Desalination and Water Treatment
www.deswater.com

doi: 10.5004/dwt.2020.25981

197 (2020) 76–89
September

Decentralized treatment of domestic sewage in dynamic membrane bioreactor

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Received 23 January 2020; Accepted 16 April 2020

ABSTRACT

A pilot-scale anaerobic dynamic membrane bioreactor (AnDMBR) was monitored at ambient temperature to assess domestic sewage treatment from a housing development. The dynamic membrane (DM) was developed from polypropylene support material with an average opening of 90 μm, inside an external configuration module. To minimize energy costs, the AnDMBR system was operated under hydraulic pressure, in two Cycles, without backwashing (Cycle 1), and with backwashing (Cycle 2). The HRT was 18 h and the initial permeate flow was 780 L m^{-2} h^{-1}. The CRT of Cycle 1 was 91 d, and Cycle 2 was 49 d. The average concentrations of MLTSS in Cycle 1 and 2 were 29.40 and 29.60 g L^{-1}, respectively. The system achieved good average efficiency of removing organic matter, with a total COD value of 86.0% and soluble COD of 76.0%, being able to remove 91.0% of suspended solids, producing an effluent with low turbidity (18.0 NTU). The results also show that the DM contributed to the production of effluent with a concentration of helminth eggs which meets WHO recommendations [47] for unrestricted irrigation. A significant amount of biogas was produced by the system and most came out in dissolved form with the effluent due to supersaturation. The average transmembrane pressure (TMP) of Cycle 2 was 2.0 times greater than that of Cycle 1, which suggests that fouling cannot be effectively removed with tap-water washing or with backwashing.

Keywords: Organic material; Helminth eggs; Permeate flow; Fouling; Backwashing

1. Introduction

Biological treatment is the most widely used technique in wastewater treatment plants. Anaerobic biological methods are more sustainable than aerobic ones, as the former do not consume large amounts of energy [1–3].

However, research shows that conventional anaerobic systems continue to have a low removal rate of solid organic material, and pathogens when compared to aerobic systems, even in conditions of tropical areas [3–7]. To circumvent the weaknesses of anaerobic systems, several studies have coupled filtration membranes such as microfiltration (MF) and ultrafiltration (UF) to anaerobic bioreactors and achieved satisfactory performance in removing organic matter and suspended solids [8–12]. However, the main constraint of this technology is related to high membrane costs [13–17].

A promising solution to replace anaerobic membrane bioreactor (AnBR) processes is the use of dynamic membrane

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(DM) technology. A DM is a cake- layer formed from a base of support material that can be a mesh made from woven or non-woven filter cloth; inexpensive material, with relatively large pores of approximately 30–200 μm [16,18]. Due to the pore size, these materials do not act as a filtration material, but rather as a support material. Advantages of this technology include high filtration flow, the low cost of the membrane module, and its ease of washing [16].

The formed cake-layer which makes up the DM is rich in active microorganisms and organized in biofilms, sludge particles, and biological flocs. On these, organic and inorganic molecules, metals, and nutrients are deposited; many of them forming new chemical compounds such as struvite, and ammonia and potassium phosphate [19–22].

According to Ersahin et al. [20], Ersahin et al. [21], Ma et al. [23] and Siddiqui et al. [24)], in a dynamic membrane anaerobic bioreactor (AnDMBR) it is possible to perform complete biomass retention in the anaerobic system by controlling cell retention time (CRT) regardless of hydraulic retention time (HRT), making it possible to treat large volumes of effluents in small areas. However, Rosenberger et al. [25] state that while excess sludge production can be completely suppressed by manipulating HRT and the food/microorganisms (F/M) ratio, a small amount of sludge should be regularly removed due to accumulation of inorganic substances in the reactor, which may reach levels that are toxic to microorganisms.

Guan et al. [26] ensure that pore blocking of the support material in DM bioreactor systems is mainly caused by biological flocs, which are mostly bacteria covered with gel-like substances. Blockage of the support material pores with extracellular polymeric substances (EPS) and soluble microbial products (SMP) is the main fouling mechanism in conventional membranes (MF and UF) [27,28]. This does not occur with AnDMBRs because their pores are too large to block with EPS and SMP.

Periodic DM cleaning aims to restore permeate flow to values close to initial flow. Backwashing transports the particles adhering to the pore structure into the liquid and partially removes the cake-layer formed on the membrane surface. The frequency and the backwash flow are related to the operating conditions and characteristics of the effluent to be treated [24,26].

According to Guan et al. [26], backwashing is one of the most common physical cleansing strategies applied to DMs. Siddiqui et al. [24] understood that the DM formed on the support material can be removed after washing. However, DM residue that was gradually accumulated over the entire operating period within the support material pores could not be removed effectively by backwashing.

However, many studies using AnDMBR systems have been developed with the aid of pumps, one for recirculating the concentrate and another for suctioning the permeate, which leads to greater consumption of electricity. Thus, the present study aims to investigate the AnDMBR system under hydraulic pressure (without the concentrate re-circulation and permeate suction pumps), for the treatment of domestic wastewater at ambient temperature in pilot scale. This was done to evaluate the performance of the system in the removal of organic matter and helminth eggs, for possible use of the effluent in agriculture.

2. Material and methods

2.1. Experiment location and collection of the domestic sewage

The experimental system was built and monitored at the Experimental Station for Biological Treatments of Sanitary Sewers (EXTRABES), located in the municipality of Campina Grande, state of Paraíba, Brazil. The station is at an altitude of 550 m, the ambient temperature ranges from 19°C to 30°C, and the geographical coordinates are 7°, 14′, 23.26″ S and 35°, 53′, 03.23″ W.

The sewage used during the experimental period came from a housing development (HD) of 72 apartments located 200 m from the EXTRABES area, with an average flow of 20 $m^3\ d^{-1}$. The average concentration of the raw COD was 1,075 mg COD L^{-1}, strong sewage, according to Metcalf & Eddy [29]. The characterization of the domestic sewage used in the present work is shown in Table S1 of the supplementary data.

2.2. Description of the experimental system

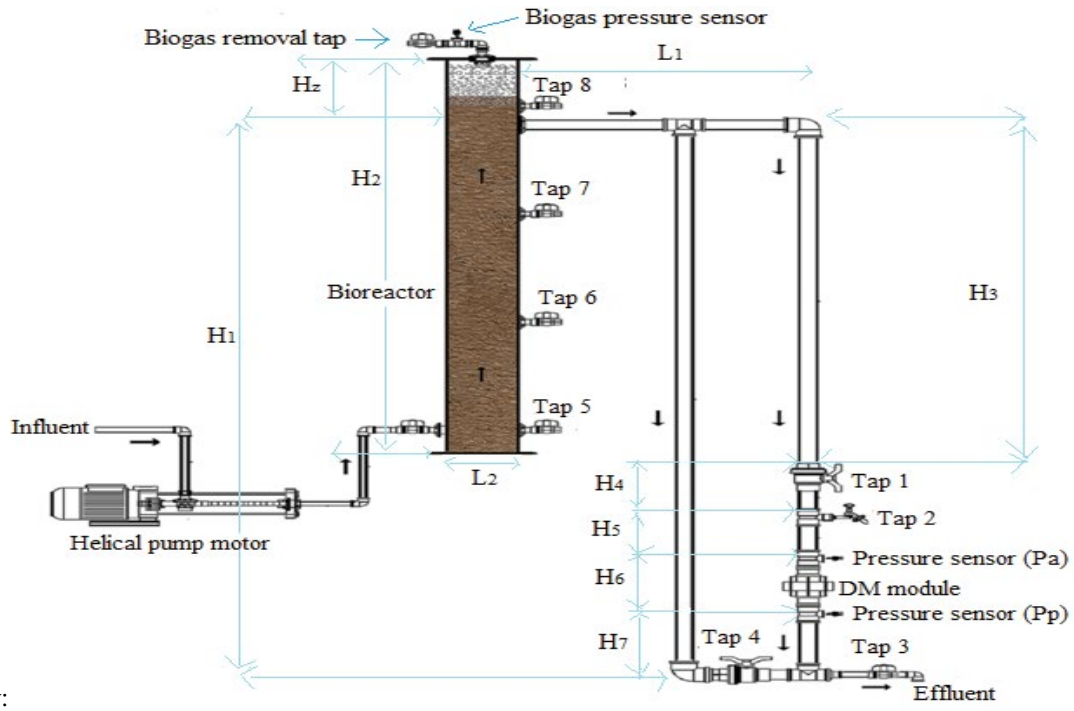
The experimental AnDMBR system consisted of an anaerobic bioreactor and an outer membrane module for filtration (Fig. 1). The bioreactor was made of fiberglass and the membrane module was made of polyvinyl chloride (PVC). The support material (mesh) for forming the dynamic membrane was polypropylene, a widely available and inexpensive commercial material (Fig. 2). To support the mesh, a stainless steel screen was used to provide reinforcement and structure to the layer under the support mesh when subjected to high internal pressure gradients. The dimensions of the anaerobic bioreactor and dynamic membrane module are presented in Table 1.

