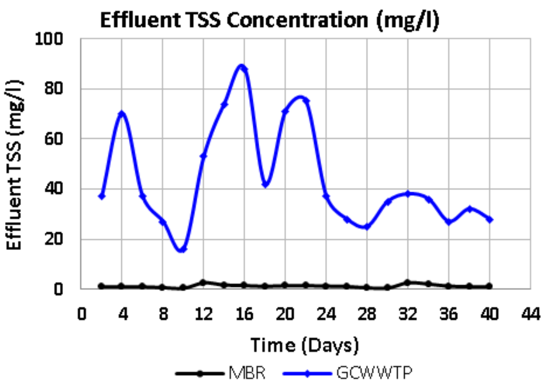

Fig. 15. TSS Effluent Concentration (mg/l)

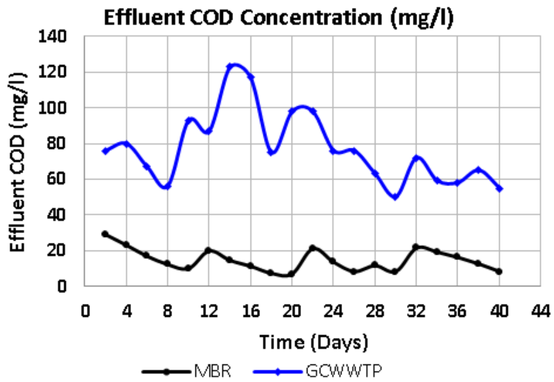

Fig. 16. COD Effluent Concentration (mg/l)

4. Conclusions

The study concluded that the removal efficiency for the TSS was improved at high HRT values as compared with low HRT values for a given SRT. The highest removal efficiencies for the TSS were obtained at HRT of 10 and 8 hours as compared to HRT of 4 and 6 hours. Improvement in COD removal efficiency was noticed as HRT increased from 4 to 10 hours for a given SRT value. The highest removal efficiencies for COD were reported at HRTs of 10, 8 and 6 hours respectively, while the lowest removal efficiency was reported at HRT of 4 hours.

For a certain HRT, the removal efficiency for TSS was improved as SRT increased; the highest values were reported at SRTs of 25, 20, 15, 10 and 5 days respectively; with 25 and 20 days were the highest at all experiments. Additionally, the COD removal was improved as SRT increased from 5 to 25 days, the highest removal efficiencies for COD were reported at HRT of 10, 8 and 6 hours respectively, while the lowest one was got at HRT of 4 hours. The COD highest removal efficiency was achieved at SRT of 25 and 20 days. Additionally, the highest nitrogen removal efficiency took place at HRT of 10 hours and SRT of 25 days while the second highest removal efficiency took place at HRT of 8 hours and SRT of 25 days.

The study also concluded that at MLSS < 10,000 mg/l, there was no concrete relationship between TSS removal efficiency and MLSS concentrations, but better removal efficiencies of TSS could be achieved for higher MLSS concentrations. The relation between MLSS and COD removal efficiency was clearer than that of the TSS; the COD removal was improved as the MLSS increased; the higher removal efficiencies were obtained at MLSS > 10,900 mg/l.

With the TSS removal efficiencies ranging from 97.72% to 99.71%, MBRs proved to be excellent eliminator for TSS. On the other side, the performance of MBRs in removing the COD ranged from 94.17% to 97.59% which is not easy to attain using conventional wastewater treatment systems.

5. Conflicts of interest

The authors declare that there are no conflicts of interest.

6. Formatting of funding sources

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8. References

[1] Park, H.-D., Chang, I.-S., and Lee, K.-J. (2015), Principles of membrane bioreactors for wastewater treatment, CRC Pres, CRC Press, Taylor & Francis Group, Broken Sound Parkway NW, USA.

