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RESEARCH PAPER

Biological Efficiency and Control of a Membrane Bioreactor and Conventional Activated Sludge Process for Treating Municipal Wastewater

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الكفائة و التحكم البيولوجي في مفاعل حيوي غشائي و عملية الحمأة المنشطة التقليدية لمعالجة مياه الصرف الصحي البلدية

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ABSTRACT. The performance of a membrane bioreactor (MBR) was compared to a conventional activated sludge (CAS) process and it was aimed to identify the best technological option for a municipal sewage treatment plant (STP). The MBR system was fed by the diluted sewage coming from the main municipal sewer network, which contained an averagely lower concentration of organics, inorganics and biological pollutants. While the CAS system was fed by a concentrated sewage coming from household septic tanks, contained averagely high concentration of organics, inorganics and biological pollutants. CAS showed a higher removal efficiency of biochemical oxygen demand (BOD), chemical oxygen demand (COD), total suspended solids (TSS), volatile suspended solids (VSS), Fat-Oil-Grease (FOG), nitrogen, phosphorous, helminths ova (HO), and pathogenic bacteria compared to the MBR. Nevertheless, the removal efficiencies of nitrogen, HO and pathogenic bacteria in the case of CAS were lower than MBR due to the high concentration of those parameters in the influent fed to CAS. However, both the efficiency and the amount of removal for phosphorous in the case of CAS was quite higher than that of MBR due to extended aeration in CAS. The pathogenic bacteria and HO were removed almost 99.97% by the MBR, whereas the CAS removed 91±5% of the pathogenic bacteria and HO. Therefore, the effluent of the CAS system required additional disinfection for the reduction of pathogens and HO. In terms of biological efficiency and influent flexibility, both the systems can satisfy the national standards. Overall, the data suggested that CAS possessed a higher capacity of treating concentrated sewage for removing all pollutants to satisfactory limits except complete removal of pathogenic bacteria and HO. It was obvious that MBR possessed a membrane barrier to retain the pathogens and HO; therefore, they could be removed up to very low levels. However, further investigation is necessary to verify the MBR performance using the same concentrated sewage as CAS.

KEYWORDS: Membrane bioreactor; Conventional activated sludge; Municipal wastewater treatment; Removal efficiency; Sewage treatment plant; National standards.

المستخلص:تمت مقارنة أداء مفاعل غشائي حيوي (MBR) بعملية الحمأة المنشطة التقليدية (CAS) وذلك لتحديد الخيارالأفضل التكنولوجي لمحطة معالجة مياه محطة صرف الصحي بلدية. تمت تغذية المفاعل الحيوي الغشائي من مياه الصرف الصحي المخفف القادمة من شبكة الصرف الصحي بالمناطق الحضرية الرئيسية، التي تحتوي على معدل تركيز أقل من المواد العضوية، غير العضوية والملوثات البيولوجية. في حين تمت تغذية نظام المنشطة التقليدية من مياه الصرف الصحي المركزة القادمة من خزانات الصرف الصحي المنزلية،و التي تحتوي على متوسط تركيز عالٍ من المواد العضوية وغير العضوية والملوثات البيولوجية. أظهرت نظام الحمأة المنشطة التقليدية على كفاءة إزالة أعلى من الطلب البيوكيميائي الأكسجين (BOD) ، الطلب على الاكسجين الكيميائي (COD) ، إجمالي المواد الصلبة العالقة (TSS) ، المواد الصلبة المعلقة ،(VSS) ، المركبات الدهنية (FOG) ، النيتروجين ، الفوسفور، بويضات الديدان(HO) ، و البكتيريا المسببة للأمراض، مقارنة بالمفاعل الغشائي الحيوي. ومع أن كفاءة إزالة النيتروجين ، بويضات الديدان، والبكتيريا المسببة للأمراض في حالة نظام الحمأة المنشطة التقليدية كان أقل من المفاعل الغشائي الحيوي بسبب التركيز العالي من هذه العوامل في النظام المغذي للحمأة المنشطة التقليدية. ومع ذلك، فإن كلا من كفاءة وكمية إزالة الفوسفور في نظام الحمأة المنشطة التقليدية كان أعلى جدا من ذلك في المفاعل الغشائي الحيوي بسبب التهوية الممتدة في نظام الحمأة المنشطة التقليدية. تمت إزالة البكتيريا المسببة للأمراض و بويضات الديدان بنسبة ٩٩,٩٧٪ تقريبًا بواسطة المفاعل الغشائي الحيوي ، في حين أزالت نظام الحمأة المنشطة التقليدية ٩١ ± ٥٪ من البكتيريا المسببة للأمراض و بويضات الديدان. لذلك ، يتطلب تدفق نظام الحمأة المنشطة التقليدية تطهيرًا إضافيًا لتقليل مسببات الأمراض و بويضات الديدان. من حيث الكفاءة البيولوجية ومؤثر المرونة ، فإن كلا النظامين يمكن أن يلبي المعايير الوطنية. وعموما، تشير البيانات إلى أن نظام الحمأة المنشطة التقليدية يمتلك قدرة أعلى على معالجة مياه الصرف الصحي المركزة لإزالة جميع الملوثات إلى حدود مرضية باستثناء إزالة كاملة للبكتيريا المسببة للأمراض وبويضات الديدان. كان من الواضح أن المفاعل الغشائي الحيوي وضع حاجزًا غشائيًا للاحتفاظ بمسببات الأمراض و بويضات الديدان ؛ وبالتالي، فإنه يمكن إزالتها إلى أدنى المستويات. ومع ذلك، فانه من الضروري إجراء المزيد من البحث للتحقق من أداء المفاعل الغشائي الحيوي باستخدام نفس مياه الصرف الصحي المركزة مثل نظام الحمأة المنشطة التقليدية.

