OPTIMIZATION OF WASTEWATER TREATMENT BIOTECHNOLOGY USING A MEMBRANE BIOREACTOR

Kyrylo Kyrychenko[1], *Larisa Sablii*[1]

[1]National Technical University of Ukraine «Igor Sikorsky Kyiv Polytechnic Institute», Ukraine;

kyrychenko.kyryll@lll.kpi.ua, larisasabliy@ukr.net

DOI: https://doi.org/10.20535/2218-930032024327505

The growing environmental concerns associated with elevated levels of ammonium nitrogen in municipal wastewater, along with increasingly stringent discharge regulations, necessitate the development and implementation of advanced and highly efficient treatment technologies. This study is aimed at optimizing the operational parameters of a membrane bioreactor system for urban wastewater treatment, focusing on the balance between treatment performance and operational sustainability. Membrane bioreactor systems offer several key advantages over conventional biological treatment methods, including higher biomass retention, improved effluent quality, compact system design, and the ability to support simultaneous nitrification and denitrification processes within a single reactor. To investigate optimal operating conditions, GPS-X simulation software was used to model 36 combinations of filtration duration and washing duration over a 10-day dynamic period. The impact of these parameters on critical performance indicators – transmembrane pressure, hydraulic load, hydraulic permeability, nitrogen removal efficiency, and washwater consumption – was assessed. The simulations demonstrated that the optimal operating regime involved a filtration duration of 30 minutes combined with a washing duration of 180 seconds. Under these conditions, transmembrane pressure was minimized (1,586 kPa), while ammonium and nitrate nitrogen concentrations in the treated effluent were effectively reduced to 0.13 mg N/L and 11.36 mg N/L, respectively – well below the regulatory limits for discharge. Additionally, the system exhibited favorable hydraulic permeability (0.3635 $m^3/(m^2 \cdot kPa \cdot day)$) and moderate washwater usage (13.1 m^3/day), contributing to operational cost efficiency and membrane longevity. These results not only confirm the suitability of membrane bioreactor technology for nutrient removal but also emphasize its practical potential for municipal implementation in Ukraine. The study highlights the role of simulation-based optimization in achieving both environmental compliance and resource-efficient operation, reinforcing the relevance of membrane bioreactor systems as a core component of modern wastewater management strategies.

Keywords: *biotechnology, wastewater, biological wastewater treatment, membrane bioreactor, optimization.*

Received: 4 December 2024 Revised: 22 December 2024 Accepted: 30 December 2024

1. Introduction

Adverse environmental impacts associated with the presence of ammonium nitrogen include eutrophication, which has a negative effect on aquatic organisms due to reduction of dissolved oxygen in water, which is used to oxidise ammonia to nitrate. Given these adverse impacts, it is necessary to limit and/or remove ammonium nitrogen emissions. According to the regulatory and technical documentation, the maximum permissible total nitrogen concentration, including ammonium, nitrite and nitrate, at the outlet of a water treatment plant is no more than 42 mg/L (Sablii et al., 2021).

Due to the increasingly stringent requirements for the quality of treated wastewater (WW) discharged into water bodies, the need to develop new treatment methods and improve the efficiency of the existing ones has grown. Today, biological nitrogen removal is mainly carried out through nitrification and denitrification (as in Anoxic/Oxic technology) in such facilities as an aerotank nitrifier and denitrifier, respectively. Aerobic autotrophic nitrifiers oxidise ammonia to nitrite and then to nitrate. Under oxygen-free conditions, nitrate is reduced to nitrogen gas by heterotrophic denitrifying bacteria. Since autotrophic ammonia-oxidising bacteria have a low growth rate, nitrification is the limiting factor in biological nitrogen removal. Thus, the main challenge in biological nitrogen removal is maintaining the proper level of nitrifiers in the aeration tank.

