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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 MSBR was tested for three different hydraulic retention times (HRTs: 12.8, 10.4 and 9.2 h) to examine nutrient and organic matter removal. A submerged flat-type ultrafiltration membrane unit was applied as a policing step in order to improve the characteristics of the sequencing batch reactor effluent. The membrane module operated at 16, 20 and 25 L/m^2 h flux during the three examined periods. The MSBR efficiency for organic content removal was demonstrated with a chemical oxygen demand (COD) treated 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 ammonium nitrogen (NH_4–N) achieving 99.8% nitrification and >86% denitrification at an HRT = 12.8 h with <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 always 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 nutrient and COD removal; the impact was higher in the case of PO_4–P with 10% of them being removed in the membrane chamber during period 1.

Keywords: Membrane sequencing batch reactor; Hydraulic retention time; Membrane flux; Liquid fraction of manure; Organic content; Nutrients

1. Introduction

The development of membrane bioreactors (MBRs) for the treatment of different wastewater streams (industrial and municipal) has been driven by the need to meet increasingly strict discharge and reuse legislative standards, by the decrease in investment cost and by the potential for upgrading existing wastewater treatment plants (WWTPs) [1–4]. Compared with conventional activated sludge (CAS) systems, MBRs achieve superior treated effluent quality due to the complete rejection of suspended solids [5–7]. On the other hand, membrane fouling and energy consumption remain serious barriers to the wider spread of the MBR process [4,8]. MBR remains more expensive compared with CAS systems,

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particularly for small and decentralized schemes. Membrane sequencing batch reactors (MSBRs) combine the membrane technology with the sequencing batch reactors (SBRs). The membrane integration in the SBR addresses space limitations and settling problems encountered in the CAS system, allowing more process flexibility and potential to operate at much higher SRT. Thus, higher mixed liquor suspended solids (MLSS) concentrations can be achieved. Even though MSBRs were engineered in order to attain higher efficiencies than the MBRs and SBR technologies per se, the final MSBR performance relies on the selection of target operational parameters [9,10]. For instance, high dissolved oxygen (DO) has been found to slow down the increase of the transmembrane pressure (TMP) and, subsequently, the fouling in an MSBR system [9]; however, it also increases the operating expenses of the process.

Operation at very low HRT may result in low removal of nutrients and organic carbon due to the short contact time between the wastewater and the biomass. During SBR operation, continuous HRT decrease has been associated with the limited or problematic growth of bacteria. The latter is attributed to insufficient time for the active biomass to perform satisfactory substrate degradation [11–13]. MBR studies have demonstrated that the high growth of bacterial populations performing substrate degradation or the optimal chemical oxygen demand (COD) removal combined with a satisfying energy production were achieved after applying a minimal required HRT [14–16]. Moreover, the HRT decrease can result in higher MBR fouling rates [17–19]. Lower HRT requires higher membrane fluxes to be maintained, fact which can accelerate membrane fouling. The above findings show the importance of testing different HRTs for the optimization of the system's performance. Ng et al. [20] investigated the impact of HRT on COD removal in a lab-scale MBR treating high-salinity pharmaceutical wastewater. The COD removal was 68% at HRT = 60 h (flux = 1.46 L/m^2 h) and slightly lower (61%) for the decreased HRT = 40 h (flux = 2.19 L/m^2 h). Under the decreased HRT condition, the increased membrane flux and MLSS concentration led to quicker membrane fouling and, finally, to poorer reactor performance. In a lab-scale submerged anaerobic MBR study by Huang et al. [21] for the treatment of synthetic, low-strength wastewater, three different HRTs (12, 10 and 8 h) were tested. Total COD removal >97% was attained in all cases. Nevertheless, the higher MLSS concentrations hastened biocake development and, thus, membrane fouling at the lower HRTs (i.e., 10 and 8 h). All in all, these findings underline the importance of testing different HRTs to allow the determination of the one providing the optimal system operation. To the best of our knowledge, however, there is currently limited availability of studies [22,23], focusing on the HRT effect during industrial wastewater treatment in integrated setups concentrating the advantages of both membrane treatment and SBR technology (i.e., MSBRs).