الكلمات المفتاحية: المفاعل الحيوي، نظام الحمأة المنشطة التقليدية، الصرف الصحي، كفائة الازالة، نظام الصرف الصحي، المعايير الوطنية

Introduction

The growing scarcity of water resources in arid regions, like the Sultanate of Oman, has extensively increased the necessity to preserve the current resources for drinking purposes (Oliver et al., 2008; Zanetti et al., 2010). To do so, municipal wastewater plants have been established to treat wastewaters and support the sustainable development of the country (Baawain et al., 2020; 2019a; 2019b; Iglesias et al., 2010; Papa et al., 2016).

Wastewater is often treated by a conventional activated sludge (CAS) process, which includes the steps of biological, physical and chemical treatment. The physical treatment during the CAS process, such as conventional solids settling and sand filtration, cannot remove all the contaminants up to the desired level. Therefore, subsequent chemical or physical treatment steps, such as chlorination and/or UV ray treatment are required. The implementation of such chemical treatments already has identified as risks and threats to the environment and public health as it discharges chemicals and chemicals by-products as effluent into aquatic systems (Chitrakar et al., 2019; Al-Mamun, 2017; Baawain et al., 2017; Zanetti et al., 2010). In order to improve the effluent quality before final disposal, membrane-based technology can be better alternatives for removing tiny solid particles and pathogenic microbes without any usages of eco-threatening chemical treatment steps (chlorination or ozonation) (Jafary et al., 2018; 2020a, 2020b, Al Lawati et al., 2019).

In sewage treatment plants (STPs), a microporous membrane for filtration purposes combined with a biological wastewater treatment known as a membrane bioreactor (MBR) is utilized (Collivignarelli et al., 2017; Melin et al., 2006). Over the last decades, MBR has proven to be a valuable alternative for CAS plants (Van den Broeck et al., 2010). Because, MBR has some major advantages than that of the CAS, including small footprint, superior quality effluents (no chemicals and chemical by-products), and sludge reduction (Drews, 2010; Jeison and Van Lier, 2007; Judd, 2010; Tewari et al., 2010). For example, the MBR processed water from an integrated process in Germany provided a water quality that fully meets the requirements of a washing process (Hoinkis and Panten, 2008). However, the MBR has the drawback of membrane fouling, leading to an increased energy demand due to increased trans-membrane pressure and influenced the removal efficiencies and nitrous oxide emission (Van den Broeck et al., 2012; Mannina et al., 2017). For this reason, an upgraded version of MBR with microbial fuel cell (MFC) for sewage treatment is quite essential for combined removal of organics and nitrogen, and recovery of electrical energy (Ryue et al., 2020; Lefebvre et al., 2008a; 2008b; 2009; 2010; Al-Mamun and Baawain, 2015). However, this up-gradation can be feasible only by exploring the cost-effective materials and appropriate reactor designs with combined MBR-MFC system (Al-Mamun et al., 2016; 2017a; 2017b; Chung et al., 2020).