In recent years, membrane bioreactor (MBR) have become a focus of designing WW treatment plants. The combination of membrane technologies and a bioreactor (aerotank/anaerobic digester) is a new direction in WW treatment that has not yet been implemented in Ukraine. For example, there is a pressing problem of sewage treatment in the pharmaceutical industry, which traditional biological treatment plants cannot cope with due to a number of disadvantages. These include large volumes of aeration tanks and secondary settling tanks, as well as an insufficient degree of treatment, which in most cases does not meet the standards for the permissible discharge of pollutants, requiring the use of post-treatment facilities. Traditionally, the pharmaceutical industry has used aerobic treatment methods in aerotanks to treat WW. However, operational experience has shown that this method is ineffective in removing all potentially hazardous pollutants in WW (Khrystenko A. M., 2023).

The MBR process was introduced in the late 1960s, as soon as commercial ultrafiltration (UF) and microfiltration (MF) membranes became available. The original technology was introduced by Dorr-Olivier Inc. and combined the use of an activated sludge bioreactor with a cross-flow membrane filtration circuit (C.V. Smith et al., 1969). The flat sheet membranes used in this process were polymeric and had a pore size of 0.003 to 0.01 m (D. Enegess et al., 2003). Although the idea to replace the settling tank in the traditional activated sludge process was attractive, it was difficult to justify the use of such a process due to the high cost of the membranes and the potential for rapid loss of performance due to fouling. As a result, the focus was on achieving turbulent flows, and therefore it was necessary to pump suspended solids at high cross-flow rates at high energy costs (in the order of 10 kWh/m^3) to reduce fouling. Due to the low efficiency of the first generation of MBRs, they were only used in niche areas with special needs, such as isolated trailer parks or ski resorts, for example.

The breakthrough for MBR came in 1989 with Yamamoto's idea to immerse membranes in a bioreactor (K. Yamamoto et al., 1989). Until then, MBRs were designed with a separation device located outside the reactor and relied on high TMP to maintain filtration. The lower operating costs obtained with the submerged module configuration, as well as the steady decline in membrane costs, contributed to the exponential growth in the number of MBR installations starting in the mid-1990s. While the first MBRs operated at solids retention times (SRT) of up to 100 days with suspended solids levels of up to 30 g/L, the trend in recent years has been toward shorter SRT (around 10-20 days) and, as a result, more manageable suspended solids levels (10-15 g/L). Due to these new operating conditions, overall maintenance has been simplified, as membrane cleaning is required less frequently. A number of MBR systems are now commercially available, most of which utilize submerged membranes, although some external modules are also available; these external systems also utilize two-phase flow to combat fouling. In terms of membrane configurations, hollow fiber and flat sheet membranes are mainly used for MBRs (D. Enegess et al., 2003).

The MBR has attracted the attention of engineers mainly because it can maintain a high dose of activated sludge (AS) in the reactor (up to 6-8 g/L). Accordingly, the following advantages can be distinguished due to this feature:

1. The retention time of biomass can be controlled as long as desired, which will create favourable conditions for the normal growth of some species of bacteria with low growth rates, such as nitrifier bacteria.
2. It is possible to implement simultaneous nitrification and denitrification due to the high dose of AS, which makes it easy to form an aerobic zone and an oxygen-free zone in one reactor.
3. Better and more reliable effluent quality compared to the conventional process and no need for post-treatment and usually disinfection.
4. Simple automatic control and compactness of the entire system.

The purpose of this work is optimisation of technological parameters of biological treatment of urban sewage sludge using MBR-based technology to ensure efficient removal of nutrient compounds and use of MBR membranes.

2. Materials and Methods

The GPS-X software (v8.0.1, Hydromantis Environmental Software Solutions, Inc., Hamilton, ON, Canada) was used in the course of the study. The software uses the Runge-Kutta-Felberg method, an algorithm for numerical solution of differential equations, to calculate technological parameters.

One of the GPS-X software features is dynamic analysis, which allows you to set the time interval in which the programme will constantly calculate the system parameters. In this study, a period of 10 days was chosen, during which the software calculated the outlet concentrations of pollutants (BOD_5, ammonium nitrogen, nitrate nitrogen) and the hydraulic parameters of the MBR membranes (transmembrane pressure, Hydraulic load, flux).

The inlet parameters of municipal WW used for the calculation and normative values as the target ones are shown in Table 1.