The transmembrane pressure (TMP) was monitored daily by MPX4250 pressure sensors installed in the membrane module inlet and outlet line to monitor the behavior and formation of the dynamic membrane, as well as to evaluate the physical and chemical characteristics. The sensors were connected to an Arduino Uno ATmega328 microcontroller board, responsible for communication between the bioreactor and the computer. Pressure values were made available through spreadsheets generated by SisMonBio software every 5 min and stored in the system. The software records and shows information in real-time, as well as providing a tool in which it is possible to query data from the bioreactor according to the desired date.

The biogas produced was quantified by measuring the pressure accumulated in the headspace over the days of operation, using the biogas pressure sensor, and visualized through the SisMonBio software developed by Albuquerque [30]. The daily quantified pressures were transformed into biogas volume under normal temperature and pressure conditions (NTP) according to the law of gases. The COD of methane was calculated based on Eq. (1). The theoretical production of methane was estimated by applying Eqs. (2) and (3).

$$COD_{CH_4} = Q \cdot (S_0 - S) - Y_{obs} \cdot Q \cdot S_0 \quad (1)$$

where, COD_{CH_4} is the load converted into methane (kg $COD_{CH_4}\ d^{-1}$); Q is the influent sewage flow ($m^3\ d^{-1}$);



Key:

H1: Height of the water column; H2: Height of the bioreactor; H3: Pipe height to tap 1; H4: Distance from tap 1 to tap 2; H5: Distance from tap 2 to pressure sensor (Pa); H6: Distance between Pa and Pp pressure sensors. ; H7: Distance from outlet pressure sensor to effluent outlet tap; L1: Pipe width; L2: Bioreactor width.

Fig. 1. Schematic drawing of the experimental system.

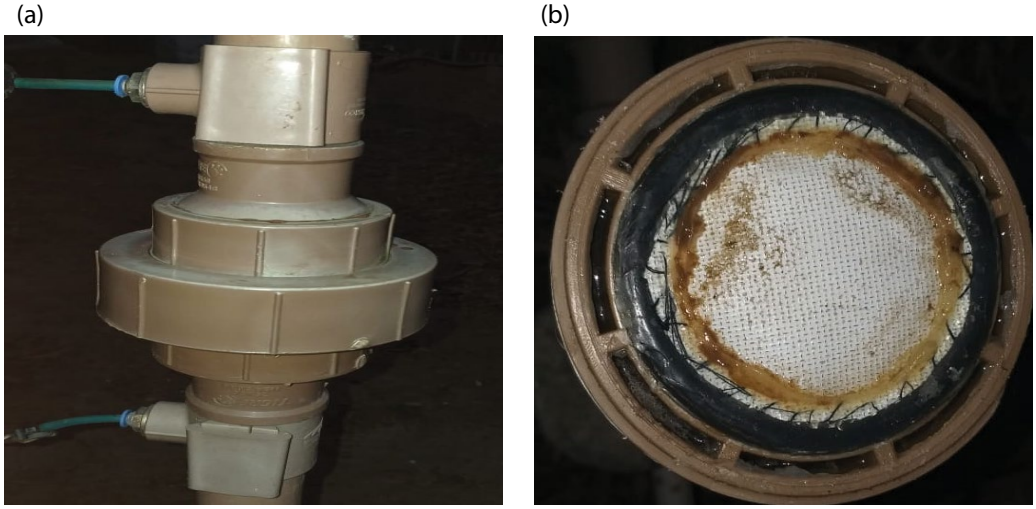


Fig. 2. Dynamic membrane module and support mesh images.

S_0 and S are the COD concentration (kg COD m^{-3}) of influent and effluent, respectively; and Y_{obs} is the coefficient of production of solids in the system, in terms of COD (0.10 to 0.20 (kg COD_{sludge} kg^{-1} $COD_{applied}$)).

$$Q_{CH_4} = 22,4\frac{L}{mol}\left(\frac{273,15+t}{273,15}\right)\cdot\frac{COD_{CH_4}}{64gCOD\cdot mol^{-1}CH_4} \quad (2)$$

where, Q_{CH_4} is the estimated volumetric methane production (m^3 d^{-1}); t is the temperature under NTP equal to 0°C.

$$Q_{biogas} = \frac{Q_{CH_4}}{\%C_{CH_4}} \quad (3)$$

where Q_{biogas} is the volumetric production of biogas quantified in the system (m^3 d^{-1}); Q_{CH_4} is the estimated volumetric

Table 1
Dimensions of the AnDMBR system

Bioreactor	Connections	Membrane module	Operating parameters
L_2 = 20 cm	L_1 = 92 cm	D_m = 7 cm	HRT = 18 h
H_2 = 200 cm	H_1 = 290 cm	A_m = 38.465 cm^2	CRT_1 = 91 d
H_z = 30 cm	H_3 = 190 cm	T_m = 90 μm	CRT_2 = 49 d
A_2 = 314 cm^2	H_4 = 30 cm		Q_e = 3 L h^{-1}
V_2 = 62.8 L	H_5 = 18 cm		J_p = 779.93 L m^{-2} h^{-1}
V_u = 53.4 L	H_6 = 25 cm		
V_z = 9.42 L	H_7 = 27 cm		
	D_t = 5 cm		
	V_{tu} = 5.534 L		
H_T = 3.2 m			

A_2: area of bioreactor; H_z: height of the headspace; V_2: total volume of the bioreactor; V_u: useful volume of the bioreactor; V_z: volume of the headspace; V_{tu}: volume of the pipe between L_1 and H_3; D_m: internal diameter of membrane module; A_m: useful area of membrane module; Q_e: feed flow rate of influent in the system; J_p: permeate flow; CRT_1: cycle 1 cell retention time; CRT_2: cycle 2 cell retention time; T_m: average pore size of support mesh.

methane production (m^3 d^{-1}); C_{CH_4} is the methane content (%) in biogas was 70%, used as van Haandel and Letiinga [31], Chernicharo [32], and Hu et al. [33] state that the methane content in the anaerobic treatment of domestic sewage generally varies from 70% to 80%.

2.3. Experimental system monitoring

The AnDMBR system was started in April 2019 without sludge inoculum. The system feeding process was performed continuously under constant flow with the aid of a Line-R helical gearmotor (Sew-Eurodrive). The effluent from the anaerobic bioreactor was conveyed by hydraulic pressure (as the driving force) to the membrane module. After passing through the dynamic membrane, the effluent (permeated) flowed by gravity into a collection vessel. The filtration was performed by transverse flow (perpendicular) and the AnDMBR system operation was carried out in two Cycles: Cycle 1 and 2.

Cycle 1: started without inoculum, the goal was to check the maximum potential of the permeation period, therefore, the system was not backwashed until it was completely clogged, which was after 91 d of operation. After complete clogging, backwashing was attempted, but without success. The membrane module was opened and the polypropylene support mesh was washed with tap water.

Cycle 2: in this Cycle started with inoculum (19.7 g VSS L^{-1}. 20 L = 397 g VSS), backwashing was employed, which was performed after a 10% reduction in permeate flow. During backwashing with effluent from the bioreactor, taps 1 and 3 were closed while taps 2 and 4 were opened to reverse the flow, as shown in Fig. 1. Backwashing time was 1 min, enough to leave an average volume of 0.12 L d^{-1} of the solution concentrated through tap 2, with an average COD of 8.5 g L^{-1}, producing 1.020 g COD d^{-1}.

2.4. Analytic methods and data analysis

Daily, weekly, and bi-weekly analyses were performed to characterize the influent and permeate of the AnDMBR. It should be noted that the samples used for soluble COD and suspended solids analyses were centrifuged at a rotation of 6,000 rpm for 15 min. Sludge analyses were performed in duplicates.