Recent studies have revealed some insight on comparing CAS to MBR process in a variety of industrial wastewater systems, such as a winery (Valderrama et al., 2012), tannery (Munz et al., 2008), textile factory (Malpei et al., 2003), or municipal sewage (De Luca et al., 2013; Liu et al., 2009; Zanetti et al., 2010). However, the biological efficiency of MBR and CAS processes in the municipal wastewater industries has not been carried out extensively. The review of previous studies revealed that selected polar pollutants in municipal wastewater, the MBR removal efficiency in laboratory studies was significantly greater than that of the CAS, while no improvement has been recorded for other pollutants (Weiss and Reemtsma, 2008). The pilot MBR resulted in higher removal of chemical oxygen demand (COD) (i.e. 93%), suspended solids (>99%) and microorganisms as well as a color abatement. While, the chemical removal efficiency was very variable and it was particularly amongst the different classes of organic contaminants (Gerbersdorf et al., 2015). In other words, the MBR system has demonstrated consistent performance in treating high-strength and fluctuating strength wastewater in pilot scales (Chang et al., 2008).

In recent decades, advanced wastewater treatment technologies, such as MBR, are of particular attention, because of the thorough removal efficiency of the suspended and dissolved chemical and biological components from wastewater (Petrović et al., 2003; Barua et al., 2018; 2019). However, the experimental efforts to compare the removal efficiency of different components in real plants have been lacking. This is due to the fact that it is not feasible to acquire statistical rigorous data from a full-scale treatment plant. Thus, the available comparative studies have normally been limited to only a few pilot-scale cases, which make it extremely problematic to generalize the results on a global scale with any sort of assurance. Therefore, in order to gain an understanding of the removal efficiencies of organics, inorganics and biological pollutants from a full-scale treatment plant, a case study of municipal wastewater treatment comparing the MBR and CAS technologies was carried out. The samples were collected from three different locations, which were influent raw sewage (RS), biological aeration tank and treated effluent. The emphases of this study were to characterize the strength of influent RS, distinguish the concentration load in the biological treatment tank, calculate the removal performance of each parameter, and compare the quality of treated effluents to the ministry of environment and climate affairs (MECA) standards in Muscat, Sultanate of Oman. Furthermore,

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Table 1. Wastewater Characteristics at Al-Ansab STP

Parameter	Units	Minimum	Maximum
Biochemical Oxygen Demand (BOD_5)	mg L^{-1}	350	400
Chemical Oxygen Demand (COD)	mg L^{-1}	600	900
Total Suspended Solids (TSS)	mg L^{-1}	350	500
Volatile Suspended Solids (VSS)	mg L^{-1}	280	400
VSS/TSS Ratio	%	75	85
Total Kjeldahl Nitrogen (TKN)	mg L^{-1}	50	70
Ammonia Nitrogen (NH_3-N)	mg L^{-1}	35	45
Total Phosphorous (TP)	mg L^{-1}	9	15
Total Alkalinity (as $CaCO_3$)	mg L^{-1}	100	200
Oil and Grease	mg L^{-1}	NA	200
pH	[-]	6.0	8.0
Temperature	°C	20	35

the performance of the current CAS and MBR systems were compared with respect to the measured parameters. This study allows a technological recommendation for the optimization of the STPs in the municipal wastewater treatments.

Materials and Methods

Process Description of Old Al-Ansab STP

Old Al-Ansab STP, located in south Muscat (Figure 1), was commissioned in 1990 and then handed to Haya Water in 2006. The old STP was designed to treat annual average flow of 12,000 m^3 day^{-1} with a peak flow of up to 24,000 m^3 day^{-1}. The old STP consists of five main units, including tanker discharge area, pre-treatment facilities, secondary biological treatment, filtration, and chlorination. The plant was designed to treat the wastewater by the CAS process at solids retention time (SRT) of 21 days.

Process Description of the New Al-Ansab STP

The new Al-Ansab STP is an integral part of the Muscat wastewater scheme project (MBR based technology) with a plant average capacity of 55,000 m^3 day^{-1} . The new plant was commissioned in 2010 to serve the Bausher Catchment. The treatment process consisted of six main units, which were preliminary treatment, biological treatment and solids separation, treated effluent storage, sludge dewatering, chemical storage/dosing and odor control system. The MBR process included flat sheet membrane panels (Kubota Submerged Membrane UnitTM, SPC400, Japan) housed in units. The flat sheet membrane was made of chlorinated polyethylene with maximum (nominal) pore size of 0.4 μm (average: 0.2 μm) which blocks most microorganisms in the activated sludge. The submerged membrane panel was aerated by a coarse bubble system underneath each unit, which was necessary to prevent rapid membrane fouling and microbial degradation of the pollutants. The flat plate configuration kept enough space between the membranes so that the debris accumulation was minimum. In-situ chemical cleaning was the only maintenance typically required for such system. The chemical cleaning was done using the standard protocol supplied by the manufacturer (Sánchez, 3013).