Table 1. *Characteristics of WW entering the WW treatment plant (average daily discharge = 2000 m^3/day)*

Indicator	Inlet value	Normative value
Suspended solids, mg/L	250	15
BOD_{total}, mg O_2/L	220	3
Ammonium, mg/L	30	0,5
Nitrate, mg/L	45	40

The diagram of the water treatment plant used for modelling is shown in Fig. 1.

The design and technological parameters of the treatment plant were specified and presented in Table 3.

After the design parameters of the WW treatment plant were calculated and entered into the programme along with the process parameters, the modelling and optimisation of the target parameters was started. The input data of the process parameters were set, namely the flushing flow, bubbling air flow, washing (WD) and filtration (FD) duration of the MBR (the latter two parameters were subject to optimisation).

For optimisation, the following FD and WD were selected as shown in Table 2 (Alnaizy et al., 2012; Aidan et al., 2008; Albasi et al., 2002; Hashino et al., 2011; Bouhabila et al., 2001; Hirani et al., 2010; Ivanovic et al., 2008; Jiang et al., 2003; Jiang et al., 2005; Ngo et al., 2009; Rosenberger et al., 2002; Schoeberl et al., 2005; Smith et al., 2005; Srijaroonrat et al., 1999; Villarroel et al., 2013; Yigit et al., 2009).

Table 2. *Input data for FD and WD*

WD, s	FD, min
30	10
60	20
90	30
120	40
150	50
180	60

Next, 36 FD and WD value pairs were formed and 36 simulations were run.

The biological treatment of the effluent is represented by an anoxic–aerobic sequence involving a denitrifier and an aeration tank. In the denitrifier, denitrification processes are carried out under anoxic (oxygen-free) conditions, which are maintained through the prevention of aeration and the use of mechanical mixers. These mixers ensure homogeneous distribution of substrates and biomass throughout the reactor, improving the efficiency of contact between denitrifying bacteria and available nitrate nitrogen. Under these conditions, nitrate is reduced to nitrogen gas (N_2), which escapes into the atmosphere, effectively removing nitrogen from the wastewater.

The success of this biological process depends heavily on the availability of easily biodegradable organic matter, which serves as an electron donor for denitrifying microorganisms. Optimizing this stage is crucial, as incomplete denitrification may lead to accumulation of intermediate forms such as nitrite or even nitrous oxide (N_2O), a potent greenhouse gas.

Following the denitrification stage, wastewater enters the nitrifier aeration tank, where aerobic conditions are provided by pneumatic aeration systems. This reactor supports both the oxidation of residual organic pollutants and the two-step nitrification process. The first step involves ammonia-oxidizing bacteria (AOB), which convert ammonium (NH_4^+) into nitrite (NO_2^-). In the second step, nitrite-oxidizing bacteria (NOB) further oxidize nitrite into nitrate (NO_3^-). These processes are strictly aerobic and require tight control of dissolved oxygen levels to ensure high efficiency and avoid inhibition of nitrifying bacteria due to oxygen deficiency or overloading.

To enhance the overall nitrogen removal efficiency, an internal recirculation system is used. A portion of the treated flow – ranging from 100 to 300% of the influent flow, and in some cases up to 500% – is returned from the end of the nitrifier (aerobic stage) back to the denitrifier (anoxic stage). This nitrate-rich flow, referred to as nitrate recirculation, provides sufficient nitrate for the denitrifying microorganisms to act upon in the anoxic zone, reducing nitrate levels in the final effluent.

This recirculation system also ensures hydraulic balance and consistent nutrient availability throughout the system. It supports the stability of the nitrogen cycle, reduces fluctuations in effluent quality, and minimizes reliance on chemical additives. Furthermore, operational flexibility can be achieved by adjusting the recirculation rate depending on the influent load, seasonal variations, or specific treatment goals.