2. Materials and methods

2.1. MSBR system

The configuration of the integrated SBR-membrane assisted system is shown in Fig. 1. The volumes of the lab-scale SBR (R2) and membrane tank (M1) were 5 L with 4 L of effective capacity, respectively. The glass-made reactor was inoculated with 3 L of activated sludge, which was collected

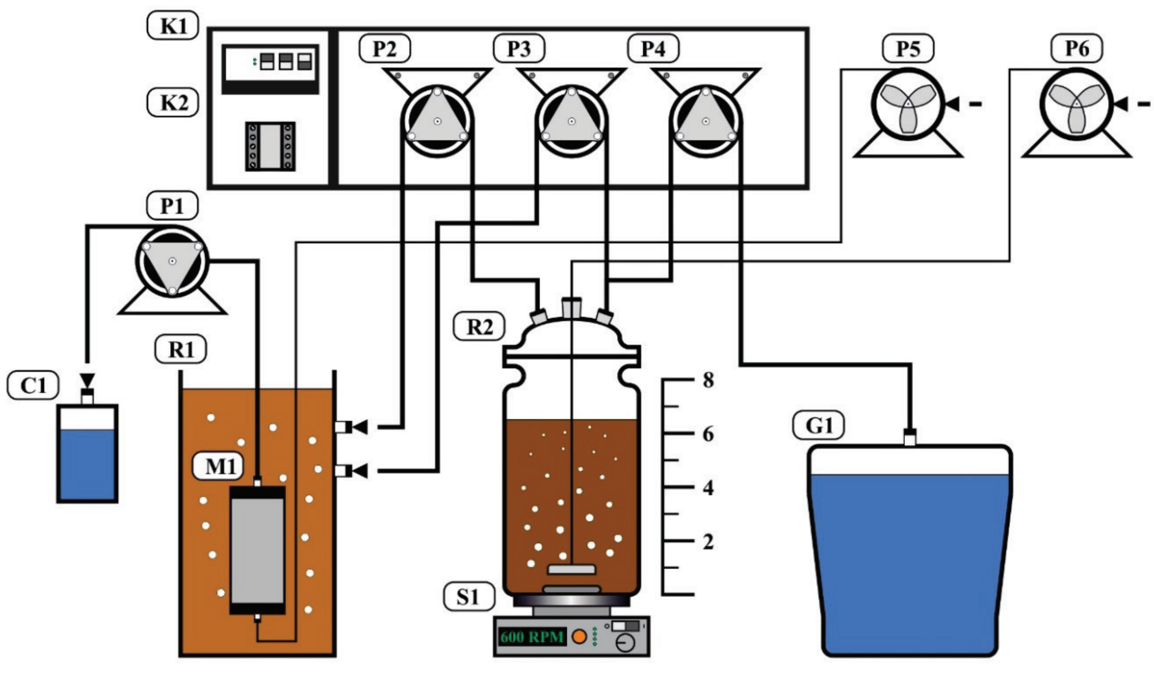

Fig. 1. Process diagram of the MSBR applied for the treatment of synthetic wastewater simulating the liquid fraction of manure. P1, vacuum pump; P2, permeate pump of SBR; P3, recirculation pump; P4, influent pump; P5, blower for membrane; P6, blower for SBR; G1, storage tank; C1, permeate tank; R1, MBR tank; R2, SBR tank; M1, membrane; S1, magnetic stirrer; K1, PLC; K2, conductor.

from a 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 a MLSS concentration of 3,500 mg/L and a SRT of 25 d. During the start-up period that lasted 45 d, sludge was not removed from the SBR. Once the process was stabilized at a MLSS concentration of 8,000–8,500 mg/L, the main system operation initiated. The MSBR operated for 92 d, while the main operation period was divided into three cycles with different HRTs (i.e., 12.8, 10.4 and 9.2 h) and, thus, different cycle durations (i.e., 465, 390 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 20 L storage tank (G1). Then the membrane tank (M1) was fed with the SBR effluent through the SBR permeate pump (P2). A vacuum pump (P1) was used for the filtration process.