Sampling Procedure

The sampling procedure consisted of sampling locations, sample types, sample equipment and sample collection. Influent RS, biological aeration tank and treated effluent locations were selected as the sampling points. To ensure good mixing and minimization of settled solid samples were collected near the center of the flow channel at approximately 40 to 60% of the water depth, where the turbulence was at a maximum level. However, the most desirable locations were not accessible all the time. Sample collection was carried out from January to March 2014 and the reported values demonstrated the average values of different experiments (n = 24) with their standard deviations.

Design Characteristics

Plant Design Condition for RS: Wastewater arrives at the Al-Ansab STP from the sewage pumping stations and by tanker trucks, which are mainly from domestic sources (residential, commercial, and institutional). The combined influent wastewater was analyzed in accordance with the standard methods for the examination of water and wastewater. Table 1 shows the characteristics of the RS. Detailed discussion in this regard has been provided elsewhere (Baawain et al., 2014).

Analytical Methods

A set of analytical methods was implemented to understand the performance of the CAS and the MBR process. Total suspended solids (TSS) and volatile suspended solids (VSS) were determined by applying the standard method (method 2540) and the gravimetric method was carried out using a glass-fiber filter. The measurement and analysis of nitrogen are important because it is the building block in the synthesis of organic matters. Total nitrogen (TN) was calculated from the major form of nitrogen as comprised of organic nitrogen, ammonia, nitrite and nitrate. The following equation shows the determination of TN from its elements (Sawyer et al., 1994).

$$\mathbf{TN = Organic\ N + NH_3\text{-}N + NO_2\text{-}N + NO_3\text{-}N} \quad \text{(Eq. 1)}$$

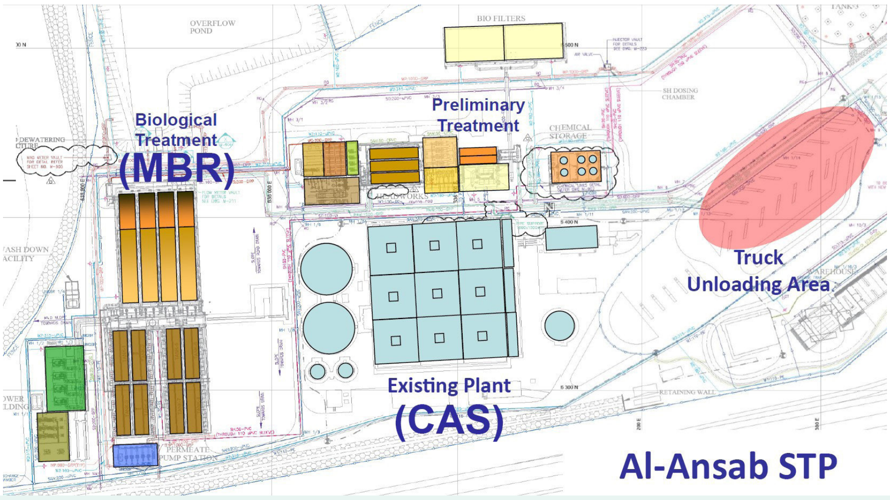

Figure 1. Areal map of Al-Ansab STP showing the location of the treatment units and facilities.

The organic nitrogen and total Kjeldahl Nitrogen (TKN) were determined analytically according to the standard method for examination of water and wastewater (method 4500-N) (Eaton, 1995). TKN is the total amount of organic and ammonia Nitrogen. Depending on the pH of wastewater, ammonia nitrogen exists in aqueous solution as either the ammonium ion (NH_4^+) (dominant at pH<7) or ammonia gas (NH_3). Nitrate and nitrite were measured by using ion chromatography method. Total phosphorus was determined in the wastewater matrix using HACH/LANGE test cuvettes. The intensity of the blue color was measured using a spectrophotometer. The procedure is suitable for the concentration of 0.05 to 20 mg L^{-1} of PO_4^{3-}-P.