After completing this anoxic–aerobic loop, the biologically treated water is directed into the MBR unit, where final polishing and solid–liquid separation occur. MBR integrate biological treatment with membrane filtration, resulting in high-quality effluent and compact system design. Within the MBR, concentrations of BOD_5, ammonium, and nitrate are further reduced to values below discharge limits. Ultrafiltration membranes retain suspended solids, activated sludge and pathogens, allowing only treated water to pass through. This results in low turbidity and pathogen-free effluent, which is suitable for reuse or direct discharge into natural water bodies.

To maintain optimal microbial conditions in the denitrifier, a portion of the AS is recirculated from the MBR back to the anoxic reactor at a rate of 30–100%. This internal recycling of biomass helps sustain microbial activity and supports continuous denitrification without introducing fresh influent.

At the same time, permeate (clarified treated water) is directed to a UV disinfection unit. Here, any microorganisms that may have passed through the membrane, including viruses or ultrafine bacteria, are exposed to ultraviolet radiation that damages their DNA and renders them inactive, further enhancing effluent safety.

The biological and membrane treatment stages together result in minimal sludge production compared to traditional systems.

However, excess sludge inevitably accumulates and must be managed. Surplus sludge from both the primary clarifier and the MBR is directed to a sludge thickener, where water is separated to concentrate the solids.

This thickened sludge is then treated in an anaerobic digester, where microbial fermentation processes decompose 40–50% of the organic content into biogas—primarily methane (CH_4) and carbon dioxide (CO_2). The resulting biogas can be captured and utilized as a renewable energy source for internal plant needs (e.g., heating, electricity generation).

The stabilized (digested) sludge, with reduced volume and odor, is transferred to sludge drying beds or storage facilities. Due to its nutrient content and pathogen reduction during digestion, the biosolids can be repurposed as agricultural fertilizer or soil conditioner, thus contributing to circular economy principles and sustainable waste management.

This closed-loop approach minimizes environmental impact, recovers valuable resources, and enhances the overall ecological efficiency of the wastewater treatment plant.

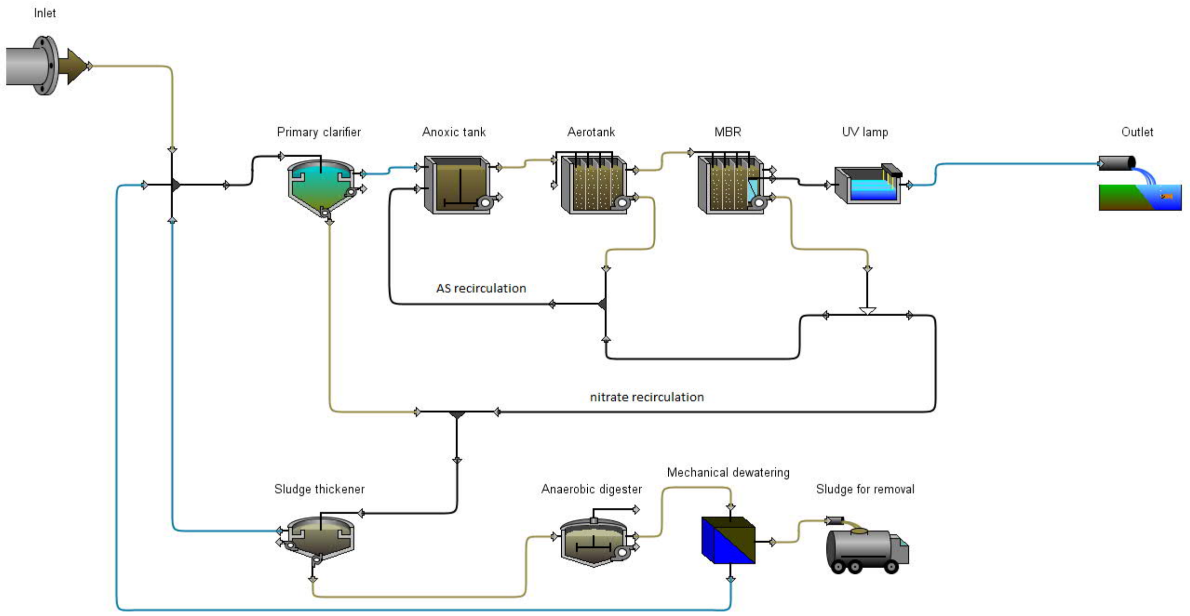

Fig. 1. *Schematic of a water treatment plant with a capacity of 2000 m³/day based on MBR*