Bioreactor sludge, sludge from backwashing, and from the DM were also characterized. Sludge flocculability was determined by supernatant turbidity, measured with a turbidity meter (MS, TECNOPON, model TB-1000P) after 30 min of sedimentation.

Physical and chemical analyses followed recommendations from the Standard Methods for the Examination of Water and Wastewater [34]. Helminth eggs followed modified Bailenger methodology [35]. SMP concentrations were measured as proteins and carbohydrates. For this, the collected samples were centrifuged at 6,000 rpm for 30 min, and then the extracted supernatant was filtered through a 0.45 μm membrane. The filtrate of the centrifuged supernatant was considered to be SMP. The proteins followed the Lowry method modified by Frølund et al. [36] with the BSA standard (bovine serum albumin, Sigma fraction V, 96%), and the reading of the final solution (prepared) was taken on the spectrum at a wavelength of 750 nm. Carbohydrates followed the method described by Dubois et al. [37] with a glucose standard, and the reading of the final solution (prepared) was taken on the spectrum at a wavelength of 490 nm.

Data treatments were based on descriptive statistics in Microsoft Excel 2007. Graphs were plotted on the STATISCA 12 statistical package.

2.5. AnDMBR system mass balance

The quantification of the organic matter expressed as COD fractions in the effluent, the excess sludge, and the DM, as well as in the methanized fraction, was estimated with mass balance from Eq. (4). The same equation was also used for the nutrients.

$$M_A + M_I = M_{LE} + M_P + M_T + M_B + M_C \quad (4)$$

where, M_A is the daily mass of feed; M_I is the daily mass of inoculum; M_B is the daily mass converted to methane; M_{LE} is the Daily mass of backwashing sludge; M_P is the daily mass of effluent; M_T is the daily mass of dynamic membrane; and M_C is the daily mass of bioreactor sludge.

3. Results and discussion

3.1. Behavior of the transmembrane pressure and the permeate flow

Fig. 3 shows the transmembrane pressure (TMP) behaviors over the operating time obtained for Cycle 1 and 2 of the AnDMBR.

In both Cycles, the TMP curve increased sinusoidally and progressively over most of the operating time (Fig. 3). In Cycle 1, in the interval of 40–60 d, the TMP increased considerably (from 8.5 to 26.4 kPa), suggesting that this was the period in which the stage of formation and development of the dynamic membrane took place. After 60 d, TMP gradually increased, reaching a maximum value of 34.6 kPa at 89 d, suggesting that this was the period that the dynamic membrane maturation stage took place. Yu et al. [38] explain that the formation of the dynamic membrane occurs mainly in two stages. The initial formation, by the interactions of support mesh-sludge flocs, defined as the adherence behavior of the sludge, is known as the adhesion process. The maturation stage of the DM, when the interactions of sludge flocs-sludge flocs occur, is known as the cohesion process.

In Cycle 2, the maximum TMP was 38.9 kPa at 46 d, and after 21 d the TMP had little variation, with an average of 36.0 kPa. The averages of Cycle 1 and 2 TMP throughout the whole operation were 16.0 ± 11.4 and 32.0 ± 7.0 kPa, respectively. The mean TMP of Cycle 2 was 2.0 times higher than that of Cycle 1, even with backwashes performed daily during the operation period of Cycle 2 (except the first 7 d). This fact suggests that washing the support mesh with tap water at the end of Cycle 1 partially removed the particles causing the fouling. Considering this, Siddiqui et al. [24] state that formed DM can be removed by washing with water, however, the residue of the DM that has accumulated gradually over the entire operating period within the support material pores cannot be removed effectively by backwashing corroborated by Guan et al. [26].

However, the maximum TMP values recorded in both Cycles of the present study are higher than the maximum TMP values (20 kPa) recorded by Alibardi et al. [39] in the treatment of domestic sewage, using a AnDMBR system operated at ambient temperature and with concentrate recirculation.

The permeate flow behavior during the operating time of Cycle 1 and 2 is shown in Fig. 4.

From Fig. 4, it can be seen that the permeate flow of Cycles 1 and 2 decreased over the bioreactor's period of operation. However, in the first 5 d, the permeate flow had little variation, but the TMP in the same period increased from 2.4 to 2.8 kPa in Cycle 1, and from 10.0 to 23.0 kPa in Cycle 2. On the 7th day there was a reduction of approximately 10% in the permeate flow, when TMP reached 25.3 kPa in Cycle 2. It was at this point that backwashing was started. Between the 40th and 60th days of Cycle 1, there was a significant reduction in the permeate flow (from 638.2 to 208.5 L m^{-2} h^{-1}), which may be associated with the maturation stage of the dynamic membrane, as previously explained.

Therefore, even with backwashing carried out from the 7th day in Cycle 2 of the present work, the permeate flow continued to decrease, and TMP to increase. Alibardi et al. [39] identified similar behavior of TMP and permeate flow in their AnDMBR system after 90 d of operation. The researchers justified this fact based on Darcy's Law, which confirms the development of a stable DM when there is an approximate proportionality between the permeate flow and the TMP in the system.

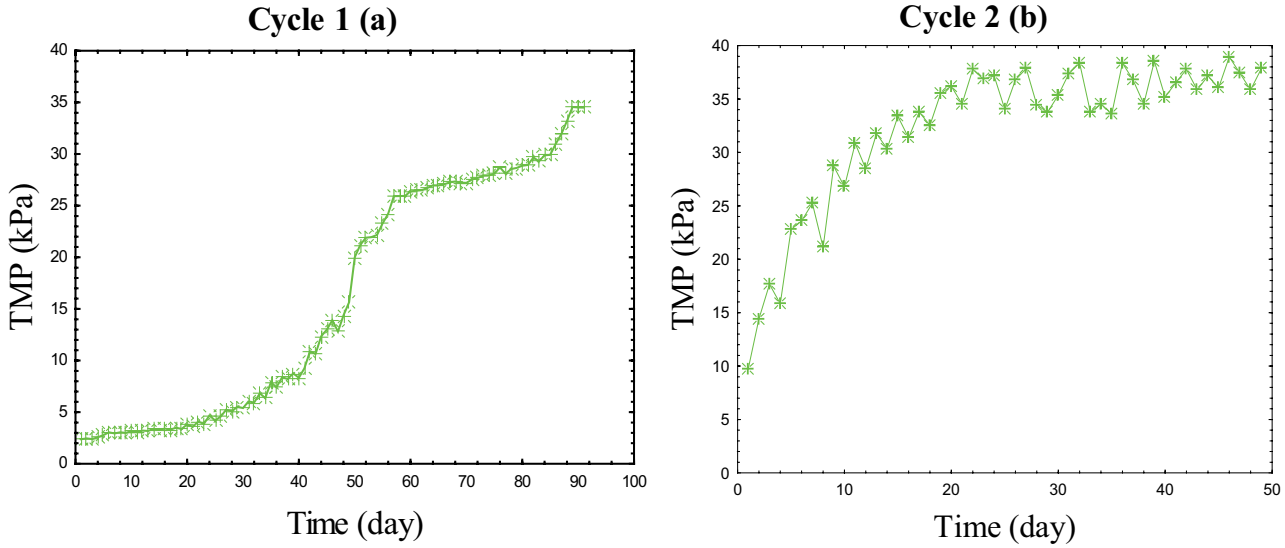


Fig. 3. TMP behavior in Cycle 1 and 2 throughout time of operation.

3.2. AnDMBR system performance in sewage treatment

The influent and effluent turbidity values during the operating time of Cycle 1 and 2 are presented in Fig. 5.

Analyzing the behavior of Fig. 5, it can be observed that in Cycle 1 the effluent turbidity started to be significantly reduced from 49 d of operation, and reached the lowest value of 23.6 NTU at 91 d, with maximum efficiency of 92.4%. In Cycle 2, effluent turbidity started to decrease significantly from 22 d of operation, and reached the lowest value of 18.0 NTU at 47 d, with a maximum efficiency of 95.2%. In the stationary period, the average turbidity value was 48.0 ± 26.0 NTU for Cycle 1, and 32.0 ± 16.0 NTU for Cycle 2.

Similar results for turbidity values in the stationary period were observed in the study by Hu et al. [33]. The authors attributed these values to the effective retention of particulate matter by the stable DM layer.