The respirometric method covers the determination of biochemical oxygen demand (BOD) of water and wastewater within a 5-day incubation period (BOD_5). The test analysis was based on the standard methods for the examination of water and wastewater (method 5210) (Eaton, 1995). Besides, the COD was determined by the spectrophotometric method (method 5220). The oil and grease were identified by infrared spectroscopy according to the standard method 5520. Determination of fecal coliform (FC) in water and wastewater was carried out by using multiple tube fermentation (method 9221) as explained by Eaton (1995). Helminths ova (HO) were measured by the standard provided here (ASTM, 2004).

Results and Discussion

The performance analysis of CAS and MBR systems was achieved by investigating different biochemical parameters in influents and effluents of the two systems. The results were compared with the MECA standards (A and B), which indicated the national requirements of the final effluent for irrigation applications or sea-disposal.

RS Characteristics

In order to quantify the performance in CAS and MBR systems, the characteristics of RS has in terms of physicochemical and biological parameters of wastewater. Figure 2 showed the average concentration of RS parameters during the study period. The RS influent showed the physicochemical parameters with low or even trace concentration of FOG, nitrogen, phosphorus, and HO compared to the other biological parameters. As shown in Figure 2, the differences between the other sewage parameters (BOD, COD, TSS, and VSS) were significant. This was due to the fact that the MBR was fed by a large quantity of diluted municipal wastewater through domestic sewer network; while, the CAS system was fed with concentrated wastewater from household septic tanks, commercial and light industries through tankers.

The average values of BOD_5 and COD are presented in Figure 2. According to Metcalf and Eddy (2004), the average values of BOD_5 in RS were categorized as high strength for CAS (491.81 mg L^{-1}); whereas, it was classified as a medium-strength concentration (229.44 mg L^{-1}) for MBR. Simultaneously, the average values of COD for the CAS and MBR were 808.42 mg L^{-1} and 607.82 mg L^{-1}, respectively. This might be related to the introduction of some industrial organic pollutants that were received by tankers at CAS. The higher concentrations of degradable COD required a large-volume aeration basin, more oxygen transfer facilities and greater sludge production.

In order to save cost and time, it was also useful to know the relation between BOD_5 and COD in each sampling location. The RS BOD_5/COD ratios for CAS and MBR were measured as 0.61 and 0.38, respectively. These ratios were within the typical range of 0.30 to 0.80 for RS as reported by Metcalf and Eddy (2004). Moreover, the values indicated that the RS was mainly composed of domestic wastewater without any toxic elements. The absence of toxic elements in RS was favour-

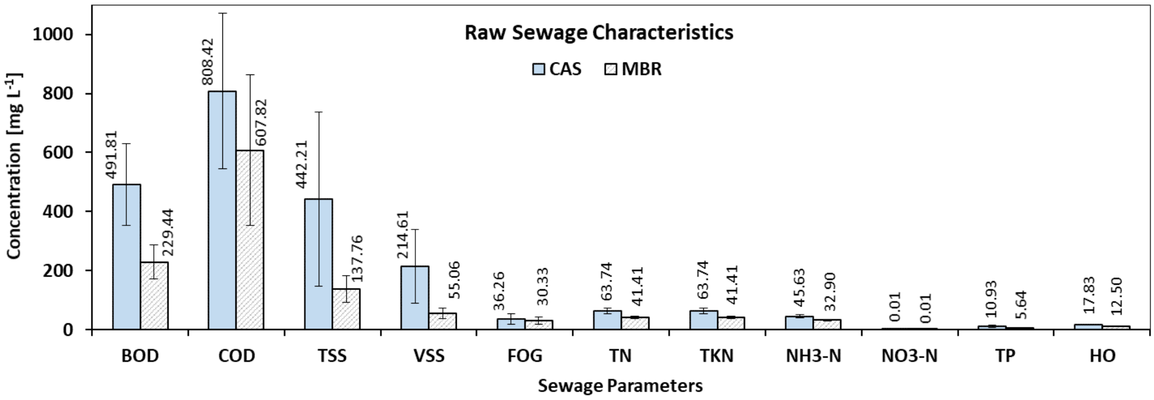

Figure 2. Raw sewage characteristics of the CAS and MBR processes.

able to decompose the organic matters easily. Besides, in the CAS system, BOD concentration in the aeration tank rose slightly by 260 mg L^{-1} compared to those of the MBR. Such increment of BOD in the aeration tank of CAS system was within the limiting value of STP's design criteria, where the moderately concentrate microbial community (mix liquor suspended solid, MLSS) could oxidize the organics load in a longer retention time.