Table 3. *Design and technological parameters of the plant's treatment facilities*

Process	**Design parameter**	**Value**	**Process parameter**	**Value**
Anoxic reactor	Maximum value	250 m^3	-	-
	Depth	4.0 m	Mixing method	Mechanical
Aerotank	Maximum volume of the regenerator	250 m^3	Air flow rate	~ 23500 Nm^3/day
	Maximum volume of the aerator	750 m^3	Dose of sludge in the regenerator	9.33 g/L
	Depth	4,0 m	Dose of sludge in the aeration tank	6 g/L
MBR	Reactor volume	51 m^3	Air flow rate	5721 Nm^3/day
	Total membrane area	3814 m^2	Washing duration	10-210 s
	-	-	Filtration time	5-60 min

3. Results and Discussion

Dependencies of TMP, Hydraulic load, productivity, ammonium nitrogen, nitrate nitrogen concentration and washingwater consumption on the duration of filtration and washing are shown in Fig. 2-7, respectively.

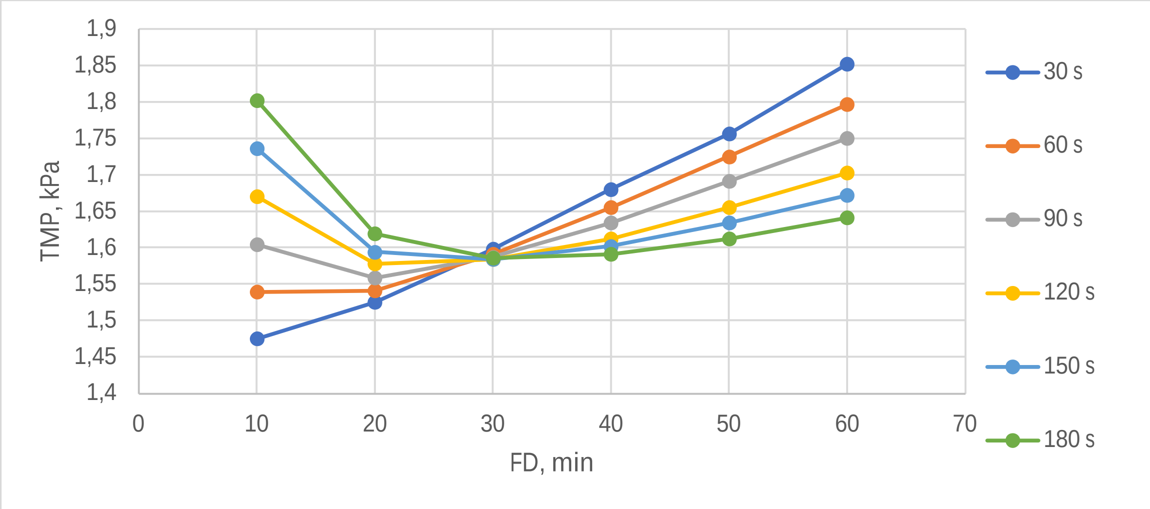

Fig. 2. *Dependence of TMP on FD at different WD (marked in different colours)*

The transmembrane pressure increases with increasing filtration duration. The higher transmembrane pressure observed at 10 minutes of filtration compared to 20 minutes is likely due to unstable operating conditions — short cycles don't allow the membrane to reach a steady filtration state, causing frequent startups and pressure spikes due to initial fouling layer formation. The lowest TMP (1,586 kPa) is achieved at FD = 30 min and WD = 180 s, which indicates lower energy consumption and reduced membrane wear. This is the ideal mode for reducing operating costs.

