**Effect of permeate flux in a membrane SBR (MSBR) treating the liquid fraction of manure**

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**Abstract**
In this study, a lab-scale membrane sequencing batch reactor (MSBR) was applied for the treatment of synthetic wastewater simulating the liquid fraction of manure. The system performance was tested at 3 different hydraulic retention times (HRTs: 12.8h, 10.4h and 9.2h) to examine nutrients and organic matter removal. A submerged flat-type ultrafiltration membrane unit was applied as a policing step in order to improve the SBR's effluent characteristics. The membrane module operated at 16, 20 and 25 L/m$^2$·h flux during the three examined periods. The efficiency of the MSBR for organic content removal was demonstrated with a chemical oxygen demand (COD) effluent concentration ranging from 77 to 204 mg/L that is below the Turkish limits for discharge to the environment. Additionally, the integrated system effectively removed $NH_4$-N achieving 99.8% nitrification and more than 86% denitrification at an HRT=12.8 h with less than 1 mg/L $NH_4$-N concentration in the effluent. The decrease of the HRT in periods 2 and 3 reduced the $NH_4$-N removal efficiency to 93% and 81% and the denitrification performance to 74% and 56%, respectively. However, the $NH_4$-N effluent concentration was within the limits for discharge set by the Turkish legislation. The phosphates ($PO_4$-P) efficiency was 80%, 60% and 39% for periods 1, 2 and 3, respectively. The membranes enhanced nutrients and COD removal; the impact was higher in the case of phosphates with 10% of $PO_4$-P being removed in the membrane chamber in period 1.

**Keywords**
Membrane sequencing batch reactor; hydraulic retention time; flux; liquid fraction of manure; organic content; nutrients

| **Nomenclature** | |
|---|---|
| BOD | Biological Oxygen Demand |
| COD | Chemical Oxygen Demand |
| DO | Dissolved Oxygen |
| F/M | Food to Microorganisms ratio |
| HRT | Hydraulic Retention Time |

| | |
|---|---|
| MBR | Membrane Bioreactor |
| MLSS | Mixed Liquor Suspended Solids |
| MLVSS | Mixed Liquor Volatile Suspended Solids |
| MSBR | Membrane Sequencing Batch Reactor |
| N | Nitrogen |
| P | Phosphorus |
| PLC | Programmable Logic Controller |
| SBR | Sequencing Batch Reactor |
| sNLR | soluble Nitrogen Loading Rate |
| SRT | Sludge Retention Time |
| TKN | Total Kjeldahl Nitrogen |
| TN | Total Nitrogen |
| TSS | Total Suspended Solids |
| WWTP | Wastewater Treatment Plant |