Solids in STPs were analyzed by using gravimetric method. As shown in Figure 2, the average TSS was about 442.21 mg L^{-1} and 137.76 mg L^{-1} for CAS and MBR, respectively. Based on Metcalf and Eddy (2004), RS influent of the CAS and MBR plant could be classified as high strength and medium strength, respectively. Such an amount of TSS could be attributed to the high load of solids received by the tankers. The average VSS concentrations in the RS were 214.61 and 55.06 mg L^{-1} for CAS and MBR plant, respectively. From the obtained values of TSS and VSS, the VSS/TSS ratios in influent were 0.49 and 0.40 for CAS and MBR plants, respectively. The rests were fixed inorganic suspended solids that remained even after ignition at 550 °C.

TN and TP data could be used to evaluate the treatability of wastewater by biological processes. The results in Figure 2 showed that the major parts of the TN compounds were ammoniacal and only small parts were nitrate. It was worth to mention that the ammoniacal nitrogen (NH_3-N) served as substrates of the nitrifying microbes. The CAS plant received a denser concentration of nutrients (N and P) than that of the MBR, which was classified as a high strength influence according to Metcalf and Eddy (2004). The TP fed to the CAS system was approximately double the concentration that fed to the MBR. This might be due to the partial mixing of septic tank sewage with the light industrial wastewater in the case of CAS. The higher concentration of TP was due to the mixing of industrial wastewater as it contained a higher concentration of phosphorus. Overall, the TP concentration in the MBR influent was reasonably low.

Removal Performance

Similar to influent, the physicochemical and biological parameters of the treated effluent from two systems, CAS and MBR, were measured and analyzed. The analytical results of the treated effluent parameters are shown in Figure 3. In order to check the suitability of the treated wastewater for irrigation purposes or discharge to the sea, the compliance of treated water was identified by comparing it with the MECA standards. Figure 3 illustrates that the BOD5 quality of the treated effluent for CAS and MBR were within the acceptable range defined by MECA standards (7.38 mg L^{-1} and 3.28 mg L-1, respectively). For COD, the treated effluents were in compliance with the MECA standards with the values of 36.78 mg L^{-1} and 15.14 mg L^{-1}, respectively; where the MECA standards were defined as 150 mg L^{-1} and 200 mg L^{-1} for the upper and lower limits. In addition, no standard had been reported for VSS by MECA.

The TSS and VSS values for the CAS process were obtained after a sand filter and before chlorination, while in the MBR process, the samples were taken after filtration. In practice, the high percentage of TSS from the CAS process could be due to improper mechanical screening. Moreover, negligible primary sedimentation tank had been installed in both STPs that allowed the heavy solids to settle down. The concentration level of FOG was almost negligible from both systems. The effluent concentrations of nitrogen and TP were found in a reasonable range, except for TKN and NH_3-N. The concentration level of TKN at old STP was about 24.11 mg L^{-1}, which was above the limit of MECA standards (5 and 10 mg L^{-1}, respectively). The concentration of TKN, NH_3-N, and NO_3-N of the MBR were within the standard limits, where the measured values were 0.86, 0.26, and 5.96 mg L^{-1}, accordingly. Furthermore, the concentration limits of TN for both processes were obtained satisfactorily.

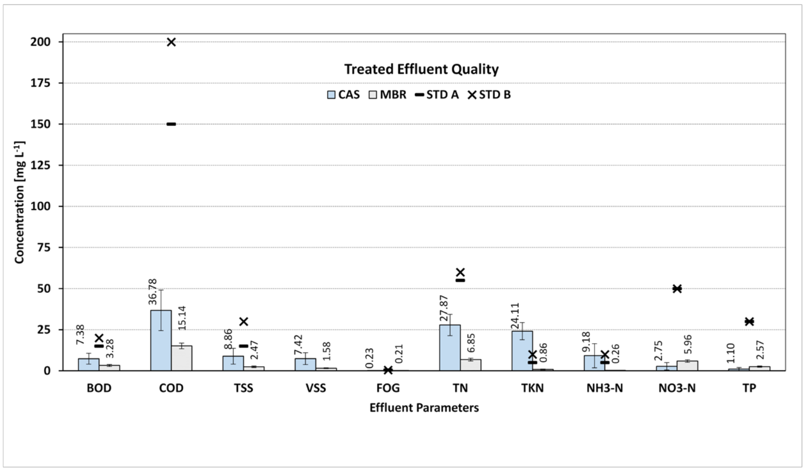

Figure 3. Effluent characteristics of the CAS and MBR processes.