It can be seen from Fig. 5a that turbidity was extremely high in the first 10 d of operation, due to the fact that the DM had not yet developed. A similar situation was

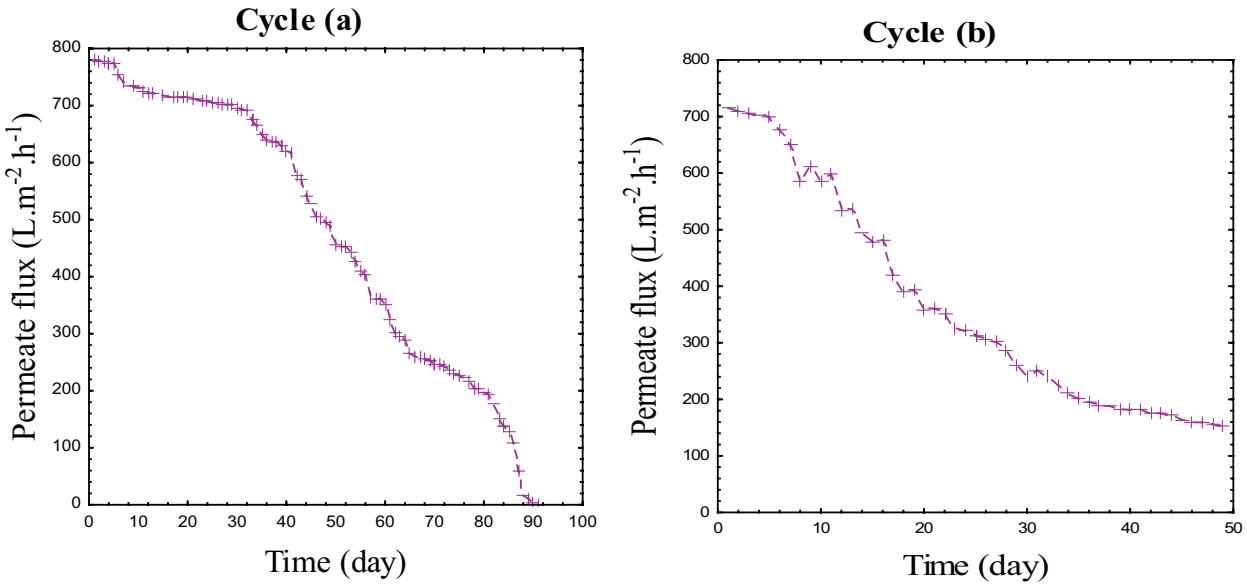


Fig. 4. Permeate flow profile of Cycle 1 and 2 during operating time.

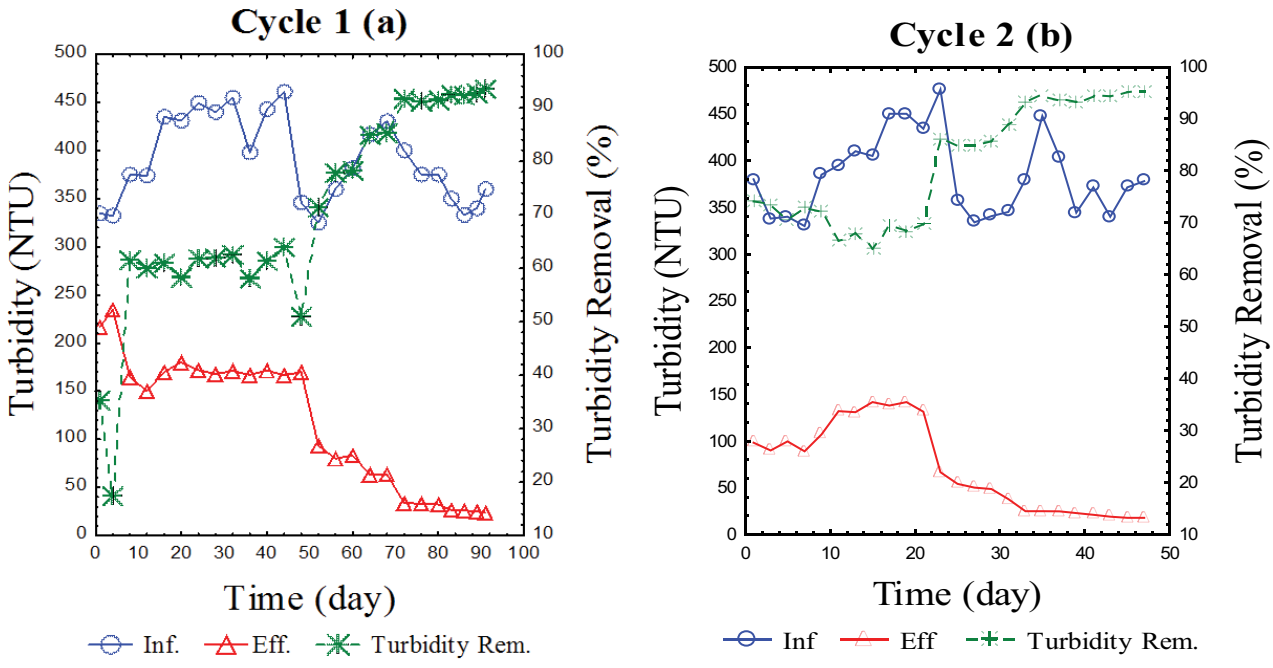


Fig. 5. Turbidity variation in Cycle 1 and 2 during system operation time.

observed by Alibardi et al. [18] in domestic wastewater treatment using a bench-scale AnDMBR.

Siddiqui et al. [24] ratified this phenomenon, confirming that effluent quality gradually increases with prolonged operation. Hu et al. [40] and Yu et al. [38] point out that the indicator of initial DM formation is a marked reduction in permeate turbidity, along with a drastic decrease in permeate flow.

The values of total suspended solids (TSS) and volatile suspended solids (VSS) during the operating times of Cycle 1 and 2 are shown in Fig. 6.

Fig. 6 shows that the stabilization of the solids in the effluent of Cycle 1 and 2 showed the same behavior regarding turbidity. System stabilization occurred after 49 d of operation in Cycle 1 and after 22 d in Cycle 2. At steady-state, TSS and VSS concentrations of effluent in Cycle 1 ranged from 49.1 to 93.5 mg L^{-1}, and from 32 to 58 mg L^{-1}, respectively. In Cycle 2, steady state effluent TSS and VSS concentrations ranged from 36 to 92 mg L^{-1} and from 28 to 46 mg L^{-1}, respectively. In Cycle 1 and 2, maximum TSS removal efficiencies of 90.1% were reached at 91 d and 92% at 49 d, respectively. Similar results of TSS and VSS variation with the system in steady state were observed by Alibardi et al. [39].

The behavior of the concentration of the total chemical oxygen demand (COD*t*) of the influent and effluent during the operating time of the AnDMBR system (Cycle 1 and 2) are shown in Fig. 7, as well as the same for soluble chemical oxygen demand (CODs) concentrations.

Total COD removal efficiency reached a maximum of 86.0% at 70 d in Cycle 1 and 88.0% at 49 d in Cycle 2 (Figs. 7a and b). Mean efficiencies of total COD removal during the stationary period were 86.0% ± 0.5% and 87.0% ± 1.8% for Cycle 1 and 2, respectively. The maximum soluble COD removal efficiencies were 74.0% at 91 d of operation, and 78.0% at 49 d, for Cycle 1 and 2, respectively (Figs. 7c and d). The mean removal efficiencies during the stationary period were 72.7% ± 2.4% for Cycle 1 and 70.2% ± 8.4% for Cycle 2. Hu et al. [33] treated sewage with high permeate flow (22.5 L m^{-2} h^{-1}), and achieved efficiencies of total COD removal between 70% and 90%, and 54% to 70% for soluble COD.

Alibardi et al. [39] stated high total and soluble COD removal efficiencies in the ranges of 80.0%–85.0% and 90.0%–95.0%, respectively, operating at a flow rate of 5 L m^{-2} h^{-1}. Ma et al. [19] treated raw sewage under a flow of 60 L m^{-2} h^{-1}, achieving 81.6% removal efficiency of total COD. Similar values were obtained by Wang et al. [41]. Therefore, compared to those observed in the present study, it can be stated that the AnDMBR system performed well with regards to removing total COD and soluble COD in both Cycles.