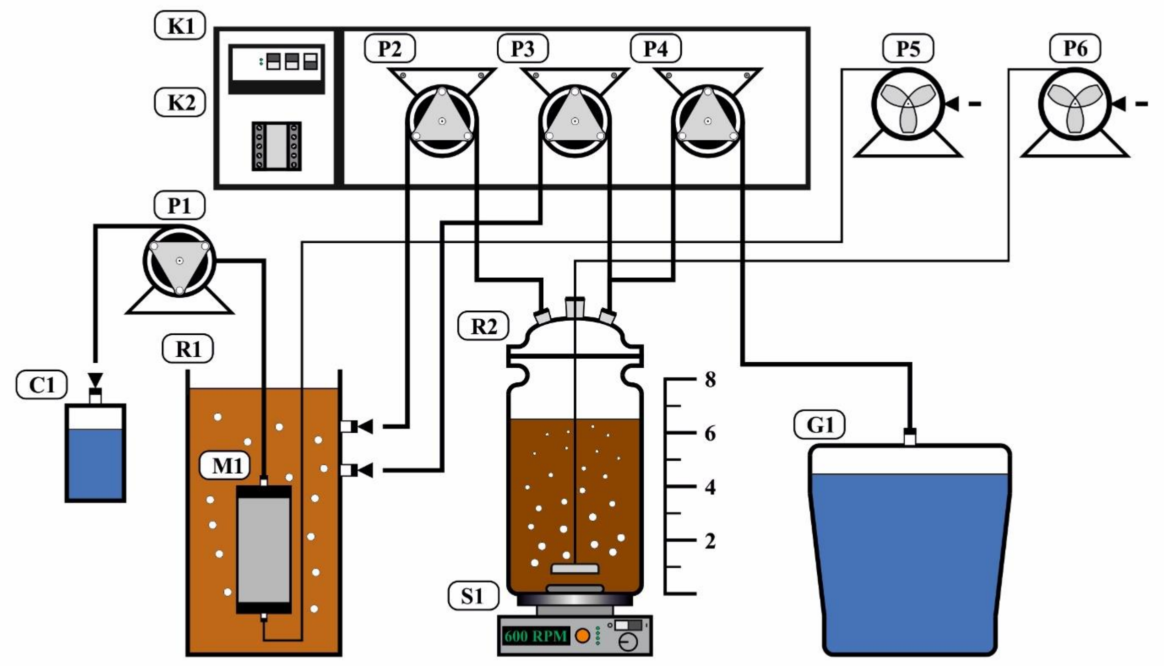
## INTRODUCTION

In the domain of wastewater treatment, the need to produce effluents able to meet strict discharge criteria under a reasonable overall carbon footprint led to the implementation of Membrane Bioreactors (MBRs) for various wastewater streams (industrial, municipal, domestic) (Visvanathan et al., 2000; Yoon, 2003; Yang et al., 2006; Komesli et al., 2007). Compared to conventional activated sludge systems (e.g. sequencing batch reactors (SBRs)), MBRs achieve higher effluent quality with less sludge production (Zhao et al., 2009; Ittisupornrat et al., 2015). On the other hand, the main MBR drawbacks are related to energy requirements and membrane cleaning/replacement costs due to fouling (Bae et al., 2003). The combination of membrane technology and SBRs had as a result the development of membrane SBRs (MSBRs). The membrane addition requires no settling and results in higher biomass concentration. Thus, both shorter operational times and higher mixed liquor suspended solids (MLSS) concentrations can be achieved. Even though the MSBRs were engineered in order to attain higher efficiencies than the MBR and SBR technologies, the final MSBR performance relies massively on the choice of various operational parameters (Krampe and Krauth, 2000; Kang et al., 2003). For instance, high dissolved oxygen (DO) was reported to slow down the rise in the transmembrane pressure and, subsequently, the fouling in a MSBR system (Kang et al., 2003). The amount of excess sludge wasting has been also suggested as a factor potentially limiting the nutrients removal in a MSBR (Bae et al., 2003). Moreover, the abrupt changes in the hydraulic retention time (HRT) have been investigated as a parameter affecting the microbial communities performing nutrients removal and, thus, the overall reactor performance (Boonnorat et al., 2016; Win et al., 2016; Zhang et al., 2016). It is essential to test different HRTs and, then, conclude on the one providing the optimal system operation. Hence, the main purpose of the work was to examine the performance of a MSBR system treating synthetic wastewater that simulated the liquid fraction of manure produced in Turkish farms under different decreasing HRTs (12.8 h, 10.4 h and 9.2 h) and, finally, compare the impact on the COD and nutrient removal.

## MATERIALS AND METHODS

### MSBR system

The configuration of the integrated SBR-membrane assisted system is given in Figure 1. The volume of the lab-scale SBR (R2) was 5L with 4L effective capacity. The reactor (made of glass) was inoculated with 3L of activated sludge, which was collected from the full-scale MBR plant in Middle East Technical University (Ankara, Turkey) treating municipal wastewater. Activated sludge was taken from the aeration tank of the MBR plant that operated at an MLSS concentration of 3500 mg/L and Sludge Retention Time (SRT) of 25 days. During the start-up operation that lasted 45 days, sludge was not removed from the SBR. Once the process was stabilized at a MLSS concentration of 8000-8500 mg/L, the main operation initiated. The system operated for 92 days, while the main operation period was divided into phases with different HRTs (i.e. 12.8 h, 10.4 h, 9.2 h) and, thus, different cycle durations (i.e. 495 min, 390 min and 345 min). A peristaltic pump (P4) was used to feed wastewater to the SBR with a rate of 71.4 mL/min from the 20L storage tank (G1). Then the membranes (M1) were fed with SBR effluent through the SBR permeate pump (P2) and a vacuum pump (P1) was used for the filtration.




| | | | |
|---|---|---|---|
| **P1** | Vacuum Pump | **G1** | Storage Tank |
| **P2** | Permeate Pump of SBR | **C1** | Permeate Tank |
| **P3** | Recirculation Pump | **R1** | MBR Tank |
| **P4** | Influent Pump | **R2** | SBR Tank |
| **P5** | Blower for membrane | **M1** | Membrane |
| **P6** | Blower for SBR | **S1** | Magnetic Stirrer |
| **K1** | PLC | **K2** | Conductor |

**Figure 1.** Schematic diagram of MSBR applied for the treatment of synthetic wastewater simulating the liquid fraction of manure.