[2] Jadhao, R.K., and Dawande, S.D. (2012a), A Review on Application of Membrane Bioreactor for Wastewater Treatment, *International Journal of Biotechnology, Chemical and Environmental Engineering*, 1(2), 46-54**.** ISSN 2278 – 0696

[3] Zhidong, L., Yong, Z., Xincheng, X., Lige, Z., and Dandan, Q. (2009), Study on Anaerobic/Aerobic Membrane Bioreactor Treatment for Domestic Wastewater, *Journal of Environmental Studies*, 18 (5), 957–963. ISSN: 1230 – 14

[4] Raharjo, S., Istirokhatun, T., and Susanto, H. (2019), Reuse of Domestic Wastewater by Membrane Technologies Towards Sustainable City Development, Proc. International Conference on Smart City Innovation, IOP Conf. Series: Earth and Environmental Science, West Java, Indonesia, 248, 1-7

[5] Cummings, G., and Frenkel, V.S. (2008), Membranes for Industrial Water Reuse–They're Not just for Municipal Applications Anymore, Proc. of the Water Environment Federation, USA, 77-91**.**

[6] Verstraete, W., Van de Caveye, P., and Diamantis, V. (2009), Maximum use of resources present in domestic "used water". *Bioresource technology*, 100 (23), 5537-5545**.** https://doi.org/10.1016/j.biortech.2009.05.047

[7] Vyrides, I., and Stuckey, D. (2009), Saline sewage treatment using a submerged anaerobic membrane reactor (SAMBR): effects of activated carbon addition and biogas-sparging time, *Water research* 43(4), 933-942**.** https://doi.org/10.1016/j.watres.2008.11.054

[8] Abdel-Kader A. (2007), A review of membrane bioreactor (MBR) technology and their applications in the wastewater treatment systems, Proc. 11th Int. Water Technology Conf. (IWTC11), Sharm El-Sheikh, Egypt,269-278**.**

[9] Coutte, F., Lecouturier, D., Firdaous, L., Kapel, R., Bazinet, L., Cabassud, Corinne, and Dhulster, P. (2017), Recent trends in membrane bioreactors, In: Current Developments in Biotechnology and Bioengineering, Christian L., Maria Á. S., Guocheng D., and Ashok P. Elsevier, Cambridge, United States 279-311

[10] Sánchez, A.S. (2013), "Combining submerged membrane technology with anaerobic and aerobic wastewater treatment", PhD Dissertation, Universidade de Santiago de Compostela, Spain.

[11] Jadhao, R.K., and Dawande, S.D. (2012b), Reverse osmosis and ultrafiltration membrane for hospital wastewater treatment, *International Journal of Chemical Sciences and Applications*, 3 (2), 283-288**.** ISSN 0976-2590, Online ISSN 2278 – 6015

[12] Ferraris, M., Innella, C., and Spagni, A. (2009), Start-up of a pilot-scale membrane bioreactor to treat municipal wastewater, *Desalination* 237 (1-3), 190-200**.** https://doi.org/10.1016/j.desal.2007.12.032

[13] Jain, M. (2018), Anaerobic membrane bioreactor as highly efficient and reliable technology for wastewater treatment—a review, *Advances in Chemical Engineering and Science*, 8 (02), 82 – 100. DOI: 10.4236/aces.2018.82006

[14] Judd, S., and Judd, C. (2011), The MBR Book: Principles and Applications of Membrane Bioreactors for Water and Wastewater Treatment, Elsevier, The Boulevard, Langford Lane, Oxford OX5 1GB, UK.

[15] Judd, S. (2008), The status of membrane bioreactor technology, *Trends in biotechnology* 26 (2), 109-116**.** https://doi.org/10.1016/j.tibtech.2007.11.005

[16] Du, X., Shi, Y., Jegatheesan, V., and Haq, I.U. (2020), A review on the mechanism, impacts and control methods of membrane fouling in MBR system, *Membranes*, 10 (2), 1-33**.** https://doi.org/10.3390/membranes10020024

[17] Shah, V. (2021a), MBR Membrane, Neya Water Solutions, Vinzol, Ahmedabad - 382440, Gujarat, India**.**

[18] Shah, V. (2021b), Simplifying Sewage Treatment and Recycling with Neya MBR, Neya Water Solutions, Vinzol, Ahmedabad - 382440, Gujarat, India**.**

[19] Corwin, B. (2023), WHAT IS A SOLENOID VALVE? Universal Tower Parts, 1921 W. Mountain View Rd, Phoenix, AZ 85021, USA, Accessed Online [2023].