3.3. Carbohydrate and protein behavior as a function of operating time

Fig. 8 shows the concentrations of carbohydrates and proteins of the influent and effluent, obtained during the system operation period (Cycle 1 and 2). As shown in Fig. 8, there is a decreasing trend in carbohydrate and protein concentrations, both present in the effluent SMP (Cycle 1 and 2). In the stationary period, the mean carbohydrate concentrations present in the Cycle 1 influent and effluent SMP were 21.2 ± 2.5 and 8.2 ± 4.9 mg L^{-1}, respectively, and in Cycle 2 were 21.0 ± 2.3 and 5.3 ± 2.9 mg L^{-1}, respectively. The mean protein concentrations present in the influent

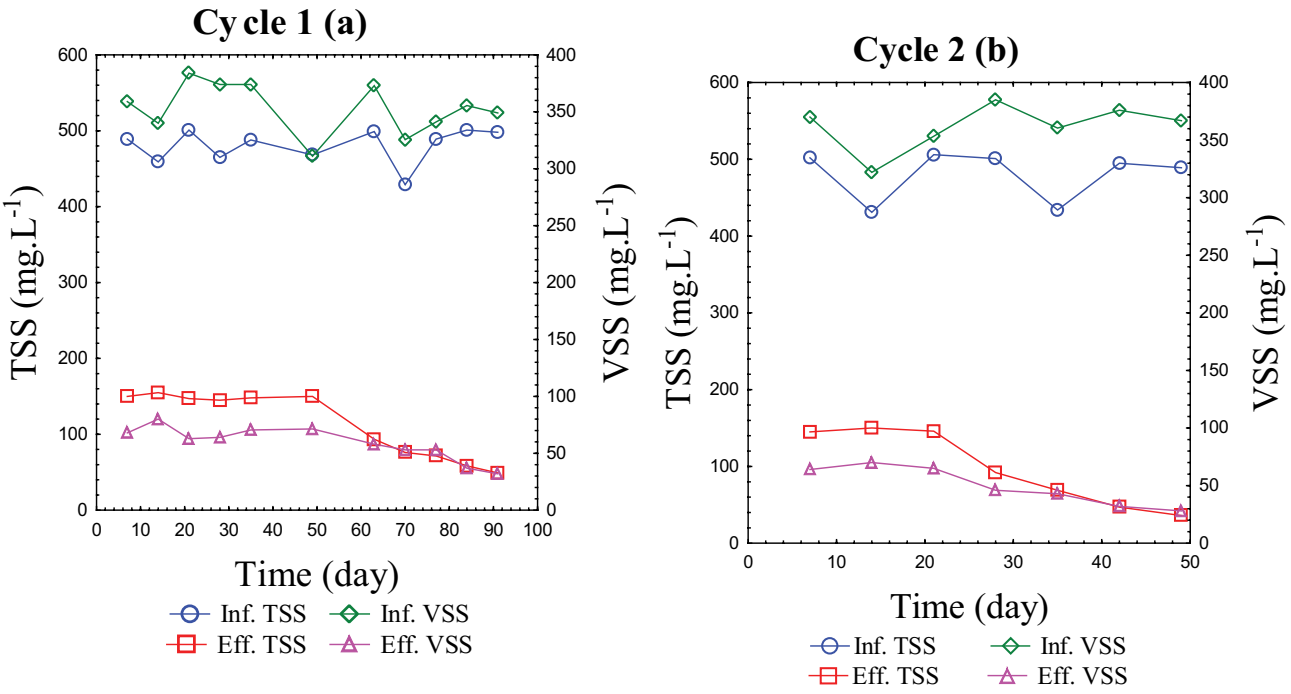


Fig. 6. Average values for fractions of solids for Cycle 1 and 2 during operation.

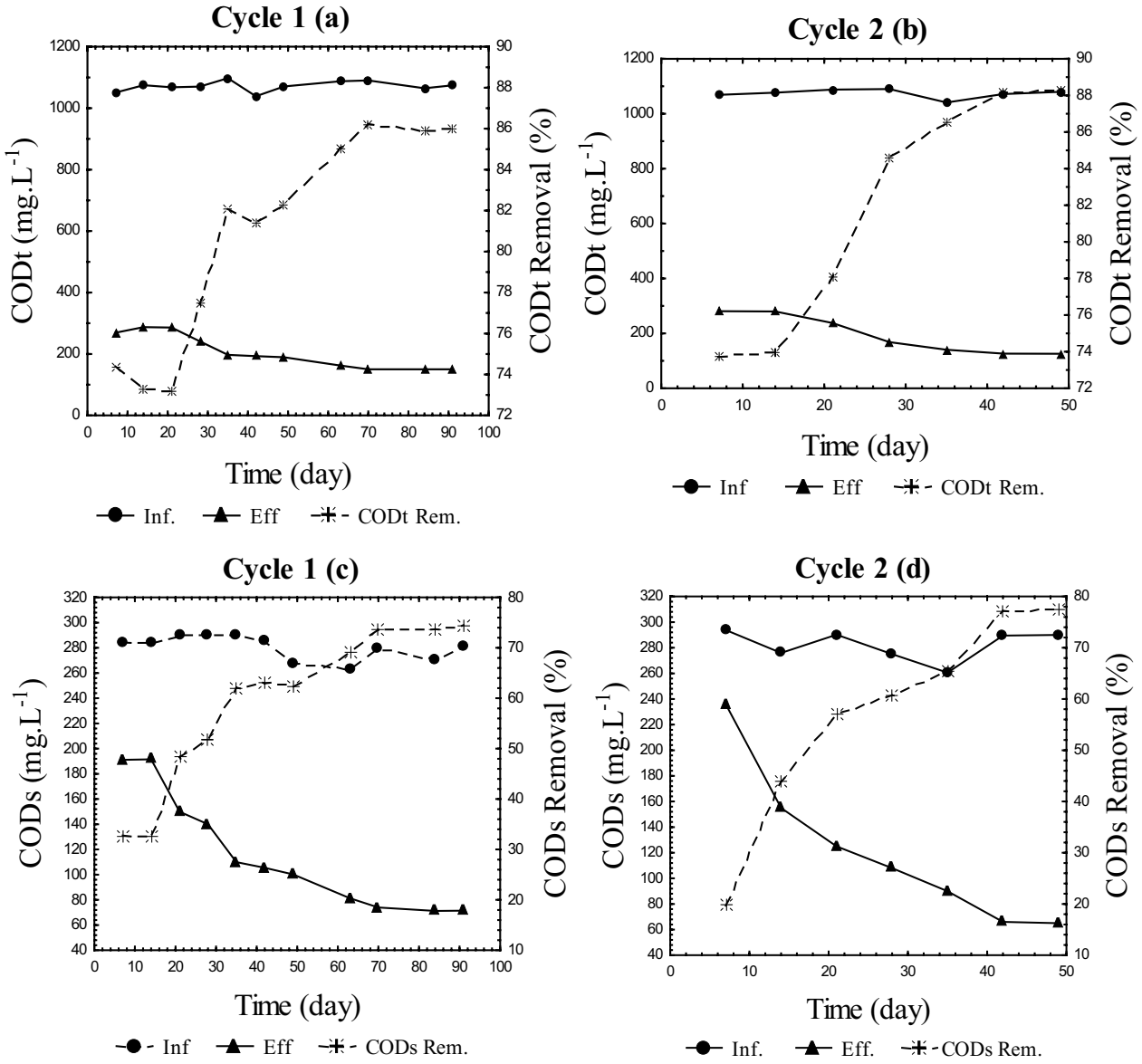


Fig. 7. Variation of total and soluble COD concentrations during system operation time (Cycle 1 and 2).

and effluent SMP were 42.0 ± 5.4 and 12.7 ± 6.8 mg L^{-1}, respectively. In Cycle 2 they were 42.7 ± 4.5 and 9.0 ± 4.1 mg L^{-1}. Therefore, there was a greater decrease in protein concentration than in carbohydrate concentration in both Cycles evaluated. This behavior was also observed by Hu et al. [33], who considered the proteins present in SMP to be the main causes of fouling, responsible for the rapid increase in TMP and the high resistance to filtration during long-term AnDMBR operation.