**Operating characteristics of SBR-Submerged membrane system**

Table 1 summarizes the main operating parameters of the SBR for each period of operation. The system was controlled by a Programmable Logic Controller (PLC), while the DO and pH were measured manually using a Hach Lange HQ40D oxygen meter and pH meter. The SBR operated at ambient temperature (22±3 °C) and each period lasted approximately 30 days. The MLSS concentration in the SBR reactor was 8000-8600 mg/L during period 1 and it increased slightly during periods 2 and 3. The HRT decreased from 12.8 to 9.2 h, increasing the soluble Nitrogen Loading Rate (sNLR) from 0.29 to 0.34 kgN/kgVSS·d and Food to Microorganisms ratio (F/M) from 1.71 to 2.10 kgCOD/kgVSS·d in order to examine the system performance for the removal of COD, $NH_4$-N and $PO_4$-P.

**Table 1.** Operating conditions of the SBR (average value ± standard deviation)

| Parameter | SBR | | |
|---|---|---|---|
| | Period 1 | Period 2 | Period 3 |
| SRT (h) | No wasting | No wasting | No wasting |
| HRT (h) | 12.8 | 10.4 | 9.2 |
| sNLR (kgN·(kgVSS·d)$^{-1}$) | 0.29-0.32 | 0.32-0.34 | 0.32-0.34 |
| MLSS (g/L) | 8.0-8.6 | 8.5-8.9 | 8.7-9.2 |
| MLVSS (g/L) | 5.4-6.1 | 6.1-6.5 | 6.2-6.8 |
| F/M (kgCOD/(kgVSS·d)) | 1.71-2.02 | 1.78-2.12 | 1.90-2.10 |
| Applied carbon source | $CH_3COONa$ | $CH_3COONa$ | $CH_3COONa$ |
| Cycle time (h) | 7h 45min | 6h 30min | 5h 45min |
| DO (mg/L) | 4 (aerobic) | 3 (aerobic) | 2.5 (aerobic) |
| Temperature (°C) | 22±3 | 22±3 | 22±3 |
| pH | 7-8 | 7-8 | 7-8 |

Table 2 summarizes the operation mode (cycle) applied in the SBR. The total time of each cycle in periods 1, 2, and 3 was 460 min, 390 min and 365 min respectively. A membrane module was applied as a post-treatment stage to further reduce the level of pollutants from the SBR effluent; the membrane unit was operated at different fluxes (16, 20 and 24 L/m$^2$·h). The configuration of the integrated system is given in Figure 1. The membrane chamber (8L) was equipped with a Poliethersulfone (PES) flat sheet membrane in plate and frame module with a pore size of 0.038 μm. The total area of each unit was 0.032 m2). In each period, the membrane module was cleaned using 500 mg/L hypochlorite. The MLSS concentration in the membrane tank was 7000 mg/L at the beginning of each cycle and 12000 mg/L at the end of the cycle. Three different rates were applied in the membrane unit by using a vacuum pump; 16 L/m$^2$·h, 20 L/m$^2$·h, 24 L L/m$^2$·h for periods 1,2 and 3 respectively (Table 3).

**Table 2.** SBR operation cycle

| | **Period 1** (min) | **Period 2** (min) | **Period 3** (min) |
|---|---|---|---|
| Filling | 35 | 35 | 35 |
| Anaerobic | 105 | 60 | 45 |
| Aerobic | 210 | 180 | 150 |
| Anoxic | 55 | 55 | 55 |
| Setling | 20 | 20 | 30 |
| Withdraw | 35 | 35 | 35 |
| Idle | 5 | 5 | 5 |
| Cycle time | 465 | 390 | 345 |
| Flux (L/m$^2$·h) | 16 | 20 | 24 |

**Wastewater characteristics**

Table 4 shows the composition of the synthetic wastewater used in the experiments. We simulated the liquid fraction of pre-treated manure wastewater.

**Table 3.** Composition of synthetic wastewater treated through the MSBR system

| **Wastewater composition** | | **Trace elements mixture** | |
|---|---|---|---|
| Compound | Concentration (mg/L) | Compound | Concentration (mg/L) |
| $CH_3COONa.3H_2O$ | 42.86 | $FeCl.6H_2O$ | 0.15 |

| | | | |
|---|---|---|---|
| $NH_4Cl$ | 31.16 | $H_3BO_3$ | 0.15 |
| $KH_2PO_4$ | 3.30 | $CuSO_4.5H_2O$ | 0.03 |
| $NaHCO_3$ | 8.30 | KI | 0.03 |
| COD (mg/L) | 960-1200 | $ZuSO_4.7H_2O$ | 0.12 |
| $NH_4$-N (mgN/L) | 160-200 | $CoCl_2.6H_2O$ | 0.15 |
| $PO_4$-P (mgP/L) | 60 | $MnCl_2.4H_2O$ | 0.12 |