The main purpose of this 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 HRTs. The SBR was chosen as it can achieve very good process stability using online control systems. It also provides high flexibility due to the option to alter the duration and sequence of each reaction phase. The membrane was added to the SBR process in order to avoid settling problems and achieve complete rejection of suspended solids and thus superior quality of the treated effluent.

2.2. 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°C ± 3°C) and each period lasted approximately 30 d. The MLSS concentration in the SBR reactor was 8,000–8,600 mg/L during period 1; it increased slightly during periods 2 and 3. The HRT decreased from 12.8 to 9.2 h, which resulted in an increase of the volumetric nitrogen loading rate (vNLR) from 0.34 to 0.47 kgN/kgVSS d and the food to microorganism ratio (F/M) from 1.71 to 2.1 kgCOD/kgVSS d. The impact of these changes on the system's performance with respect to COD, NH_4–N and PO_4–P was examined.

Table 2 summarizes the operation mode (cycle) applied in the SBR. The total duration of each cycle in periods 1, 2 and 3 was 465, 390 and 345 min, respectively. A membrane module was applied as a post-treatment stage to further reduce the level of contaminants from the SBR effluent; the membrane unit was operated at different fluxes (16, 20 and 24 L/m^2 h). The 8 L membrane chamber (Fig. 1) was equipped with a polyethersulfone 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 m^2. In each period, the membrane module was cleaned using 500 mgCl$_2$/L hypochlorite. The MLSS concentration in the membrane tank was approximately 7 g/L at the beginning of each cycle, and 12 g/L at the end of the cycle. Three different membrane fluxes were applied in the membrane unit by using a vacuum pump; i.e., 16, 20 and 24 L/m^2 h for periods 1, 2 and 3, respectively (Table 2).

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
vNLR (kgN/(m^3 d))	0.34	0.41	0.47
MLSS (g/L)	8–8.6	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	1.9–2.1
Applied carbon source	CH_3COONa	CH_3COONa	CH_3COONa
Cycle duration (h)	7 h 45 min	6 h 30 min	5 h 45 min
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
TMP increase (kPa/d)	0.085	0.083	0.091

Table 2
SBR cycle during the three operating periods

	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
Settling	20	20	30
Withdraw	35	35	35
Idle	5	5	5
Cycle time	465	390	345
Flux (L/m^2 h)	16	20	24

2.3. Wastewater characteristics

Table 3 shows the composition of the synthetic wastewater used in the experiments. We simulated the liquid fraction of pre-treated manure wastewater.

2.4. Sampling and analytical methods

Samples were collected three times/week from the SBR and the membrane effluent. The samples were characterized for their COD, NH_4–N, NO_3–N and PO_4–P content. Physicochemical characterization of the influent, the SBR effluent, the treated effluent from the SBR-membrane separation, the activated sludge was performed. The concentrations of the MLSS, the mixed liquor volatile suspended solids

(MLVSS), total suspended solids (TSS), COD and NH_4–N were determined according to standard methods of analysis [24]. More specifically, the TSS were determined according to the 2540B Standard Method and the COD analysis was carried out according to the 5220C Standard Method. 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 Pharo 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).

3. Results and discussion

3.1. SBR-membrane system performance

The COD concentration in the influent of the MSBR system ranged from 960 to 1,200 mg/L during the three periods of operation (Fig. 2). A decrease in the HRT from 12.8 to 10.4 h during the second period increased the flux in the membrane chamber by 25% (from 16 to 20 L/m²·h) and decreased the efficiency of the system in terms of COD removal from 92.3% (period 1) to 87.4% (period 2). During 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 a further decrease of the COD removal efficiency to 81.7%. As shown in Fig. 2, the average concentration of the COD in the SBR and the membrane effluent in period 1 was 100 and 77 mg/L, respectively. In the second period, the HRT was 10.4 h and the COD removal efficiency remained almost constant (around 85%) for approximately 30 d. The COD level in the SBR treated effluent was 150 mg/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 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 concentration in the treated effluent.