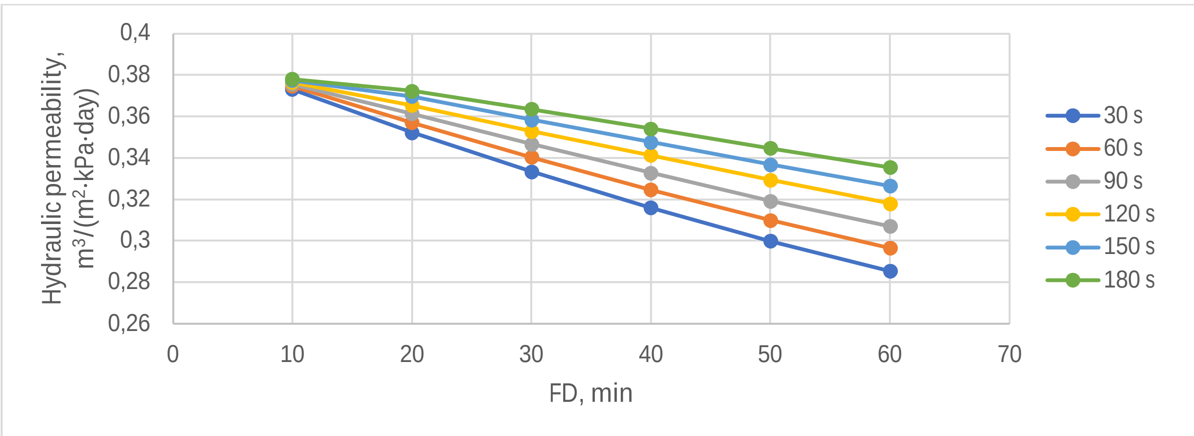

Fig. 3. *Dependence of hydraulic permeability on FD at different WD (marked in different colours)*

With increasing FD, the permeability decreases (which is expected due to membrane contamination). The high stable hydraulic permeability (0.3635 $m^3/(m^2 \cdot kPa \cdot day)$) is also observed at FD = 30 min and WD = 180 s. This ensures long-term operation of the membranes without the need for frequent cleaning.

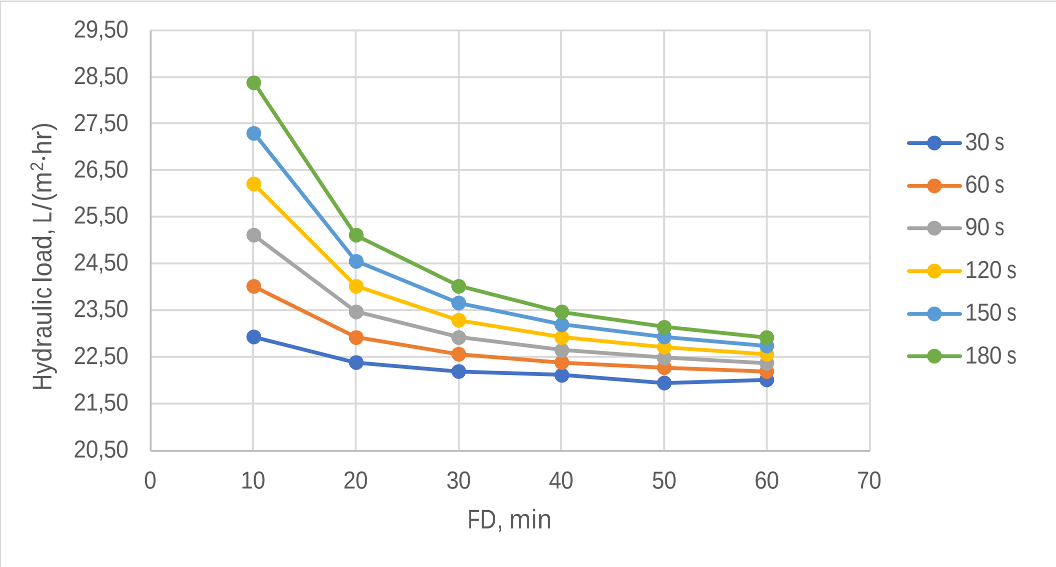

Fig. 4. *Dependence of hydraulic load on FD at different WD (marked in different colours)*

The efficient hydraulic load (23.66 $L/(m^2 \cdot hr)$) is achieved under the same conditions: FD = 30 minutes, WD = 180 seconds. This makes it possible to achieve high productivity with stable operation of the plant.