Shi et al. [42] understood that a large amount of soluble proteins are retained in the cake layer, and the larger molecules may be responsible for the high rejection rate of proteins in the liquid phase. Compared to carbohydrates, proteins have a higher affinity to sludge particles due to their higher hydrophobicity and surface charge. Yu et al. [38], pointed out that proteins are the greater influencers of sludge hydrophobicity when compared to carbohydrates because of aromatic or aliphatic amino acid side chains. Summarizing, the effects of the presence of SMP in the medium may cause fouling and decrease permeate flow [42].

3.4. Removal of helminth eggs

Average values of helminth eggs from the influent and effluent of Cycle 1 and 2 are shown in Fig. 9. In both Cycles, a decrease in the concentration of helminth eggs in the effluent was observed (Fig. 9). In the stationary period, the concentration of helminth eggs in the influent of Cycle 1 was 29.3 ± 3.8 eggs L^{-1}, and in Cycle 2 was 28.9 ± 2.7 eggs L^{-1}. In the effluent of Cycle 1 it was 0.43 ± 0.41 eggs L^{-1}, and in Cycle 2 it was 0.17 ± 0.33 eggs L^{-1}.

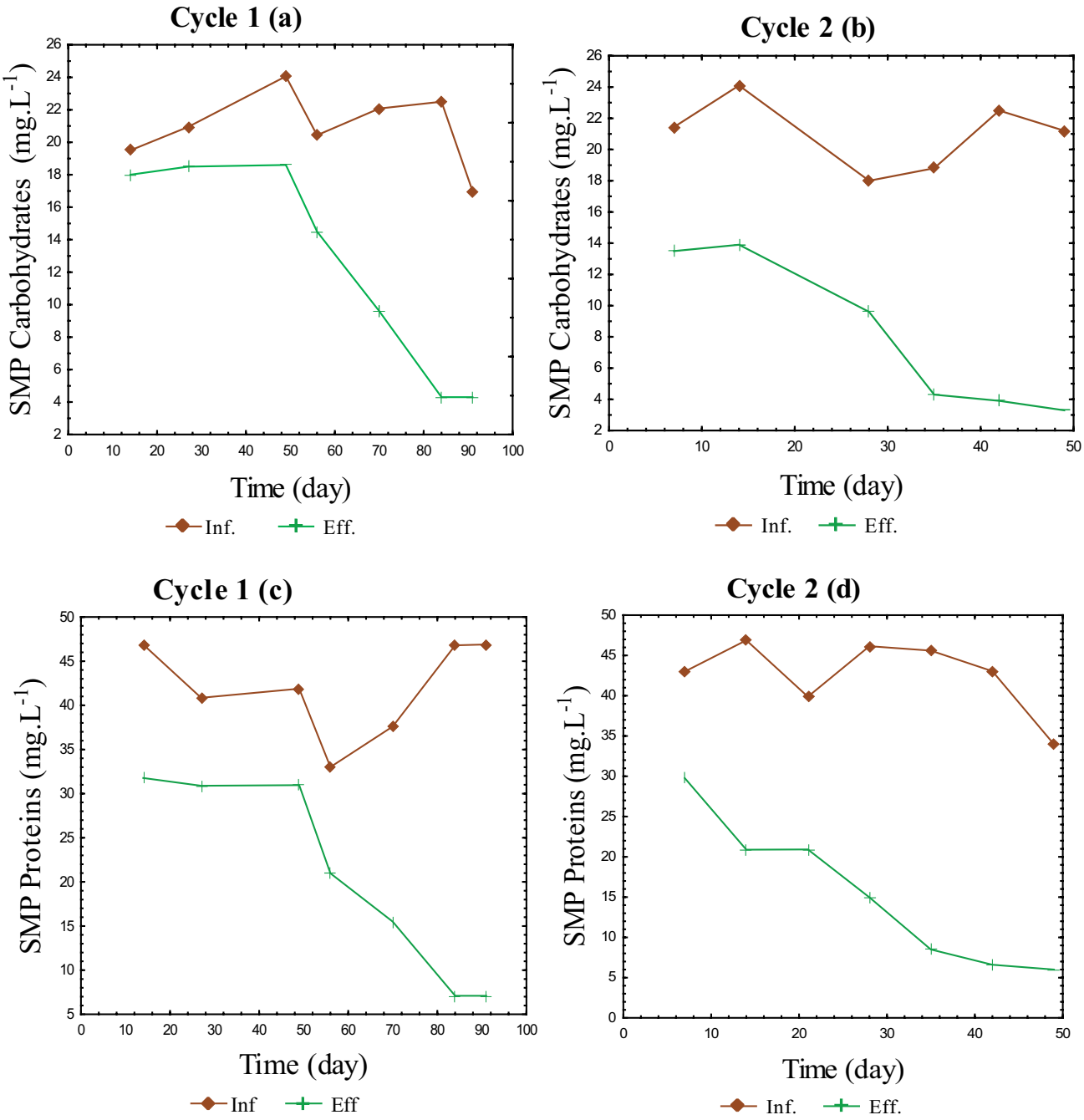


Fig. 8. Carbohydrate and protein concentrations of the influent and effluent, over the period of operation (Cycle 1 and 2).

The frequencies of helminth eggs found in the influent of Cycle 1 and 2 were 50% and 42.3% of *Ascaris lumbricoide*; 21.4% and 23.1% of *Ancilostomatideo*; 17.9% and 19.2% *Enterobius* sp., and 10.7% and 15.4% of *Hymenolepis* sp., respectively. In the effluent of Cycle 1 and 2, the frequencies were 50%–57.1% of *A. lumbricoide*; 25% and 28.6% of *Ancilostomatideo*, and 25% and 14.3% of *Enterobius* sp., respectively.

In the study by Yaya-Beas et al. [7], a concentration of helminth eggs ranging from 160 to 256 eggs L^{-1} was found in domestic wastewater, and in the UASB effluent, the results ranged from 5 to 35 eggs L^{-1}, with a predominance of *A. lumbricoide*. In the study by Sousa et al. [6], the concentration of helminths was 230 eggs L^{-1} in domestic sewage, and 160 eggs L^{-1} in UASB effluent. Sousa et al. [43] found egg concentrations of 357.3 eggs L^{-1} in raw sewage and 229.9 eggs L^{-1} in UASB effluent, with frequencies of 56.5% and 61.5% of *A. lumbricoide*; 27.7% and 21.5% of *Trichuris trichiura*, 9% and 8.7% of *Ancilostomatideo*, 5.5% and 4.4% of *Enterobius* sp., and 2.7% and 3.7% of *Hymenolepis* sp., respectively. These reports

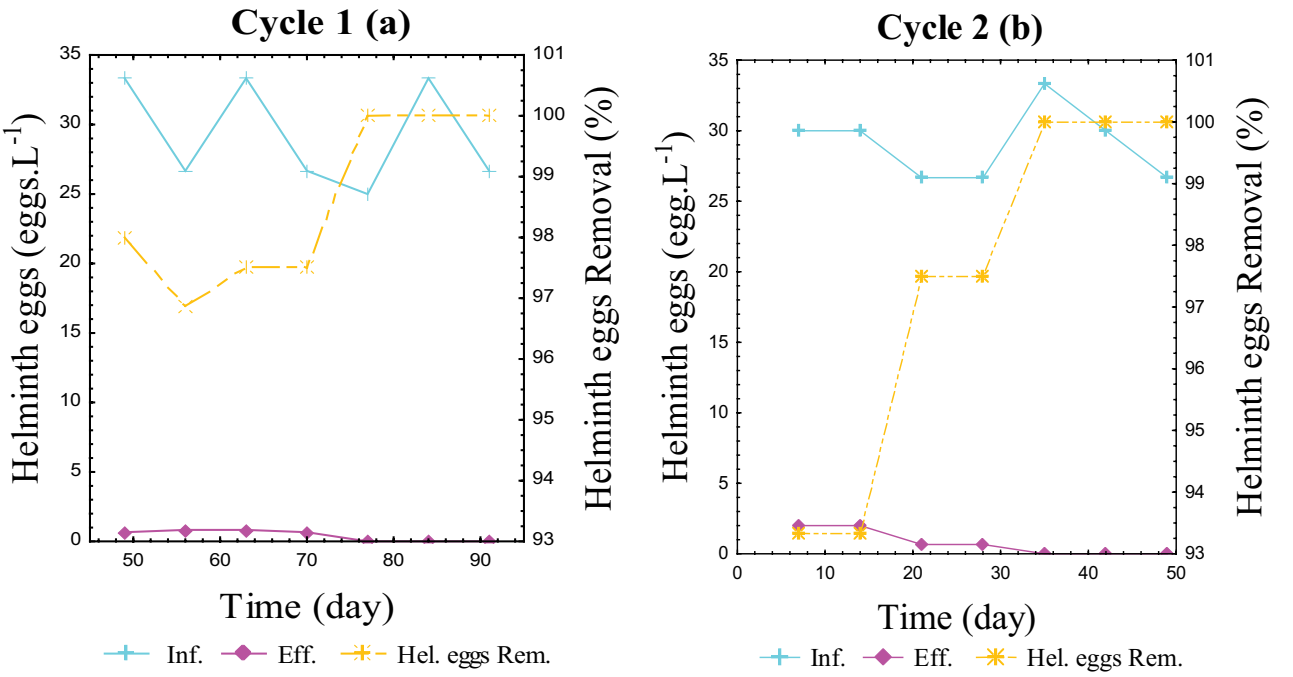


Fig. 9. Mean values of helminth eggs in Cycle 1 and 2.

show that the UASB reactor effluent contained a high concentration of helminth eggs [44].