**Sampling and analytical methods**

Samples were collected 3 times/week from the SBR and the membrane effluent. They were characterized for their COD, $NH_4$-N, $NO_3$-N and $PO_4$-P content. Physicochemical characterization of the SBR effluent, the treated effluent from the SBR–membrane separation and of the activated sludge was carried out. The concentrations of the MLSS, Mixed Liquor Volatile Suspended Solids (MLVSS), Total Suspended Solids (TSS), COD and $NH_4$-N were determined according to standard methods of analysis (ALPHA, 1998). More specifically, the TSS were determined according to 2540B Standard Method and the COD analysis was carried out according to 5220C Standard Methods. The samples were filtered through Whatman membranes (0.45 μm) and the filtrate was measured photometrically for its $NH_4$-N, $NO_3$-N and $PO_4$-P content using a Merck Phoro 300 spectrometer. $NH_4$-N, $NO_3$-N and $PO_4$-P analysis was performed by Merck kits ($NH_4$-N with no: 14752; $NO_3$-N with no: 09713 and $PO_4$-P with no: 14842).

## RESULTS AND DISCUSSION

**SBR-membrane system performance**

The COD concentration in the influent of the MSBR system was ranging from 960 to 1200 mg/L during the three periods of operation (Figure 2). A decrease in the HRT from 12.8 h to 10.4 h during the second period, increased the flux in the membrane chamber by 25% (from 16 $L/m^2 \cdot h$ to 20 $L/m^2 \cdot h$) and decreased the efficiency of the system in terms of COD removal by 5.0%. In the third operating period, a further decrease of the HRT to 9.2 h was accompanied by a 50% increase of membrane flux; thus resulting in 10% reduction of the system COD removal efficiency. As shown in Figure 2, in period 1 the average concentration of the COD in the SBR and the membrane effluent was 100 mg/L and 77 mg/L, respectively. In the second period, the HRT decreased at 10.4h, resulting in an increase of the membrane flux at 20 $L/m^2 \cdot h$. The efficiency of the system in terms of organic content removal remained almost constant (around 85%) for approximately 30 days. The COD level in the SBR effluent was 150mg/L, while the membrane reduced the COD concentration to 123 mg/L due to further biodegradation of the organic content. During the third period of operation, the COD concentration was 227 mg/L and 204 mg/L in the SBR and membrane effluent, respectively, with a total removal efficiency of ~82%. Thus, the reduction of the HRT from 12.8 to 9.2 h resulted in the increase of the COD level in the effluent. Similar results were obtained in other research studies that examined the effect of HRT in the performance of the similar processes. Wang et al. (2013) operated a lab-scale external-submerged anaerobic MBR for the treatment of bamboo industry wastewater with a HRT ranging from 2 to 10 d; the COD removal was 80% (HRT =2d) - 93% (at HRT=10d). Chu et al. (2005) applied an expanded granular sludge bed lab reactor combined with hollow fibre membrane filtration for domestic wastewater treatment. At a certain temperature (i.e. 11°C), the authors observed that the increase of HRT from 3.5 to 5.7 h led to a higher COD removal; it increased from 76 to 81%. Moreover, Ng et al. (2016) investigated the COD removal operating a lab-scale MBR treating high-salinity pharmaceutical wastewater. The COD removal was 68% at an HRT=60 h and slightly lower (61%) for a decreased HRT (40 h).