The concentration of NH_3-N slightly exceeded from the standard value, which was the same as TKN. This could be due to an insufficient amount of dissolved oxygen supplied by very old aerators as well as a lack of adequate air diffusers installed at the bottom of the tank.

Removal Efficiency

The physicochemical and biological parameters as discussed in influent and effluent, the removal performances (in removal percentages) of the similar parameters from the two systems are shown in Figure 4. Organics in terms of BOD5 and COD were removed by more than 95% in the MBR as well as the CAS treatment system. Particles in the form of TSS were removed up to 98% in the MBR and 97% in the CAS system. Regarding the VSS, the MBR performed slightly better as up to 96.8% removal compared to 94.7% in the CAS system. FOGs were removed by greater than 99% in both the systems.

Regarding the nitrogen and HO removal, the MBR showed a better performance compared to that of the CAS. The MBR was able to remove up to 99% of NH_3-N and approximately 83% of the TN, whereas the CAS was only able to remove approximately 55% of TN. Besides, TKN and NH_3-N removal in the case of MBR was greater than 98%, while such values for the CAS system were 61% and 80%, respectively. The results of the nitrogen and ammonia removal from the MBR system were similar to the reported studies for municipal wastewater (Côté et al., 1997; Mohammed et al., 2008), where González et al. (2007) found similar results in a poorly performing CAS system in terms of ammonia removal. The remaining nitrogen (organic nitrogen) had a complex structure that made it difficult to degrade. The unacceptable removal efficiency of nitrogen in CAS had a negative impact on the system performance by growing algae inside the facilities. Hence, the MBR system showed a better performance, which could be due to the fact that the old aeration equipment in the CAS system supplied oxygen to nitrifying microbes and this did not meet the demand to achieve full nitrification. However,

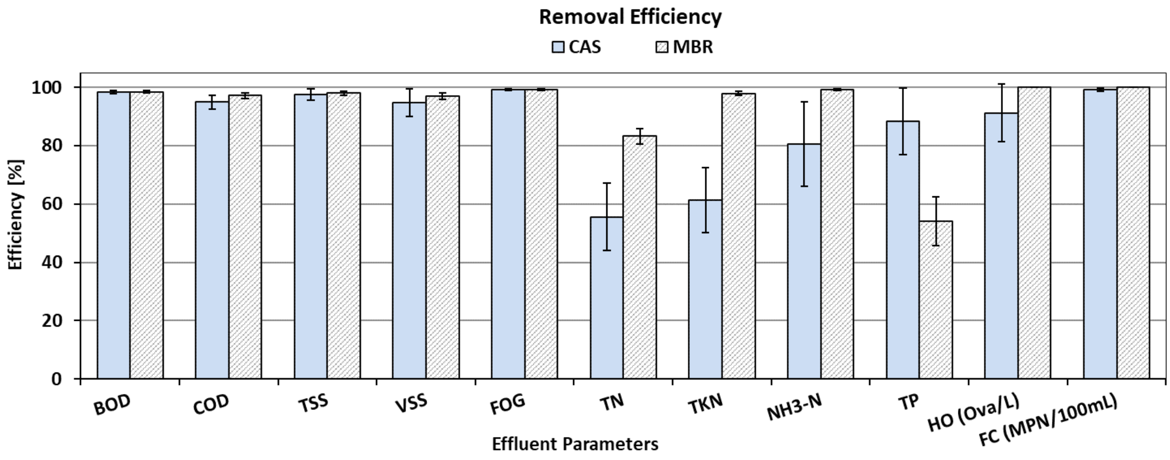

Figure 4. Treatment efficiency of the CAS and MBR processes in percentage (%).

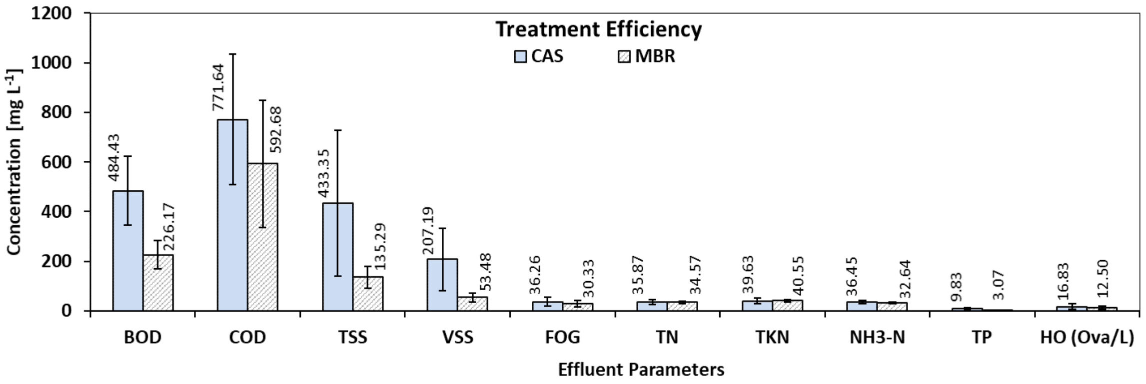

Figure 5. Treatment efficiency of the CAS and MBR processes in amount (mg·L^{-1})