According to Maya et al. [45], the concentration of helminth eggs in domestic wastewater from developing countries ranges from 70 to 3,000 eggs L^{-1}, while in developed countries it varies from 1 to 9 eggs L^{-1}. According to Chaoua et al. [46], the concentration of helminth eggs also varies according to the hygiene habits of the population. WHO [47] guidelines recommend a concentration of ≤1 eggs L^{-1} of helminths for irrigation. Thus, the effluent generated in both steady-state Cycles of the present work is promising for unrestricted irrigation.

3.5. Biogas production

The average biogas production quantified for Cycle 1 was 7.6 ± 0.9 NL d^{-1}, and for Cycle 2, 9.2 ± 2.2 NL d^{-1} (Fig. 10). According to van Haandel and Letiinga [31], Chernicharo [32], and Hu et al. [33] in the treatment of domestic wastewater by anaerobic digestion, the levels of methane in biogas are generally in the range of 70%–80%. Considering this, and that 70% of the biogas in this study was in the form of methane, the production of methane for Cycle 1 was 5.32 NL d^{-1}, which corresponds to a yield of 78 $NmLCH_4$ g^{-1} COD removed. For Cycle 2, it was 6.44 NL d^{-1}, corresponding to a yield of 96.1 $NmLCH_4$ g^{-1} COD removed. The theoretical values of biogas estimated based on Eqs. (2) and (3) were 28.0 and 26.7 NL d^{-1}, for Cycle 1 and 2, respectively. This means that the production of biogas for Cycle 1 and 2 correspond to only 27.1% and 34.5% of the theoretical value, respectively.

It is observed that biogas production and average methane yield in both Cycles was much lower than theoretical values, and this can be explained by the considerable biogas output in dissolved form with effluent from the system. Pauss et al. [48] stated that the liquid–gas mass transfer coefficient changes significantly according to reactor configuration and operating conditions, and can lead to methane concentrations in the liquid phase that are up to 12 times higher than equilibrium values.

It is understood that the low values of methane yields obtained were due to an actual concentration of methane dissolved in the liquid phase which was considerably higher than the amount calculated under thermodynamic equilibrium. This hypothesis was confirmed by Hu et al. [22], Ersahin et al. [49], Ersahin et al. [50], and Noyola et al. [51].

3.6. Mass balance

To evaluate the efficiency of the process, a mass balance was performed during a stationary period, based on the average loads of the following parameters: COD*t*, total Kjeldahl nitrogen (TKN), and total phosphorus (TP), whose values are presented in Table 2.

Looking at Fig. 11, which deals with the total COD mass balance, it can be seen that only about 12.0%–14.0% of the carbonaceous material fed into the AnDMBR system left in the effluent. Of this fraction, most of it came out in soluble form. Similar results were found by Alibardi et al. [39]. The sum of the produced sludge fractions (bioreactor, backwashing, and DM) in terms of COD was 10.9 and 14.83 g COD d^{-1} for Cycle 1 and 2, respectively. These values represent 70.9% and 96.2% of the theoretical sludge production of 15.37 and 15.42 g COD d^{-1} for Cycle 1 and 2, respectively.

However, although in Cycle 1 there was a significant difference between the values of produced COD and theoretical COD of the sludge, the sludge production coefficients

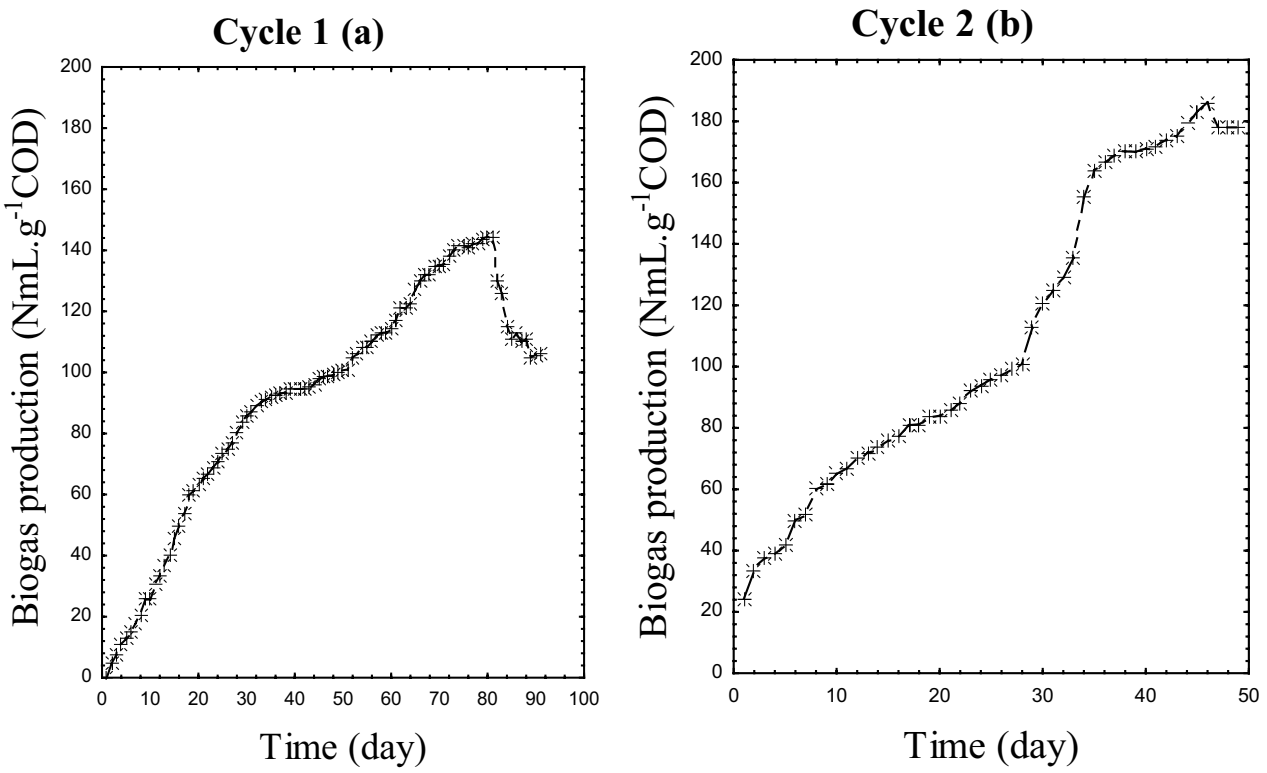


Fig. 10. Behavior of biogas production during Cycle 1 and 2 operation.