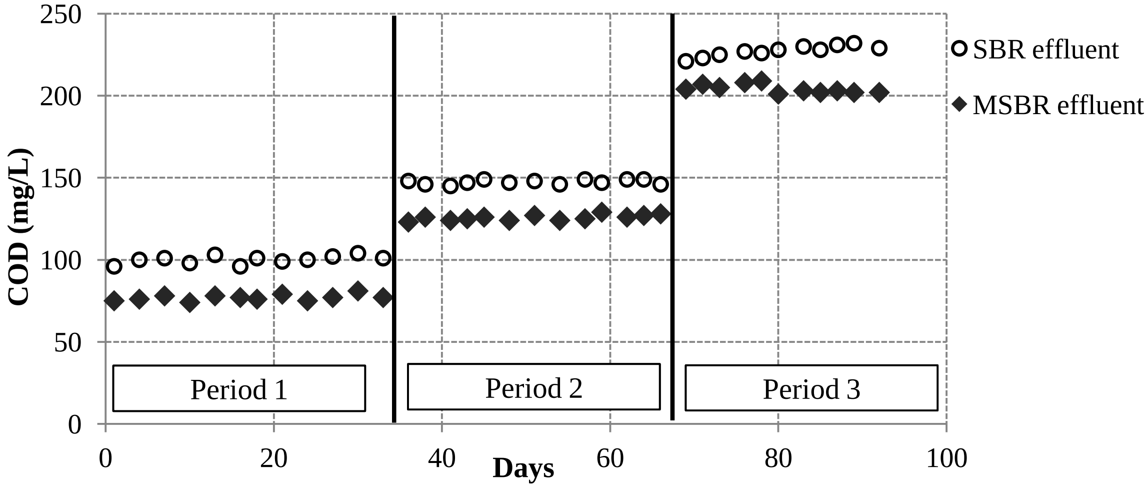



**Figure 2.** COD concentration in the SBR and MSBR effluent during the 3 periods of operation of the MSBR system

The average concentration of $NH_4$-N in the system influent was 190 mg/L for all the examined periods. As shown in Figure 3, in period 1, 99.8% of $NH_4$-N was oxidized to $NO_3$-N with an effluent concentration ranging from 0.60 to 0.95 mg/L. The denitrification efficiency was more than 90% with a $NO_3$-N concentration in the SBR effluent equal to 16-17 mg/L. However, the $NO_3$-N concentration of the MSBR effluent was approximately 25 mg/L. The latter can be explained by the decomposition of activated sludge in the membrane chamber. Therefore, $NO_3$-N was released to wastewater. During the second operating period, the $NH_4$-N concentration in the SBR effluent was ranging between 14 and 19 mg/L; the nitrification efficiency was more than 90%. Nitrification also occurred in the membrane unit, resulting in the reduction of the average $NH_4$-N concentration to 13.5 mg/L in the treated effluent. The $NO_3$-N concentration in the SBR effluent was 17 mg/L; thus, nitrification was complete. Finally, in period 3, the $NH_4$-N permeate concentration was 41-48 mg/L (81% removal efficiency); the latter is attributed to the nitrification, which occurred in the membrane unit. The denitrification efficiency in the SBR was 85% with a final $NO_3$-N effluent concentration of 51 mg/L. Thus, the decrease of the HRT from 12.8 h (Period 1) to 10.4 h (Period 2) resulted in the decrease of the N-removal from the combined system by 7%. Additional reduction of the HRT to 9.2 h increased the N-concentration in the treated effluent by 19%. Scheumann and Kraume (2009) applied a similar system (pilot-scale submerged membrane SBR) for the treatment of synthetic greywater under 3 different HRTs: 33, 24 and 12 h. It was found that the lower HRT (i.e. 12 h) was the optimal for the biomass growth and in favour of the nitrification-denitrification process. The latter was confirmed by the total nitrogen (TN) removal: ~73% (HRT=33 h), ~75% (HRT=24 h) and ~80% (HRT=12 h). Song et al. (2010) explored the effect of a decreasing HRT in total nitrogen (TN) removal operating a pilot-scale sequencing anoxic/anaerobic membrane bioreactor for municipal wastewater treatment. By decreasing the HRT from 13 h to 9.4 h the TN-removal gradually increased from 53% to 73% as a result of the enhanced denitrifying bacteria activity due to a higher F/M. A further decrease in the HRT from 9.4 h to 6.5 resulted in a decrease of the TN-removal (65%). Low HRTs along with a low SRT reduced the nitrifying bacteria concentration and, thus, led to incomplete nitrification. Low HRTs are tested with the view to reducing the overall cost. However, HRT decrease is desirable only if it does not compromise on nitrification-denitrification.