Similar results were obtained in other research studies that examined the effect of HRT on the performance of bioprocesses applied for wastewater treatment. Wang et al. [25] operated a lab-scale external-submerged anaerobic MBR for the treatment of bamboo industry wastewater with the HRT ranging from 2 to 10 d; COD removal ranged from 80% (HRT = 2 d) to 93% (HRT = 10 d). Chu et al. [26] applied an expanded granular sludge bed lab reactor coupled with hollow fiber membrane filtration for domestic wastewater treatment. At a certain temperature (i.e., 11°C), the authors observed that the increase of the HRT from 3.5 to 5.7 h led to higher COD removal;

Table 3
Composition of synthetic wastewater treated with the MSBR system

Wastewater composition		Trace elements mixture	
Compound	Concentration (mg/L)	Compound	Concentration (mg/L)
$CH_3COONa.3H_2O$	960–1,200 mg COD/L	$CuSO_4.5H_2O$	0.03
NH_4Cl	160–200 mg N/L	KI	0.03
KH_2PO_4	60 mg P/L	$ZuSO_4.7H_2O$	0.12
$NaHCO_3$	8.30	$CoCl_2.6H_2O$	0.15
$FeCl.6H_2O$	0.15	$MnCl_2.4H_2O$	0.12
H_3BO_3	0.15		

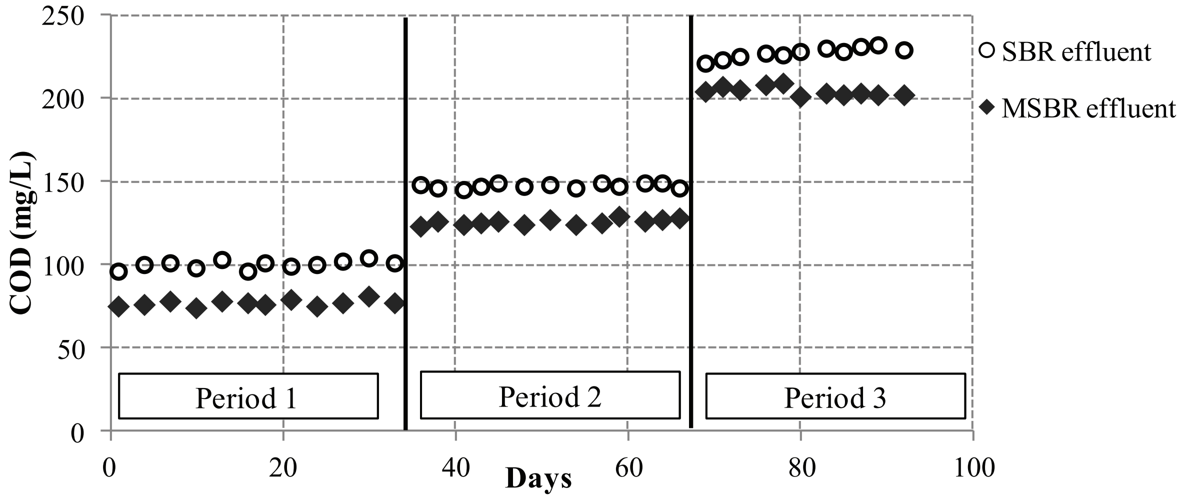

Fig. 2. COD concentration in the SBR and MSBR treated effluent during the three periods of operation of the MSBR system.