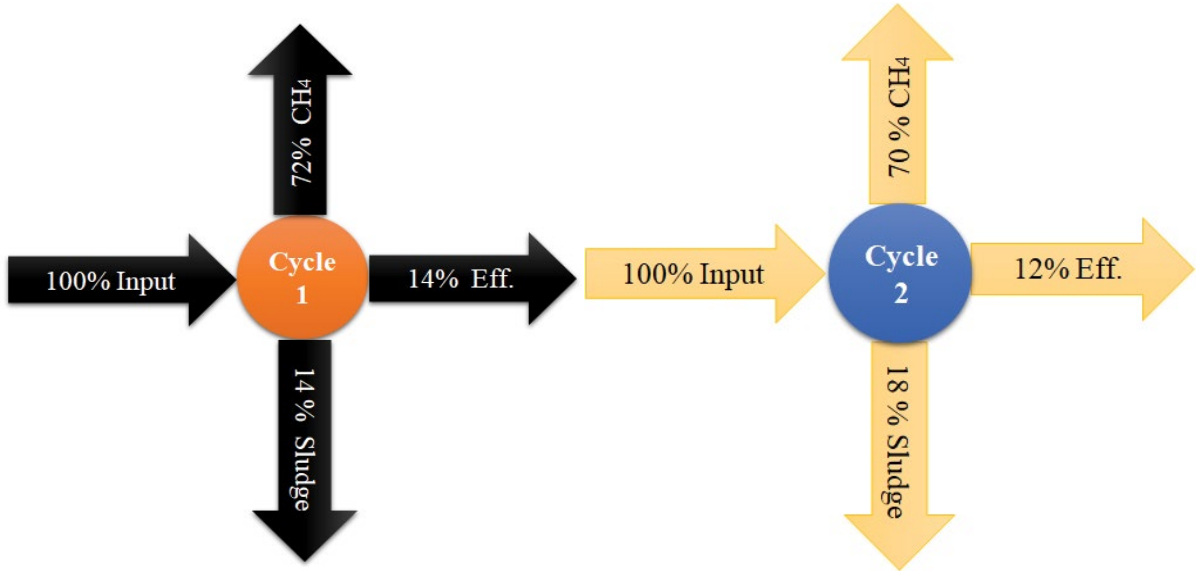


Fig. 11. Behavior of fractions of carbonaceous material mass balance.

of both Cycles varied by 14.0% and 18% for Cycle 1 and 2, respectively. Both are within the ranges of 10%–20% put forward by van Haandel and Lettinga [31] and Chernicharo [32]. It is noteworthy that this coefficient of production of solids ranging from 0.14 to 0.18 g COD_{sludge} g^{-1} $COD_{applied}$ occurred for a sludge age of 140 d, however, for higher sludge ages the Y_{obs} will probably be lower. The COD fractions of 72.0% and 70.0% converted to methane in Cycle 1 and 2, respectively, are close to the maximum values of 70% mentioned by van Lier et al. [52].

Table 2 shows the values of TKN and total phosphorus. Through the mass balance, TKN removal efficiencies of 20.1% for Cycle 1 and 20.4% for Cycle 2 were obtained. The total phosphorus removal efficiencies were 16.4% and 16.3% for Cycles 1 and 2, respectively. Similar values were found by Wang et al. [41], Ershain et al. [49], Ershain et

Table 2
Daily mass balance of COD*t*, TKN, and total phosphorus from Cycle 1 and 2

		COD*t* (g d^{-1})		TKN (g d^{-1})		TP (g d^{-1})	
		Cycle 1	Cycle 2	Cycle 1	Cycle 2	Cycle 1	Cycle 2
Input	Influent	77.863	77.103	6.000	5.868	0.964	0.928
	Inoculum	0.000	5.284	0.000	0.155	0.000	0.326
	Total	77.863	82.387	6.000	6.023	0.964	1.255
Output	Effluent	10.900	9.886	4.795	4.673	0.806	0.777
	DM	5.6087	3.306	0.320	0.222	0.083	0.057
	Backwashing	0.000	1.020	0.000	0.085	0.000	0.019
	Bioreactor	5.284	10.503	0.155	0.326	0.072	0.149
	Methane	56.06	57.671	–	–	–	–
	Total	77.774	78.104	5.270	5.232	0.964	1.001

al. [50], and Sousa et al. [53]. Anaerobic systems really do not remove nutrients. The decay of nutrients in anaerobic digestion is mainly due to the absorption of these macronutrients for the growth of biomass in the anaerobic process. This observation makes it evident that the use of AnDMBRs should be recommended for the production of effluent for reuse in agriculture, mainly due to the large amount of nitrogen and phosphorus available.

4. Conclusions

The results showed that an anaerobic DM can be formed in a support mesh with a large pore size (90 μm), treating domestic sewage at ambient temperature in pilot scale. The dynamic membrane can be generated without backwashing or with daily backwashing for a long period, under high flow of the initial permeate (780 L m^{-2} h^{-1}) at an average TMP of between 16.0 and 32.0 kPa, respectively. However, after the beginning of the DM formation, the permeate flow cannot be restored to the previous value by backwashing daily, or rather, the permeate flow tends to decrease continuously and the TMP tends to increase proportionally, even with daily backwashing. After the complete formation of the DM, fouling in the support mesh is difficult to remove by backwashing.

The results also showed that there was a greater decrease in the concentration of proteins than of carbohydrates, suggesting that the proteins present in the SMP were main causes of fouling. The AnDMBR performed well with regards to total COD removal efficiency (86.0%–88.0%), maintaining a soluble COD efficiency ranging from 74.0% to 78.0%. The removal of suspended solids reached 91.0% efficiency, producing an effluent with low turbidity (18.0 NTU) and meeting WHO recommendations [47], which recommend <1 helminth egg per liter for unrestricted irrigation. This suggests suitability for irrigation.

Although the amount of biogas measured in the system was low, when compared to its theoretical value, the mass balance shows that the fraction of COD converted to methane was greater than 70%. This ensured that a significant amount of biogas was produced by the system, and most of it probably left in dissolved form with the effluent due to supersaturation in the liquid medium.

Acknowledgments

This study was supported by Coordination of Higher Education Personnel Improvement (CAPES) and National Council for Scientific and Technological Development (CNPq). The authors would like to thank Financier of Studies and Projects (FINEP), CAPES, and CNPq for the financial support and fellowships.

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Supplementary information

Table S1
Physico-chemical and biological characteristics of influent and effluent

	Cycle 1			Cycle 2		
	Mean values ± SD			Mean values ± SD		
Parameter	Influent	Effluent	Rem. (%)	Influent	Effluent	Rem. (%)
COD*t* (mg L^{-1})	1,079.4 ± 11.0	151.4 ± 6.0	86.0	1,070.9 ± 8.0	137.3 ± 4.2	87.0
COD*s* (mg L^{-1})	280.0 ± 14.0	74.0 ± 19.9	74.0	290.0 ± 14.0	65.0 ± 14.5	78.0
Helminth eggs (egg L^{-1})	29.3 ± 3.8	0.43 ± 0.41	99.0	28.9 ± 2.7	0.17 ± 0.33	99.0
carbohydrates (mg L^{-1})	21.2 ± 2.5	8.2 ± 4.9	61.0	21.0 ± 2.3	5.3 ± 2.9	75.0
Proteins (mg L^{-1})	42.0 ± 5.4	12.7 ± 6.8	70.0	42.7 ± 4.5	9.0 ± 4.1	79.0
Turbidity (NTU)	371.0 ± 32.8	48.0 ± 26.0	87.0	376.0 ± 41.7	32.0 ± 16.0	92.0
TSS (mg L^{-1})	483.2 ± 38.9	63.8 ± 12.3	87.0	488.0 ± 30.9	48.4 ± 28.8	90.0
VSS (mg L^{-1})	342.8 ± 12.9	42.8 ± 10.9	88.0	372.0 ± 10.7	35.2 ± 8.6	91.0
TKN (m L^{-1})	83.3 ± 1.9	66.6 ± 11.7	20.1	81.5 ± 1.2	64.9 ± 6.3	20.4
TP (mg L^{-1})	13.4 ± 1.17	11.2 ± 1.2	16.4	12.9 ± 1.06	10.8 ± 1.1	16.3
VFAs (mg L^{-1})	91.0 ± 1.58	39.3 ± 2.1	57.0	91.2 ± 1.6	38.1 ± 2.7	58.0
pH	7.1 ± 0.13	7.3 ± 0.12	–	7.2 ± 0.16	7.4 ± 0.10	–
*NO_3^- (mg L^{-1})	1.1 ± 0.4	1.1 ± 0.1	0.0	1.1 ± 0.6	1.1 ± 0.1	0.0

COD*t*: total chemical oxygen demand; COD*s*: soluble chemical oxygen demand; TSS: total suspended solids; VSS: volatile suspended solids; TP: total phosphorus; TKN: total Kjeldahl nitrogen, VFAs: volatile fatty acid.