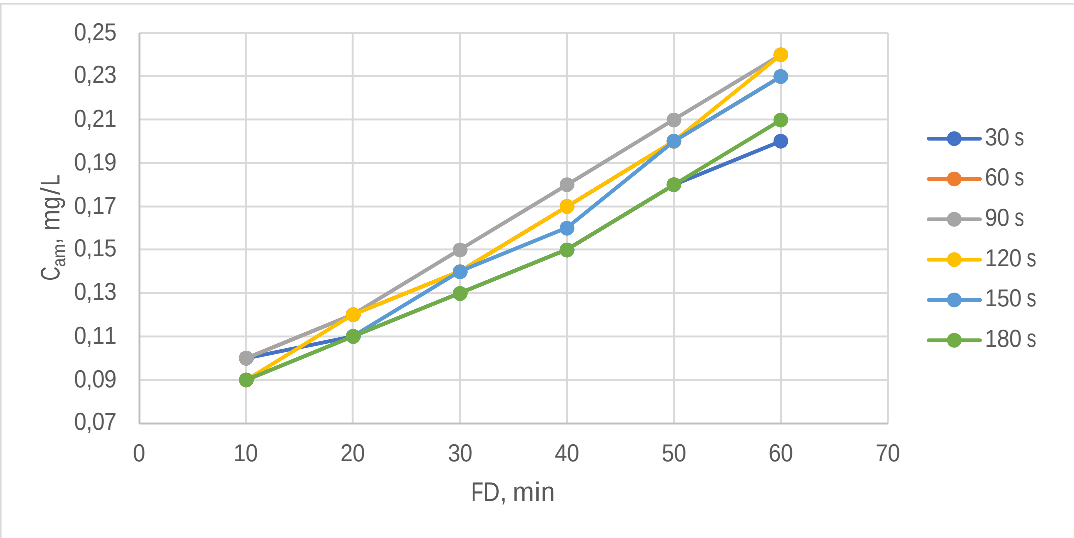

Fig. 5. *Dependence of ammonium concentration in treated water on FD at different WD (marked in different colours)*

Having FD = 30 min, WD = 180 s, the normative level ammonium concentration is achieved: 0.13 mg/L, which is lower than the standard (0.5 mg/L). This indicates effective nitrification due to sufficient aeration time and good conditions for the growth of nitrifiers.

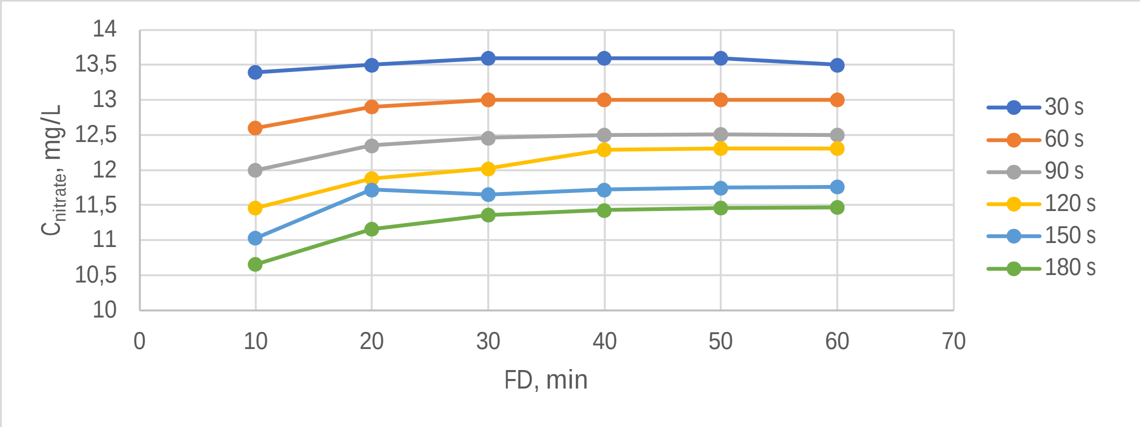

Fig. 6. *Dependence of nitrate concentration in treated water on FD at different WD (marked in different colours)*

With the same parameters, the nitrate concentration is 11.36 mg N/L, which is also lower than the standard (40 mg/L). This indicates effective denitrification.