it increased from 76% to 81%. Longer contact time between the biomass and the substrate was obtained at the highest examined HRT, thus enabling enhanced substrate degradation. Similar trend was obtained by Ng et al. [27] who implemented a lab-scale (salt marsh sediment) MBR for the treatment of pharmaceutical wastewater. Lowering the HRT from 120 to 60 h resulted in a decrease of the COD removal from 88.9% ± 1.2% to 82.5% ± 2.3%. The latter is explained by the increase of the organic loading rate (OLR) from 3.3 ± 0.2 kgCOD/m^3 d (HRT = 120 h) to 7.2 ± 1 kgCOD/m^3 d (HRT = 60 h). The higher OLR hindered the nutrient utilization and substrate degradation capacity of the system. In another study, Ng et al. [20] investigated the COD removal operating a lab-scale MBR treating high-salinity pharmaceutical wastewater. The COD removal was 68% at HRT = 60 h (flux = 1.46 L/m^2 h) and slightly less (61%) at HRT = 40 h (flux = 2.19 L/m^2 h). At lower HRT, the increased membrane flux and MLSS concentration led to faster membrane fouling and, thus, to poorer process performance.

In the lab-scale submerged anaerobic MBR study by Huang et al. [21] for the treatment of synthetic low-strength wastewater, three different HRTs (12, 10 and 8 h) were tested. Total COD removal >97% was attained in all cases. Nevertheless, the higher MLSS concentrations hastened biocake development and, thus, membrane fouling at the lower HRTs (i.e., 10 and 8 h). In our work, the gradual HRT decrease among the three periods (i.e., 12.8, 10.4 and 9.2 h) and the respective membrane flux increase (16, 20 and 24 L/m^2 h; Table 2) initiated no important fouling during the entire period of the current study. This observation can be reinforced by the fact that the MLSS content was not largely different: 8–8.6 g/L (period 1), 8.5–8.9 g/L (period 2) and 8.7–9.2 g/L (period 3; Table 1). Under the comparable MLSS concentration in all periods, the gradual flux increase did not adversely impact on membrane fouling since the rate of increase of the TMP was not statistically significant for the three different periods.

The average NH_4–N concentration in the system influent was 190 mg/L for all the examined periods. As shown in Fig. 3, in period 1, 99.8% of NH_4–N was oxidized to NO_3–N with a treated effluent ammonium 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 further nitrification taking place in the membrane chamber resulting in the production of nitrate. During the second operating period, the NH_4–N concentration in the SBR effluent ranged between 14 and 19 mg/L; 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. Finally, in period 3, the NH_4–N permeate concentration was 41–48 mg/L (81% removal efficiency); the significant increase of the vNLR in period 3 resulted in lower nitrification efficiency. 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 [22] applied a similar system (pilot-scale submerged membrane SBR) for the treatment of synthetic greywater under three different HRTs: 33, 24 and 12 h. It was found that the lowest HRT (i.e., 12 h) was optimal for biomass growth and in favor 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. [28] explored the effect of HRT decrease on the TN removal of a pilot-scale sequencing anoxic/anaerobic MBR for municipal wastewater treatment. By decreasing the HRT from 13 to 9.4 h TN removal gradually increased from 53% to 73% as a result of the enhanced denitrifying bacteria activity under a higher F/M. A further decrease in the HRT (from 9.4 to 6.5 h) resulted in reduced TN removal (65%). Low HRTs along with a decreased SRT