[20] Hollander, B.R. (2023), Technical Principles of Valves, Omega Engineering, Inc. USA, Accessed Online [2023]. https://www.omega.com/en-us/resources/valves-technical-principles**.**

[21] Willem, P., and Willem, J. (2023), Solenoid Valve - How They Work? USA and Worldwide, Accessed

[2023]. https://tameson.com/pages/solenoid-valve-types.

[22] Smith, M. (2023), Arad M Water Meter 15mm EV 1L Pulse c/w Coupling Set, New Zealand, Accessed [2023]. https://shop.waterforce.co.nz/index.php?route=product/product&language=en-gb&path=1297_1440&product_id=4807.

[23] Sparrowhawk, I. (2023), ¾ " BSP Arad Multi Jet Water Meter, UK, Accessed [2023]. https://www.betavalve.com/Product-Detail?prodref=M20.

[24] Tense-Elektronik (2021), ERV-09, Flasher Relay: User Guide, Turkey, Accessed [2023]. https://tense.com.tr/en/products/flasher-relay-erv-09/

[25] Nan, C.H. (2019), JQX-10F Miniature Power Relay, China. Accessed [2023]. https://chintglobal.com/products/jqx-10f-miniature-power-relay-8-972

[26] Tchobanoglous, G., Burton, F.L., Stensel, H.D., and Metcalf and Eddy, (2003), Wastewater engineering: treatment and reuse, McGraw Hill, Dubuque, IA, USA.

[27] Côté, P., Buisson, H., and Praderie, M. (1998), Immersed membranes activated sludge process applied to the treatment of municipal wastewater, *Water Science and Technology*, 38 (4-5), 437-442. https://doi.org/10.1016/S0273-1223(98)00543-5

[28] Wicaksana, F., Fane, A.G., and Chen, V. (2006), Fibre movement induced by bubbling using submerged hollow fibre membranes, *Journal of Membrane Science*, 271(1-2), 186-195. https://doi.org/10.1016/j.memsci.2005.07.024

[29] PCU-PWA (2019), Semi Annual Progress Report, The Rolling Program of Interventions for Additional Supply of Water for Gaza Strip (RPI), Palestinian Water Authority, Gaza.

[30] Dorsch-International (2021), Gaza Central Wastewater Programme, Germany. Accessed Online [2023]. https://www.dorsch.de/en/projects/detail/project/gaza-central-wastewater-programme.

[31] Dorsch-Gruppe (2016), Gaza Central Wastewater Project, Buriej WWTP & Wadi Gaza CPS: Process Description, Gaza, Palestine.

[32] Alqeshawi, M.R. (2019), "Proposed Guidelines for Operation of Gaza Central Wastewater Treatment Plant – Al Buriej", MSc Dissertation, Islamic University of Gaza, Gaza - Palestine.

[33] Shah, V. (2021c), Neya MBR Cleaning in Place (CIP) Process, Neya Water Solutions, Vinzol, Ahmedabad - 382440, Gujarat, India.