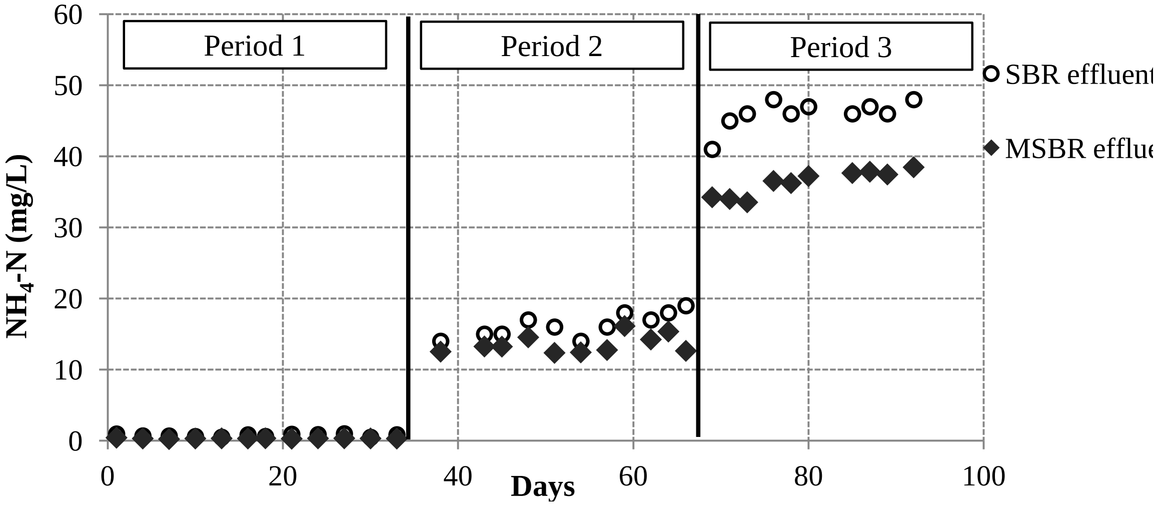



**Figure 3.** $NH_4$-N concentration in the SBR and MSBR effluent during the 3 periods of operation

The MSBR influent $PO_4$-P concentration was 60 mg/L on average (57 to 64 mg/L; Figure 3). During period 1, 80% of the initial $PO_4$-P was removed; the removal efficiency was further increased by 10% by applying the membrane post-treatment. In period 2, the reduction of the HRT at 10.4 h resulted in 53-56% $PO_4$-P removal efficiency, which increased up to 60% in the membrane chamber. Further reduction of the HRT in the last operating period (HRT=9.2 h) led to an increase of the $PO_4$-P concentration to 58-64 mg/L and ~41 mg/L in the SBR effluent and membrane permeate, respectively.

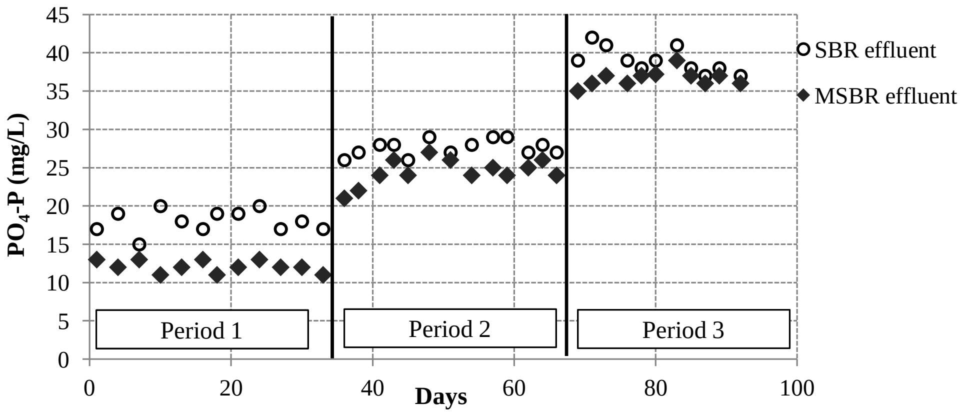



**Figure 4.** $PO_4$-P concentration in the SBR and MSBR effluent during the 3 periods of operation

**Feasibility of the MSBR system for the treatment of the liquid fraction of manure**

Animal production plays a significant role in the Turkish economy with more than 693,000 cattle and 682,000 ovine produced per annum (Farm Journal, 2012). In Erzurum (Turkey; case study area) specifically, there are more than 24,000 medium and large farms. In the current work, the applicability of a MSBR system was investigated for the treatment of the liquid fraction of dairy manure. The system performance was tested in terms of COD, $NH_4$-N and $PO_4$-P removal in order to examine whether the final effluent meets the discharge limits according to the Turkish Water Pollution and Control Regulation (Table 5; SKKY, 2004). Synthetic wastewater was used for the simulation of the liquid fraction of manure. The investment cost for the application of 1 $m^2$ of membrane is approximately 75-80€ and the treatment cost per $m^3$ of wastewater is around 0.5€

considering the membrane replacement. The MSBR investment cost increases up to 700-1,000€ per $m^2$ of membrane when supplementary equipment (e.g. tanks, pumps, aeration units) is included. Given that the cost for manure discharge in WWTPs in Erzurum (Turkey) is approximately 3.5€ per $m^3$ of liquid manure, the proposed MSBR system reduces waste management costs by 85.7%. The HRT effect on the system's performance was evaluated. The results of the study will facilitate the transferability of the proposed system in other similar cases in Turkey where numerous farms producing liquid fraction of manure exist.