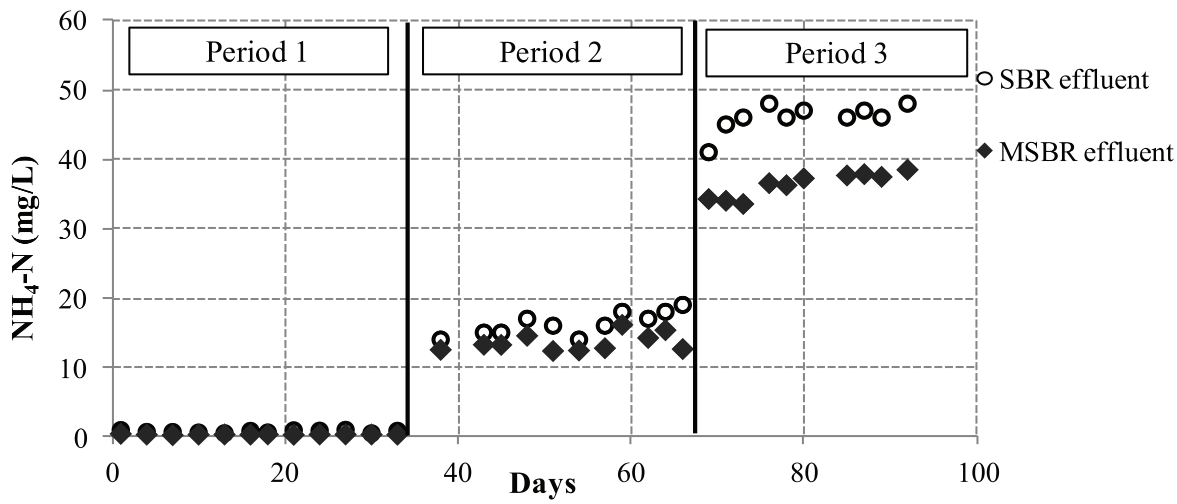

Fig. 3. NH_4–N concentration in the SBR and MSBR effluent during the three periods of operation.

(from 80 to 50 d) lowered the nitrifying bacteria concentration, thus leading to incomplete nitrification. Low HRTs can be tested with the view to avoiding reactor oversizing and, subsequently, reducing the overall cost. However, HRT decrease is desirable only if it does not compromise on nitrification–denitrification.

PO_4–P concentration in the MSBR influent was 60 mg/L on average (57–64 mg/L; Fig. 4). During period 1, 80% of the initial PO_4–P was removed; the PO_4–P removal efficiency was further increased by 10% after applying the membrane post-treatment. In period 2, a 53%–56% PO_4–P removal was observed for a HRT = 10.4 h, which increased up to 60% after the effluent went through the membrane chamber. Further HRT reduction in the last operating period (HRT = 9.2 h) provoked 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. Similarly, the HRT increase from 2.1 to 2.7 d induced almost complete P removal in the lab-scale SBR system developed by Wu and Zhu [29] for the treatment of dairy milking parlor wastewater. It was observed that a slightly higher HRT was needed to ensure that the COD provision was enough to promote adequate P release during the anaerobic conditions. Furthermore, Mouthon-Bello and Zhou [30] implemented a lab-scale MBR for municipal wastewater treatment. Raising the HRT from 6 to 8 h resulted in increasing P removal from 89% to 98%. In this case, high P removal was expected as a result of the low influent soluble P content (i.e., 1 ± 0.3 mg/L). Under these favorable conditions, the HRT increase provided adequate time for the effective P removal in the system. Taking all the above into account, it can be concluded that HRT optimization is a key factor for the achievement of satisfying COD and nutrient removal efficiency.

3.2. 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 [31]. In Erzurum (Turkey; case study area) specifically, there are >24,000 medium and large farms. In the current work, the applicability of an 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 regulation [32]. Synthetic wastewater was used for the simulation of the liquid fraction of manure. 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 960–1,100 mg/L. COD removal was steadily higher than 92% (Fig. 2) at a HRT of 12.8 h (period 1). The membrane application as a post-treatment stage increased COD removal by 20% compared with the SBR effluent. Even when the HRT was reduced to 9.2 h during the third operating period, COD removal remained higher than 82% and the treated effluent still satisfied the limits for discharge (204 mg/L with 500 mg/L limit). Table 4 compares the treated effluent characteristics with national limits for discharge. The MSBR met the limits in terms of COD for all the three

Table 4
Comparison of the MSBR effluent characteristics with the limits for discharge of animal products [32]

Parameter	Limit	Period 1	Period 2	Period 3
Chemical oxygen demand (COD), mg/L	500	77	126	204
Total suspended solids (TSS), mg/L	200	0	0	0
Ammonium nitrogen (NH_4–N), mg/L	20	0.3	13.5	36.5
Phosphate–phosphorus (PO_4–P), mg/L	3	12.1	24.8	36.7

