Test of Membrane Aerated Biofilm Reactors for Nitrogen Removal in Wastewater Treatment

Cheng Chen
School of Engineering, University of Guelph, Guelph, Ontario, N1G 2W1, Canada
lbs2018@xju.edu.cn

Abstract. Membrane aerated biofilm reactor, as a biological wastewater treatment technology, has been nearly mature on a commercial scale. It uses bubble-free aeration to provide oxygen for biological nitrification and wastewater degradation. A novel oxygen-permeable hollow fiber membrane (Zeelung cord) specifically designed for use in a membrane aerated biofilm reactors (MABR). These fibers are organized into bundles, which are wrapped around the reinforcing core to increase strength. This permeable membrane allows oxygen to diffuse into the attached biofilm, which directly leads to the biological oxidation of pollutants in the wastewater. This study aimed to determine the nitrification and oxygen transfer capacity of Zeelung fibers used in the MABR system. The effects of various C/N ratios (in the range of 1.0 to 3.0) on the membrane modules were studied using three laboratory-scale reactors over the course of 165 days. In this test, the average removal efficiency of COD can reach 74% under selected conditions, up to 90%. Meanwhile, the average nitrification rate is 3.9 g/d/m2, the average ammonia removal rate is 90%, and the maximum value can reach 99%. In addition, the oxygen transfer rate of the fiber in the liquid phase was 19.65 g/d/m2. The experiment also indicated that the nitrification rate is directly proportional to the transfer flux of oxygen and is related to the content of dissolved oxygen in the water. The nitrification rate can be controlled by controlling the concentration of dissolved oxygen in water, thus affecting the removal rate of ammonia nitrogen.

Keywords: Membrane Aerated Biofilm Reactor, Zeelung Cord, Nitrification Rate, Oxygen Transfer Rate, COD Removal Efficiency.

1. Introduction
There are many ways to reuse the effluent from municipal sewage treatment plants as reclaimed water, which can effectively alleviate the problem of water shortage in cities around the world. However, due to the limitation of nitrogen removal technology in sewage treatment, the effluent still contains a certain amount of ammonia nitrogen, which can cause a variety of public health and safety risks when discharged into the environment. Therefore, the new technology of deep removal of ammonia nitrogen and total nitrogen in the municipal wastewater treatment plant is a new problem.

Advanced wastewater treatment technologies, such as membrane aerated biofilm reactor (MABR), are gradually replacing traditional treatment processes such as activated sludge process. MABR can produce high quality treated water, and can also treat industrial grade wastewater [1]. Wastewater treatment plants must operate continuously on a daily basis, and approximately 50% to 60% of the energy used in typical conventional activated sludge (CAS) treatment plants is used for aeration units [2]. This also results in the consumption of billions of kilowatt-hours of energy per year at sewage
treatment plants. Traditional aerated bioreactors have only 25-35% oxygen transfer efficiency at 4.5m water depth [3]. MABR has great advantages in the utilization of oxygen. The oxygen transfer efficiency (OTE) of MABR can reach approximately 100%; at the same time, oxygen utilization (OUE) exceeded 80% [4]. The significant difference in OTE is MABR's advantage over conventional aerated bioreactors. Additionally, biological nitrogen removal is an effective method to remove nitrogen pollutants from wastewater. When run under low oxygen partial pressure, there will form part of nitrification in MABR area, where completely autotrophic nitrogen removal over nitrites will take place, thus removing the ammonia nitrogen in the wastewater. Therefore, the improvement of MABR aeration module is an emerging topic attracting attention in the field of sewage treatment.

The operation cost of wastewater treatment plants is usually very expensive, among which the cost of electricity is one of the main reasons for the high operating price. Sewage plants must operate 24 hours a day, consuming billions of kilowatt-hours of energy each year. In a typical conventional activated sludge (CAS) treatment plant, approximately 50% to 65% of the net energy requirements are used for aeration for biological treatment [2]. The book of Wastewater engineering: Treatment and Resource Recovery (2013) showed that due to mechanical ventilation and small bubble diffusion [3], the oxygen transfer efficiency of a typical 4.5m deep activated sludge aeration tank could only be realized at 25-35%. This offset mode of operation has generated interest in the development of more cost-effective aeration methods that improve oxygen transfer and utilization, save on capital costs, and improve the efficiency of existing infrastructure.