The COD concentration in the influent was 960-1100 mg/L. The COD removal was steadily higher than 92.0% (Figure 2) at an HRT of 12.8 (Period 1). The application of the membrane as a post-treatment stage increased the COD removal by 20.0% compared to the SBR effluent. Even when the HRT was reduced at 9.2 h during the third operating period, the COD removal remained higher than 82% and the treated effluent satisfied the limits for discharge (204 mg/L with 500 mg/L limit). Table 5 compares the effluent characteristics with national limits for discharge. The MSBR met the limits in terms of COD for all the three periods of operation. Moreover, the $NH_4$-N concentration was less than 1 mg/L in the MSBR effluent during the first period. This indicated that the total $NH_4$-N (i.e. 190 mg/L in the influent) was oxidized to $NO_3$-N. The $NO_3$-N concentration in the SBR effluent was 16 mg/L; thus, 90% of the total ammonium nitrogen was removed by the application of the SBR. During the second period (HRT 10.4 h), the $NH_4$-N and $NO_3$-N concentration in the MSBR effluent was 13.5 mg/L and 40 mg/L, respectively. The $NH_4$-N concentration in the MSBR effluent increased by 20% with the reduction of the HRT to 9.2 h (period 3). The operation of the SBR at an HRT of 12.8 or 10.4 h and flux 16 or 20 $L/m^2 \cdot h$ (Periods 1 and 2) achieved a final $NH_4$-N concentration in the treated MSBR effluent lower than Turkish limits for discharge to the environment (SKKY, Table 5.15, 2004). The influent $PO_4$-P concentration in the liquid fraction of manure was 65 mg/L, while the application of the integrated system reduced the concentration to 13 mg/L (Period 1); the membranes increased the $PO_4$-P removal efficiency by 10%. In periods 2 and 3, the effluent $PO_4$-P concentration was 12.1 mg/L and 24 mg/L, respectively. However, the $PO_4$-P concentration in the MSBR effluent did not satisfy the Turkish limits for all the examined periods. Nevertheless, low-cost chemical precipitation of $PO_4$-P can be applied as a post-treatment step in order to reach the target concentration. The increase in $PO_4$-P concentration can be attributed to the residual $NO_3$-N from the anoxic phase at the end of each cycle in periods 2 and 3 (15.4 mg/L and 27 mg/L, respectively) that limited P-release during the anaerobic phase of the following cycle.

**Table 5.** Comparison of the MSBR effluent characteristics with the limits for discharge to the environment of animal products (SKKY, 2004, Table 5.15)

| Parameter | Unit | Limits | Period 1 | Period 2 | Period 3 |
|---|---|---|---|---|---|
| Chemical oxygen demand (COD) | (mg/L) | 500 | 77 | 125.7 | 204 |
| Suspended Solids (TSS) | (mg/L) | 200 | 0 | 0 | 0 |
| Ammonium Nitrogen ($NH_4$-N) | (mg/L) | 20 | 0.3 | 13.5 | 36.5 |
| Phosphate ($PO_4$-P) | (mg/L) | 3 | 12.1 | 24.8 | 36.7 |

The current study demonstrated that the MSBR was an effective process for the treatment of wastewater (liquid fraction of manure) that is characterized by high COD, $NH_4$-N and $PO_4$-P levels. A flat-sheet membrane module with 0.038 μm pore size was used for the solid-liquid separation; further pollutants removal was achieved. The membrane unit was submerged into the activated sludge in a different tank from SBR unit. The long term operation of submerged MBR was assessed at full scale in a municipal Wastewater Treatment Plant (WWTP) (Komesli et al., 2014). The results of the study showed that the membrane application led to an almost complete removal of fecal coliforms as well as a reduced turbidity (from 115-210 to 0.1-1 NTU) during the 9-year operation and with limited need for maintenance. $BOD_5$ and COD removal were reported as 99.99 and >95%, respectively.