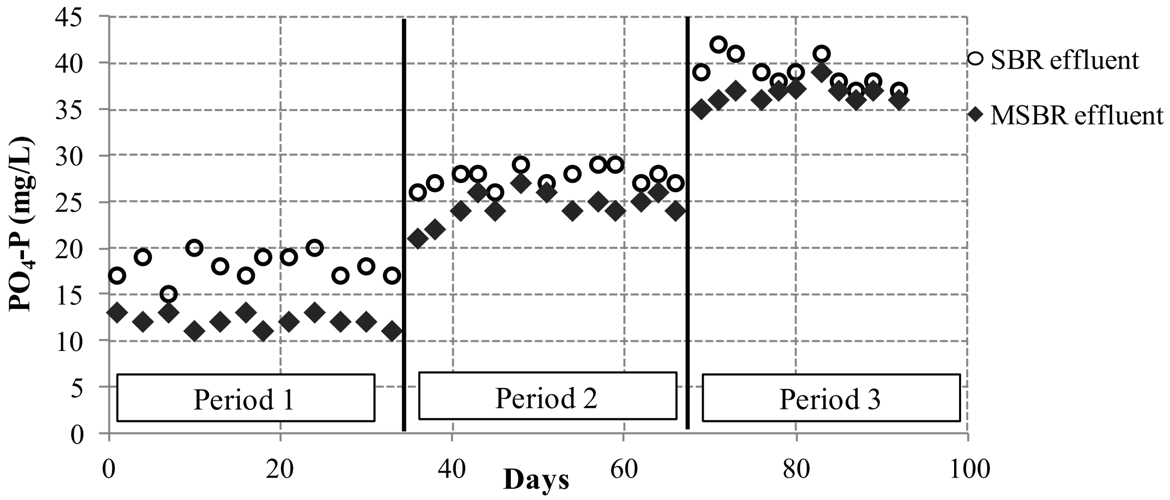

Fig. 4. PO_4–P concentration in the SBR and MSBR effluent during the three periods of operation.

periods of operation. Moreover, the NH_4–N concentration was <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 almost completely oxidized to NO_3–N. The NO_3–N concentration in the SBR effluent was 16 mg/L; thus, 90% of the total NH_4–N was removed by the application of

Table 5
Overview of findings reported in literature regarding the application of MBR/SBR/MSBR for wastewater treatment

Stream	Operation scale/process	Removal efficiency	Main findings	Source
Dairy wastewater	Lab-scale MSBR	• BOD_5: 97%–98% • Suspended solids-free effluent • N removal = 96% • P removal = 80% (after system optimization; initially 55%)	• 110 d with only one membrane washing (due to diffuser-attached module design, subcritical flux operation and intermittent suction method) • Nitrifying bacteria not adequately cultivated due to high BOD:TKN influent ratio; thus, N mainly consumed as nutrient • High P concentration in influent: low P removal due to limitation of biological P removal process • System optimization depending on excess sludge wasting amount	[8]
Raw wastewater from dormitories	Full-scale submerged MBR (9 years of operation)	• BOD_5: 99.99% • COD: >95%	• Treated effluent: appropriate for reuse for irrigation of sensitive lawns at low cost • Membrane fouling: avoided by keeping MLSS <12 g/L • Energy consumption reduced through rotation movement (average: 2 kWh/m^3)	[33]
High-strength landfill leachate	Lab-scale MBR compared with lab-scale SBR	• SBR → BOD_5: 82%, COD: 46.7%, NH_3: 71.4%, TN: 72.5% • MBR → BOD_5: 99.5%, COD: 70%, NH_3: 96%, TN: 95%	• MBR achieving higher removal rates than SBR; however, post-treatment required to attain desirable effluent quality (especially in terms of COD)	[35]
Real municipal wastewater	Bench-scale inclined plate MBR	• COD: >90% • TN: >70%	• Optimal SRT for sufficient treatment and sustainable inclined plate function: 40–80 d	[6]
Municipal wastewater	Lab-scale hybrid microfiltration-forward osmosis MBR	• Total organic carbon: 90% • NH_4–N: 99%	• 97.9% of PO_4–P rejected by the forward osmosis membrane and enriched within the bioreactor • >90% of P recovery at pH = 9	[34]
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% • Period 2 (HRT = 10.4 h): COD = 87.4%, NH_4–N = 93%, PO_4–P = 60% • Period 3 (HRT = 9.2 h): COD = 81.7%, NH_4–N = 91%, PO_4–P = 39%	• Operation at HRT = 12.8 or 10.4 h and flux = 16 or 20 L/m^2 h (periods 1 and 2) achieved a final NH_4–N concentration meeting the discharge limits • PO_4–P concentration in the MSBR effluent did not satisfy the discharge limits for all the examined periods • Low-cost chemical PO_4–P precipitation can be applied as a post-treatment	Current study