A cost-effective and promising approach that has been developing since the late 1980s is the use of a membrane aerated biofilm reactor (MABR) [5]. The technique uses a breathable hollow fiber membrane to diffuse gaseous oxygen directly into the attached nitrifying biofilm. This aeration method is known as bubble-free aeration because oxygen is absorbed inside the dense polymer film and transported by diffusion into the liquid without any bubble formation [6]. There are three reasons why MABR's oxygen supply is more efficient: firstly, the oxygen is inside the hollow fibrous membrane cavity, which is not affected by the buoyancy of the liquid, so the staying time of ocean air is prolonged. Furthermore, the gas flow does not have to overcome the static liquid pressure, so air can be transported at low pressure. Last, since MABR can achieve oxygen transfer efficiency of more than 90%, it can be operated under low-speed airflow [7]. In addition to its high oxygen transfer efficiency, MABR allows for both nitrification and denitrification in the same reactor. This function also provides four advantages that traditional processes do not: (1) Certain alkalinity can be generated to sustain nitrification; (2) The oxidation of nitrate into the water by BOD can reduce energy consumption; (3) Potential for rapid nitration; (4) The interior can be divided into the aerobic zone and an anoxic zone, and the internal circulation between the two zones can save energy [3].

MABR and ZeeLung cord have many applications today. The technology has huge market potential, and one of the applications that have attracted a lot of attention is the use of MABR to modify aeration tanks to improve the secondary processing of existing CAS. The ZeeLung fibers can be assembled in a removable cartridge and then installed in an existing aeration tank with minimal change to its own infrastructure. An existing bubble diffuser can be modified into a hybrid air supply unit. This modification not only reduces energy consumption but also increases processing capacity and facilitates future expansion needs. Cote et al. in a recent study showed that using ZeeLung™ cords MABR can achieve greater than 6 kg/O2/kWh energy efficiency [8], at the same time remained 91% of the total removal rate of suspended particulate matter, COD removal rate of 83%. 95% ammonia removal rate and 66% total inorganic removal rate for traditional domestic sewage. This energy efficiency is about 3.8 times higher than that of the air diffuser and the mechanical energy efficiency of 1.2-1.6 kg/O2/kWh [3]. However, due to ZeeLung cords exist in business time is very short, so more research is needed to quantify the various performance and parameters in secondary processing. When looking at ZeeLung cords on the growth of denitrifying microorganism membrane layer will be how to respond to the C/N ratio under different water conditions. This test aims to solve these problems.
2. Methodology

2.1. Fundamental of MABRs

The hollow fiber structure and outer membrane in a typical MABR system form the liquid phase and gas phase through separation. Casey believed that hollow fibers in MABR have two main functions [9]: they can be used as a medium for the growth of biofilms and as a carrier for oxygen diffusion, which also makes the oxygen supply first diffuse to the bacteria on the membrane surface, thus forming stable biofilms.

Organics containing oxygen and nitrogen will diffuse the biofilm to the aerobic layer for nitrification, while denitrification will occur in the outer anaerobic layer. MABR abides by the Monod growth equation and two basic principles: Fick's 1st Law and Henry's Law.

Fick's Law is the molar flux due to diffusion, which is proportional to the concentration gradient. The stratification of biofilms is a key factor in determining gas flux. Microorganisms in a biofilm gradually reduce the amount of dissolved gas, which causes the concentration of dissolved gas to be lower than in the cleaning film [10]. Henry's law means that the amount of gas dissolved is proportional to the partial pressure of the gas in the gas phase.

2.2. Principles of Gas Transfer

Fick's Law is the molar flux due to diffusion, which is proportional to the concentration gradient. The stratification of biofilms is a key factor in determining gas flux. Microorganisms in a biofilm gradually reduce the amount of dissolved gas, which causes the concentration of dissolved gas to be lower than in the cleaning film. Martin pointed out that gas dispenses to the biofilm through the membrane to the liquid phase [10], as shown in Eq. (1).

\[ J = K_{LDL} (C_{LB} - C_{L}) \]
\[ K_{LDL} = \frac{D}{t_{LDL}} \]

Eq. (1)

Where: \( J = \) gas flux \([M \cdot L^{-2} \cdot T^{-1}]\), \( K_{LDL} = \) mass transfer coefficient of the LDL \([L \cdot T^{-1}]\), \( D = \) diffusively to the dissolved gas in water \([M \cdot L^{-3}]\), \( t_{LDL} = \) thickness of the liquid diffusion layer \([L]\).