**Table 6:** Overview of findings reported in literature regarding the application of MBR/SBR for wastewater treatment.

| **Stream** | **Operation Scale/Process** | **Removal Efficiency** | **Main Findings** | **Reference** |
|---|---|---|---|---|
| Dairy wastewater | Lab-scale MSBR | • $BOD_5$: 97-98%<br>• Suspended solids-free effluent<br>• N-removal=96%<br>• P-removal=80% (after system optimization; initially 55%) | • 110 days with only 1 membrane washing (due to diffuser-attached module design, subcritical flux operation & intermittent suction method )<br>• Nitrifying bacteria not adequately cultivated due to high BOD:TKN influent ratio; thus, N mainly consumed as nutrient<br>• High P-concentration in influent: low P-removal due to limitation of biological P-removal process<br>• System optimization depending on excess sludge wasting amount | Bae et al., 2003 |
| High-strength landfill leachate | Lab-scale MBR compared with lab-scale SBR | • SBR:<br>$BOD_5$: 82.0%,<br>COD: 46.7%,<br>$NH_3$: 71.4%,<br>TN: 72.5%<br>• MBR:<br>$BOD_5$: 99.5%,<br>COD: 70.0%,<br>$NH_3$: 96.0%,<br>TN: 95% | • The MBR showed higher removal rates than the SBR; however post-treatment is required to attain the desirable effluent quality (especially in terms of COD). | El-Fadel and Hashisho, 2014 |
| Raw wastewater from dormitories | Full-scale submerged MBR (9 years of operation) | • $BOD_5$: 99.99%<br>• COD>95% | • Treated effluent: appropriate for reuse for the irrigation of sensitive lawns at a low cost.<br>• Membrane fouling: avoided by keeping MLSS<12 g/L<br>• Energy consumption reduced through rotation movement (average: 2 $kWh/m^3$) | Komesli et al., 2014 |
| Real municipal wastewater | Bench-scale inclined plate MBR | • COD>90%<br>• TN>70% | • Optimal SRT for sufficient treatment and a sustainable inclined plate function: 40-80 d | Ittisupornrat et al., 2015 |
| Municipal wastewater | Lab-scale hybrid microfiltration-forward osmosis MBR | • Total organic carbon:90%<br>• $NH_4$-N: 99% | • 97.9% of $PO_4$-P rejected by the forward osmosis membrane and enriched within the bioreactor<br>• >90% of P-recovery at pH=9.0 | Qiu et al., 2015 |
| Liquid fraction of manure | Lab-scale MSBR | • Period 1 (HRT=12.8 h): COD=92.3%, $NH_4$-N=99.8%, $PO_4$-P=80%<br>• Period 2 (HRT=10.4 h): COD=87.4%, $NH_4$-N=93%, $PO_4$-P=60%<br>• Period 3 (HRT=9.2 h): COD=81.7%, $NH_4$-N=91%, $PO_4$-P=39% | • Operation at an HRT of 12.8 or 10.4 h & flux of 16 or 20 $L/m^2{\cdot}h$ (Periods 1 & 2) achieved a final $NH_4$-N concentration meeting the discharge limits<br>• $PO_4$-P concentration in the MSBR effluent did not satisfy the discharge limits for all the examined periods<br>• Low-cost chemical $PO_4$-P precipitation can be applied as a | Current study |

post-treatment

Table 6 includes a brief overview of multiple studies (including the current one) concerning the MBR/SBR/MSBR operation in wastewater treatment. The reduction of the P concentration to desirable levels often requires post-treatment or system optimization (e.g. control of excess sludge wasting amount, operation at a certain pH). The latter is due to the fact that the biological P-removal process can be hindered; e.g. in the case of high P-content in the influent or residual $NO_3$-N from previous treatment phases (Bae et al., 2003; Qiu et al., 2015; current study). In cases of highly loaded influent, post-treatment of the MBR effluent is usually required in order to achieve higher COD removal (El-Fadel and Hashisho, 2014). Another key aspect is the optimal combination of parameters in order to decrease membrane fouling; e.g. by operating at subcritical flux and controlling the MLSS concentration (Bae et al., 2003; Komesli et al., 2014). Process optimization through the testing of several HRTs, SRTs and fluxes is additionally discussed (Ittisupornrat et al., 2015; current study). Thus, efficient N and P-removal occurs without unreasonable operational/maintenance costs.

## CONCLUSIONS

This study examined the efficiency of a lab-scale MSBR treating synthetic wastewater that simulated the liquid fraction of manure at 3 different HRTs (12.8, 10.4 and 9.2 h). The SBR operated in an anaerobic/aerobic/anoxic mode using a submerged flat-type membrane module as a polishing step. The combined system's removal efficiency was:

- 92.3%, 87.4% and 81.7% of in terms of COD,
- 99.8%, 93% and 91% in terms of $NH_4$-N and
- 80%, 60% and 39% in terms of $PO_4$-P for periods 1 (HRT=12.8 h), 2 (HRT=10.4 h) and 3 (HRT=9.2 h), respectively.

The application of the membrane unit enhanced the performance of the system up to 10% ($PO_4$-P removal in Period 1). In terms of COD, the treated effluent from the MSBR system met the Turkish limits for discharge to the environment during all the examined periods. The system performance was sufficient in terms of $NH_4$-N removal for periods 1 and 2. However, additional post-treatment (i.e. chemical precipitation) is required in order to enhance $PO_4$-P removal. .

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