in the MBR system nitrates were formed probably due to incomplete denitrification, which effectively increased the concentration of nitrate. An additional denitrification step would be necessary for complete nitrate removal. In the CAS system less nitrogenous compounds, e.g., ammonia and organic nitrogen, were removed and therefore less nitrates were formed because of relatively poor aeration equipment.

CAS system still showed a better performance in the case of TP removal compared to that of MBR. The TP was removed by 88% in CAS, while 54% in MBR. MBR system showed almost 99.97% removal of HO. This higher removal efficiency of HO in MBR was due to the physical separation of particulate matters by membrane barriers, while the CAS removed only 91±5% of HO through the sedimentation of other biomasses. Pore sizes of the MBR system were small enough to separate solids and microbes from the bulk volume of settling water by almost 100%. The presence of HO in the effluent of CAS could be due to incomplete sedimentation of it in the sand filter. However, the removal performance of biological pollutants using the MBR technology was more reliable than that of membrane filtration, because it removed particles more reliably than a settling basin (De Luca et al., 2013). However, both the values were satisfied by MECA standards. In both cases, the effluent concentration of HO was below the limits set by the national standards, deeming the treated effluent suitable for irrigation applications.

The removal performance of FCs was exceptional in both systems (>99%). This fact was attributed to the smaller pore size of membrane sheets that did not allow the bacteria (greater than 0.04 μm) to permeate. On the other hand, the discharged FCs of CAS was very small compared to that of the inlet Coliform in RS. The resultants bacteria before disinfection by sodium hypochlorite and before discharging to the network were decreased to less than 1000 MPN/100 mL and 200 MPN/100 mL as per standard B and A of MECA. Thus, additional disinfection was required for the reduction of pathogens and HO in the CAS process.

Removal Amount

Figure 5 shows the removal amount instead of removal efficiency. With the current load, CAS showed a higher amount of removal in the case of BOD, COD, TSS, VSS and even FOG. In the case of nitrogen, although the removal amounts were similar, the removal efficiency (Figure 4) was different. This was because of this fact that the influent concentration of nitrogen in the case of CAS was higher than that of MBR. In other words, the CAS system was responsible for treating concentrated wastewater from household septic tanks, commercial and light industries, which was more concentrated than the diluted municipal wastewater through the domestic sewer network to the MBR.

The results in Figure 5 suggested that the CAS system presented superior performance to the MBR in almost all of the investigated criteria, except for nitrogen removal as in this case the CAS system underperformed due to the unsuitable aeration equipment. In order to achieve full comparability of the two treatment process plants, further investigation is necessary to examine if the MBR performs equally under the same conditions as of the CAS.

Conclusion

This study investigated the biological and physical removal performances of two existing municipal wastewater treatment systems as CAS and MBR in Muscat, Sultanate of Oman. Diluted sewage from the municipal network was being treated in MBR, whereas the concentrated wastewater from household septic tanks and light industries was being treated in CAS. On average, both the systems performed more than 95% removal of BOD, COD, TSS, VSS, and FOG up to the national standards of the country. This leads to the conclusion that both systems showed stable and robust performance (removal percentage) with varying influent qualities. Specifically, the removal of nitrogenous compounds by MBR was quite superior (34% higher) to that by the CAS system. While the amount of phosphorus removal by CAS was quite higher than that of MBR due to extended aeration in CAS. For HO and pathogenic microbes, the MBR system was to be preferred due to its almost complete solid retention by the membrane, which eliminated the necessity of subsequent disinfection process as compared to CAS. However, the removal amounts (mg L^{-1}) for all the biological parameters by CAS were quite higher than that by the MBR indicated that the CAS system possessed the handling capabilities of concentrated sewage. Therefore, further investigation is needed to ensure whether the MBR is flexible enough to achieve similar removal capabilities as the CAS has for concentrated sewage under similar operating conditions.

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