On the surface of the biofilm, there is an LDL (liquid diffusion layer) formed which can reduce the amount of gas transferred to the main liquid, resulting in higher gas utilization than traditional processes [11]. LDL does not form between the fiber membrane and the biofilm.

Henry's law means that the amount of gas dissolved is proportional to the partial pressure of the gas in the gas phase. Therefore, the gas diffuses through membrane to the biofilm can also be expressed in Eq. (2) [10]:

\[ J = HS_{MK} K_{M} \left( \frac{P}{H} - C_{MB} \right) \]

Eq. (2)

Where: \( J = \) Gas flux \([M \cdot L^{-2} \cdot T^{-1}]\), \( H = \) Henry’s law constant \([L^{-2} \cdot T^{-2}]\), \( S = \) Gas/membrane partition coefficient \([L^{-2} \cdot T^{-2}]\), \( K = \) Mass transfer coefficient of the membrane \([L \cdot T^{-1}]\), \( P = \) Partial pressure in the gas phase \([M \cdot L^{-1} \cdot T^{-2}]\), \( C = \) Dissolved gas concentration \([M \cdot L^{-3}]\).

In a traditional biofilm, ammonia and oxygen molecules diffuse from the liquid into the biofilm. Thus, these molecules must penetrate the surrounding LDL before reaching the interior LDL has a high barrier to gas transfer, which also results in low oxygen utilization. MABR, additionally, shows the opposite characteristic of countercurrent diffusion. Instead of being transported by the liquid, oxygen diffuses from the hollow fiber lumen into the biofilm and completely avoids LDL. At the same time, LDL can be a barrier on the outside of the biofilm, which helps to retain internal substances and thus improve the utilization rate of oxygen [10].
2.3. Oxygen Transfer in MABRs
The transfer rate of oxygen is an important parameter to test the performance of MABR, but the experimental conditions cannot always be carried out under ideal conditions, so we need to modify Eq. (2) accordingly. The biofilm-liquid interface is where biochemical reactions occur. Oxygen needs to be diffused through the biofilm, a total of microbial life. Pellicer-Nacher modified the transmembrane oxygen transfer rate to represent the conditions of the MABR system [12]:

\[ J_{\text{gas}} = k_{\text{gas}} \left( \frac{S_{O_2,\text{bio}}}{H} - S_{O_2,\text{gas}} \right) \]

Eq. (3)

Gonzalez-brambila et al observed the transfer rate of oxygen and found a linear relationship between oxygen solubility and time in MABR [13]. In addition, the change of charging pressure will also affect the speed of air supply. The surface area of the membrane outside the outlet and intake pressure is also one of the factors influencing the oxygen transfer rate [14]. The oxygen consumption on the surface of biofilm caused by the biochemical reaction will reduce the resistance of oxygen transfer.

3. Materials & Operational Conditions
The test tested the effect of dissolved oxygen content in water on ZeeLung nitrification performance and oxygen transfer capacity. The test system consisted of three parallel 1-inch diameter MABR reactors. ZeeLung hollow fiber membrane was used for testing. Compressed air entered the membrane fibers of each reactor from the top of the reactor. Three groups of MABR were used for parallel experiments. There would be 14 days of start-up before data collection, to ensure that the biofilm grows equally at the start of the experiment. After that, data were collected once a week during the experimental phase. The entire test process lasted 165 days. The whole test operation is in mixing mode, that is, nitrogen backwash has achieved the purpose of full mixing. Nitrogen as scouring gas entered from the bottom of the reactor for aeration agitation. The sludge inoculated in the reactor was nitrated from the municipal sewage treatment plant in the city of Guelph. The experimental design MLSS concentration was 3 g/L. At the beginning of the test, excessive sludge was added to make the MLSS concentration reach about 5 g/L. The reduced concentration was gradually released during the post-culture process, and a small amount of supplementation was made every week to compensate for the loss caused by irrigation. The feed solution entered the reactor in the opposite direction to the air supply and flowed out at the top of the reactor. The total volume of each reactor was 0.8 L. The process flow chart of the reactor is shown in figure 1.