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 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 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 [32]. 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 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 increased PO_4–P concentration in the treated effluent 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 and 27 mg/L, respectively) that limited P release during the anaerobic phase of the following cycle.

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 pollutant removal was achieved. The membrane unit was submerged into the activated sludge in a different tank from the SBR unit. The long-term operation of submerged MBR was assessed at full scale in a municipal WWTP [33]. 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); this along with limited need for maintenance. BOD_5 and COD removal were reported as 99.99% and >95%, respectively.

Table 5 includes a brief overview of multiple studies (including the current one) concerning the MBR/SBR/MSBR operation in wastewater treatment. The decrease of P concentration at desirable levels often requires post-treatment or system optimization. The latter is due to the fact that the biological P removal process can be hindered; e.g., in the case of high P concentration in the influent or residual NO_3–N from previous treatment phases [8,34]. In cases of highly loaded influent, post-treatment of the MBR effluent is usually required in order to achieve higher COD removal [35]. Another key aspect is the optimal combination of parameters in order to limit membrane fouling; e.g., by operating at subcritical flux and controlling the MLSS concentration [8,33]. Process optimization through the testing of several HRTs, SRTs and fluxes is additionally discussed [6]. Thus, efficient N and P removal can occur without unreasonable operational/maintenance costs.

In the current study, the emphasis was put on the optimization of the HRT parameter within an innovative setup (i.e., MSBR) treating the liquid fraction of manure produced in Turkish farms. As discussed in section 3.1, concluding to an optimal HRT is important in order to ensure sufficient substrate degradation, maintain a MLSS concentration that does not aggravate membrane fouling [21,22,26,30] and avoid system oversizing. In this work, the minimal applied HRT respecting the Turkish legislation limits concerning the COD and NH_4–N removal was 10.4 h (period 2). Effective PO_4–P removal still remains an issue at the present form of the system, thus requiring the addition of a cost-effective post-treatment step.

4. Conclusions

- This study examined the efficiency of a lab-scale MSBR treating synthetic wastewater that simulated the liquid fraction of manure at three 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:
  1. 92.3%, 87.4% and 81.7% in terms of COD,
  2. 99.8%, 93% and 91% in terms of NH_4–N and
  3. 80%, 60% and 39% in terms of PO_4–P
  4. for period 1 (HRT = 12.8 h), period 2 (HRT = 10.4 h) and period 3 (HRT = 9.2 h), respectively.
- 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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Symbols

BOD	—	Biological oxygen demand
CAS	—	Conventional activated sludge
COD	—	Chemical oxygen demand
DO	—	Dissolved oxygen
F/M	—	Food to microorganism 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
OLR	—	Organic loading rate
P	—	Phosphorus
PLC	—	Programmable logic controller
SBR	—	Sequencing batch reactor
SRT	—	Sludge retention time
TKN	—	Total Kjeldahl nitrogen
TMP	—	Transmembrane pressure
TN	—	Total nitrogen
TSS	—	Total suspended solids
WWTP	—	Wastewater treatment plant

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