[34] Cicek, N. (2003), A review of membrane bioreactors and their potential application in the treatment of agricultural wastewater, *Canadian Biosystems Engineering*, 45, 6-37. Corpus ID: 21694745

[35] Skouteris, G., Hermosilla, D., López, P., Negro, C., and Blanco, Á. (2012), Anaerobic membrane bioreactors for wastewater treatment: A review, *Chemical Engineering Journal*, 198, 138-148. https://doi.org/10.1016/j.cej.2012.05.070

[36] Huang, X., Gui, P. and Qian, Y. (2001), Effect of sludge retention time on microbial behaviour in a submerged membrane bioreactor, *Process Biochemistry*, 36 (10), 1001-1006. https://doi.org/10.1016/S0032-9592(01)00135-2

[37] Lee, W., Kang, S., and Shin, H. (2003), Sludge characteristics and their contribution to microfiltration in submerged membrane bioreactors, *Journal of membrane science*, 216 (1-2), 217-227. https://doi.org/10.1016/S0376-7388(03)00073-5

[38] Wong, K., Xagoraraki, I., Wallace, J., Bickert, W., Srinivasan, S., and Rose, J. (2009), Removal of viruses and indicators by anaerobic membrane bioreactor treating animal waste, *Journal of environmental quality*, 38(4), 1694-1699. DOI: 10.2134/jeq2008.0232

[39] Huang, Z., Ong, S., and Ng, H.J. (2008), Feasibility of submerged anaerobic membrane bioreactor (SAMBR) for treatment of low-strength wastewater, *Water Science and Technology*, 58 (10), 1925-1931. https://doi.org/10.2166/wst.2008.749

[40] Lin, H., Xie, K., Mahendran, B., Bagley, D., Leung, K., Liss, S., and Liao, B. (2009), Sludge properties and their effects on membrane fouling in submerged anaerobic membrane bioreactors (SAnMBRs). *Water Research*, 43(15), 3827-3837. https://doi.org/10.1016/j.watres.2009.05.025

[41] Churchouse, S. (1997), Membrane bioreactors for wastewater treatment—operating experiences with the Kubota submerged membrane activated sludge process, *Membrane Technology,* 83, 5-9.

[42] Ueda, T., Hata, K., and Kikuoka, Y. (1996), Treatment of domestic sewage from rural settlements by a membrane bioreactor. *Water Science and Technology* 34 (9), 189-196. https://doi.org/10.1016/S0273-1223(96)00803-7

[43] Xu, N., Xing, W., Xu, N., and Shi, J. (2002), Application of turbulence promoters in ceramic membrane bioreactor used for municipal wastewater reclamation, *Journal of Membrane Science*, 210(2), 307-313. https://doi.org/10.1016/S0376-7388(02)00406-4

[44] Kocadagistan, E., and Topcu, N. (2007), Treatment investigation of the Erzurum City municipal wastewaters with anaerobic membrane bioreactors, *Desalination*, 216 (1-3), 367-376. https://doi.org/10.1016/j.desal.2006.10.038

[45] Saddoud, A., Hassaïri, I., and Sayadi, S. (2007), Anaerobic membrane reactor with phase separation for the treatment of cheese whey, *Bioresource technology*, 98(11), 2102-2108. https://doi.org/10.1016/j.biortech.2006.08.013

[46] Isma, M.A., Idris, A., Omar, R., and Razreena, A.P. (2014), Effects of SRT and HRT on treatment performance of MBR and membrane fouling, *International Journal of Environmental and Ecological Engineering*, 8, 485-489. Corpus ID: 12039896

[47] Dohare, D., and Trivedi, R. (2014), A review on membrane bioreactors: an emerging technology for industrial wastewater treatment, *International Journal of Emerging Technology Advanced Engineering*, 4 (12), 226-236. Corpus ID: 212554060

[48] Cornel, P. and Krause, S. (2008), Membrane bioreactors for wastewater treatment, In: Advanced membrane technology and applications, Norman N. Li, Anthony G. Fane, W. S. Winston Ho, and Matsuura T. John Wiley & Sons, Inc., Hoboken, New Jersey, 217-238

[49] Han, S.-S., Bae, T.-H., Jang, G.-G., and Tak, T. (2005), Influence of sludge retention time on membrane fouling and bioactivities in membrane bioreactor system, *Process Biochemistry*, 40 (7), 2393-2400. https://doi.org/10.1016/j.procbio.2004.09.017