![Figure 1. Process flow diagram of a single bench-scale reactor](image)

This test used synthetic wastewater as process water. Glucose was the carbon source of synthetic wastewater. The nitrogen source was ammonium chloride. At the same time, sodium bicarbonate and
tracer solution were added to the feed. The tap water was dechlorinated by air stripping and used to prepare the feed solution. During the test, the C/N ratio remained at 4:3, and the load ratios of COD and ammonia were 5.6 g/d/m² and 4.2 g/d/m², respectively. Water inlet and recirculation lines should be regularly checked and cleaned to avoid clogging. The process air pressure of the three pipelines was 33 kPa, and the air flow rate was set at 3.5 mL/min. The main operation parameters are shown in the Table 1.

Table 1. The main operation parameters

| Parameter                        | R1   | R2   | R3   | Unit   |
|----------------------------------|------|------|------|--------|
| COD Loading Rate                 | 5.6  | 5.6  | 5.6  | g/d/m² |
| NH₃-N Loading Rate               | 4.2  | 4.2  | 4.2  | g/d/m² |
| HRT                              | 4    | 4    | 4    | hour   |
| Scouring Intensity               | 150  | 150  | 150  | mL/min |
| MLSS                             | 3.0  | 3.0  | 3.0  | g/L    |
| Process Air Pressure             | 33   | 33   | 33   | kPa    |
| Reactor Back Pressure            | 15   | 15   | 15   | kPa    |
| Process Air Flow                 | 3.5  | 3.5  | 3.5  | mL/min |

4. Results & Discussion

4.1. Results

Table 2. Summary of results in seeding procedure

| Parameter                  | Reactor 1 | Reactor 2 | Reactor 3 | Unit   |
|----------------------------|------------|------------|------------|--------|
| Influent Conditions        |            |            |            |        |
| [COD]                      | 40         | 40         | 40         | mg/L   |
| [NH₃-N]                    | 30         | 30         | 30         | mg/L   |
| C/N ratio                  | 4/3        | 4/3        | 4/3        | -      |
| [DO]                       | 0.2        | 0.2        | 0.2        | mg/L   |
| [TN]                       | 32.6       | 32.6       | 32.6       | mg/L   |
| Alkalinity (as CaCO₃)      | 200        | 200        | 200        | mg/L   |
| pH                         | 8.0        | 8.0        | 8.0        | -      |
| Temperature                | 20 - 22    | 20 - 22    | 20 - 22    | ℃      |
| MLSS                       | 3          | 3          | 3          | g/L    |
| Scouring Intensity         | 150        | 150        | 150        | mL/min |
| Hydraulic Conditions       |            |            |            |        |
| HTR                        | 4.0        | 4.0        | 4.0        | hour   |
| COD loading rate           | 5.6        | 5.6        | 5.6        | g/d/m² |
| Ammonia loading rate       | 4.2        | 4.2        | 4.2        | g/d/m² |
| Effluent Conditions        |            |            |            |        |
| [COD]                      | 10         | 12         | 11         | mg/L   |
| [NH₃-N]                    | 3          | 5          | 11         | mg/L   |
| [NO₂⁻]                     | 0.4        | 0.4        | 0.1        | mg/L   |
| [NO₃⁻]                     | 25         | 24         | 0.1        | mg/L   |
| [DO]                       | 0.3        | 0.3        | 0.5        | mg/L   |
| [TN]                       | 28.3       | 29.4       | 28.4       | mg/L   |
| Alkalinity (as CaCO₃)      | 71         | 73         | 120        | mg/L   |
| pH                         | 6.8        | 6.7        | 7.1        | -      |
Removal Rates

|                      | Removal Rates | Nitrification rate | Ammonia removal efficiency | COD removal rate | COD removal efficiency |
|----------------------|---------------|--------------------|----------------------------|------------------|------------------------|
|                      |               | 3.9                | 90                         | 4.1              | 74                     |
|                      |               | 3.6                | 84                         | 3.8              | 68                     |
|                      |               | 2.7                | 62                         | 4.0              | 73                     |
|                      |               | g/d/m²             | %                          | g/d/m²           | %                      |
|                      |               |                    |                            |                  |                        |

Oxygen Transfer

|                      | Oxygen Transfer | Inlet air flowrate | Membrane Backpressure | Outlet O₂ percentage | Oxygen flux (liquid phase) | Oxygen flux (gas phase) |
|----------------------|-----------------|--------------------|-----------------------|-----------------------|---------------------------|-------------------------|
|                      |                 | 33                 | 15                    | 15.3                  | 19.65                     | 20.94                   |
|                      |                 | 33                 | 14                    | 17.8                  | 18.17                     | 10.16                   |
|                      |                 | 33                 | 10                    | 19.2                  | 14.04                     | 42.42                   |
|                      |                 | mL/min             | kPa                   | %                     | g/d/m²                    | g/d/m²                  |

The water samples should be thoroughly mixed during sampling and testing to avoid the interference of sbCOD particles in synthetic wastewater. Table 2 shows the data of three trails under steady-state circumstances. Three sets of parallel-tests, the trail 1 performed best, the average COD removal rate was 74%, and the removal rate of Ammonia is 90%. At the same time, the other two groups of COD removal rate were 68% and 73%, ammonia removal rate was 84% and 62%, respectively. On the other hand, trail 1 with the highest removal rate has the highest oxygen transfer flux (19.64 g/d/m²).

4.2. Discussion

![Figure 2. Nitrification rate (g/m²/d)](image-url)
As can be seen, digestion rate and oxygen transfer flux have almost the same trend. This indicates that oxygen transfer flux has a direct effect on nitrification. Dissolved oxygen content in water is also one of the main factors influencing the removal effect of ammonia nitrogen. Cui also got the same result through the experiment [15], that ammonia-oxidizing bacteria activity was suppressed when the water dissolved oxygen content was low, which led to the ammonium oxidation rate reducing; moreover, when the content of dissolved oxygen in water had been recovered, ammonia-oxidizing activity of bacteria would be restored. The results shown in figure 3 and 4 are also consistent with the views of Côté et al [16]. They adopted the MABR of Zeelung fiber to achieve an ammonia nitrogen removal efficiency of 95%.

Figure 3. Oxygen flux in Liquid phases (g O2/m2/d)

Figure 4. Effluent Nitrogen Species (percentage)

Figure 4 showed the proportion of components in the treated effluent. Because the air flow rate of reactor 3 was smaller than that of the other two reactors, thus the oxygen flux was also the smallest, which directly led to more ammonia nitrogen residues. Reactor 1 had the highest air flow, so more ammonia nitrogen had been oxidized into nitrite and nitrate, and finally denitrified into nitrogen and...
discharged out of water. At the same time, nitrogen as a nutrient element can promote the reproduction of bacteria, which was why the gaseous and organic nitrogen in reactor 1 was higher than that in reactor 2. The situation in reactor 3 was different, because of the small oxygen flux, anaerobic denitrifying bacteria would multiply in large quantities, which was the reason that denitrification rate of reactor 3 was very high when the digestibility is lower than other reactors.

5. Conclusive
The entire test lasted 165 days (including 14-day startup phase). Three laboratory-scale MABR reactors were used to test the nitration and oxygen transfer properties of Zeelung fibers. The test used a synthetic feed solution. Tap water supplied with the feed solution needed to be strip-dechlorinated in advance. The results of these tests provide valuable insight into the use of ZeeLung/ MABR technology for the oxidation and nitration of contaminants. The results show that MABR can provide high nitrification ability and high level of dissolved oxygen in secondary treatment. Here are the main test results:
1) Under laboratory conditions, the average COD removal efficiency of Zeelung fiber can reach 74%, 90% for maximum, and the average COD removal rate is 4.1 g/d/m2; meanwhile, its average nitrification rate was 3.9 g/d/m2, the average ammonia removal rate was 90%, and the maximum could reach 99%. In addition, the oxygen transfer rate of this fiber is 19.65 g/d/m2 in the liquid phase.
2) The nitrification rate is proportional to the transfer flux of oxygen and is also related to the content of dissolved oxygen in the water. The nitrification rate can be controlled by controlling the concentration of dissolved oxygen in water, thus affecting the removal rate of ammonia nitrogen.
3) Nitrification rate and TN removal are more sensitive to the change of oxygen transfer flux than COD loading.
4) In the middle of the test, leakage was taken place of R3 membrane resulting in low dissolved oxygen in the water. However, it also showed the nitrification performance of Zeelung fibers under low oxygen transfer flux conditions. The COD removal rate and nitrification rate was lower than that of R1 and R2. However, denitrification did not decrease significantly.
There were some errors in this test. Recommendations for future test or experimental work are the following:
1) To detect the composition of biofilm and find out the biological reasons that affect the nitrification ability of biofilm.
2) Longer test times are needed to truly test the potential of hybrid operation to affect the nitrification properties of biofilms. Effects of different C/N ratios on nitrification rate. Can also be integrated different C/N ratio and the Scouring Intensity, in order to find the optimal combination. The nitrification efficiency of ammonia nitrogen can reach more than 90%. Future studies can improve TN removal rate and organic carbon removal rate without reducing nitrification rate.
3) If possible, it is recommended to use larger reactors to simulate more realistic situations. Larger reactors can make this more apparent, and the bubbles can have a degree of horizontal motion to increase the stirring effect.
4) BOD data should have used to study the performance of sewage treatment. A carbon source containing sCOD is recommended to simulate synthetic wastewater because glucose is an easily degradable carbon source.
The above suggestions will be improved in future experiments; at the same time, more removal rates and control factors of other pollutants will be investigated.

References
[1] Aryal, R., Lebegue, J., Vigneswaran, S., andasamy, J., Grasmick, A. 2009. Identification and characterisation of biofilm formed on membrane bio-reactor. Separation and Purification Technology, 67(1), P86–94.
[2] USEPA, 1999. Wastewater technology fact sheet, fine bubble aeration, EPA 832-F-99-065. U.S.
[3] Metcalf, E., Eddy, M. 2014. Wastewater engineering: Treatment and Resource Recovery. McGraw-Hill, USA.

[4] Ahmed, T., Semmens, M. J. 1992. The use of independently sealed microporous hollow fibre membranes for oxygenation of water: model development. Journal of Membrane Science, 69(1-2), P11-20.

[5] Long, Z. 2013. Tertiary Nitrification Using Membrane Aerated Biofilm Reactors: Process Optimization, Characterization & Model Development (Dissertation). University of Guelph.

[6] Côté, P., Bersillion, J., Huyard, A. 1989. Bubble-free aeration using membranes: Mass Transfer Analysis. Journal of Membrane Science, 47, P91–106.

[7] Syron, E., Vale, P., Casey, E. 2014. Where did the bubbles go? How to reduce the energy requirements for municipal wastewater treatment. IWA LET, Abu Dhabi.

[8] Côté, P., Peeters, J., Adams, N., Hong, Y., Long, Z. 2015. A New Membrane-Aerated Biofilm Reactor for Low Energy Wastewater Treatment: Pilot Results. EFTEC Conference. P4226–4239.

[9] Casey, E., Glennon, B., Hamer, G. 1999. Review of membrane aerated biofilm reactors. Resources, Conservation and Recycling, 27(1–2), P203–215.

[10] Martin, K. J., Nerenberg, R. 2012. Bioresource Technology The membrane biofilm reactor (MBBR) for water and wastewater treatment: Principles, applications, and recent developments. Bioresource Technology, 122, P83–94.

[11] Kreulen, H., Smolders, C. A., Versteeg, G. F., Van Swaaij, W. P. M. (1993). Determination of mass transfer rates in wetted and non-wetted microporous membranes. Chemical Engineering Science, 48(11), P2093-2102.

[12] Pellicer-Nácher, C., Smets, B. F. 2014. Structure, composition, and strength of nitrifying membrane-aerated biofilms. Water Research, 57, P151–161.

[13] González-Brambila, M., Monroy, O., López-Isunza, F. 2006. Experimental and theoretical study of membrane-aerated biofilm reactor behavior under different modes of oxygen supply for the treatment of synthetic wastewater. Chemical Engineering Science, 61(16), P5268-5281.

[14] Syron, E., Casey, E. 2008. Model-based comparative performance analysis of membrane aerated biofilm reactor configurations. Biotechnology and Bioengineering, 99(6), P1361-1373.

[15] Cui, B., Yang, Q., Liu, X., Huang, S., Yang, Y., Liu, Z. 2020. The effect of dissolved oxygen concentration on long-term stability of partial nitrification process. Journal of Environmental Sciences, 90, P343–351.

[16] Côté, P., Peeters, J., Adams, N., Hong, Y., Long, Z. 2015. A New Membrane-Aerated Biofilm Reactor for Low Energy Wastewater Treatment: Pilot Results. EFTEC Conference. P4226–4239.