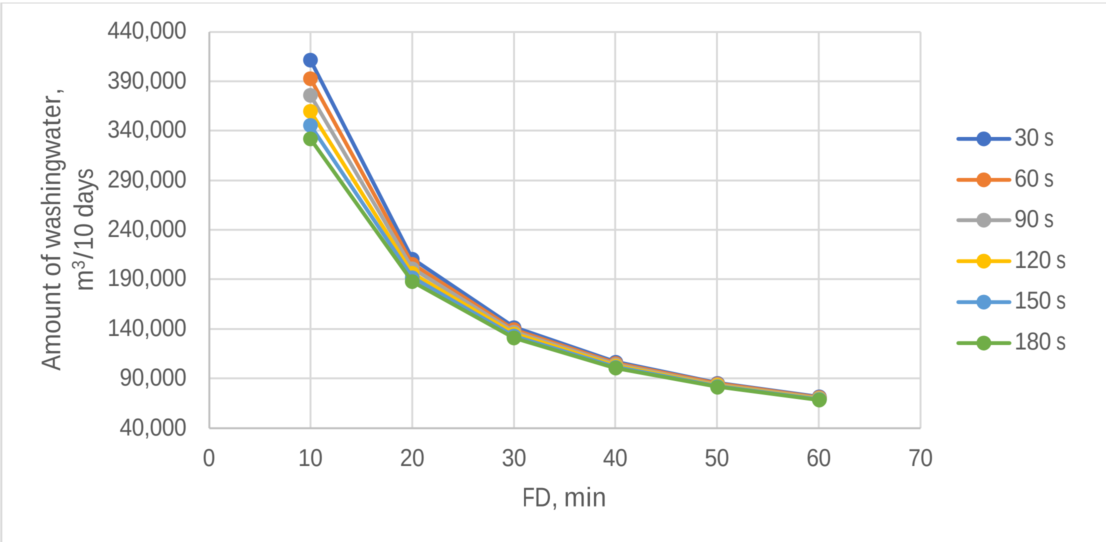

Fig. 7*. Dependence of washing water consumption on FD at different WD (marked in different colours)*

The most optimal washing regime is FD = 30 min and WD = 180 s, at which water consumption is 130.91 m³/10 days.

This allows to achieve resource savings without compromising cleaning efficiency.

4. Conclusions

The modelling and analysis of the membrane bioreactor operating modes provide efficient removal of ammonium and nitrate nitrogen to levels that meet the standards revealed that the optimal parameters among the options considered are 30 min of filtering and 180 s of washing, because superb parameters are achieved with this mode:

- the lowest *transmembrane pressure* – 1.586 kPa – which will have the lowest operating costs;
- *hydraulic permeability* – 0.3635 $m^3/(m^2 \cdot kPa \cdot day)$ – which allows for a longer membrane operation time in the filtration mode without washing;
- *hydraulic load* value – 24,0 $L/(m^2 \cdot hr)$ – at which splendid permeate yield efficiency is achieved;
- the *concentrations of ammonium and nitrate nitrogen* – 0.13 mg N/L and 11.36 mg N/L, respectively – which do not exceed the normative levels: 0.5 and 40 mg N/L, respectively;
- optimum *water discharge* for washing – 130.91 m^3/10 days.

Thus, the selected mode allows achieving high efficiency of WW treatment at reduced operating costs thanks to downsizing water discharge for washing membranes, which confirms the feasibility of using MBR for municipal WW treatment.

References

1. Sablii, L.; Bunchak, O.; Zhukova, V.; Workshop on biotechnology of water treatment: a textbook: a textbook for students of specialty 162 "Biotechnology and bioengineering", **2021**.

2. Khrystenko, A. M. Operation of biological wastewater treatment facilities using membrane technologies: PhD thesis in architecture: 192, **2023**.

3. Smith, C.W.; Di Gregorio D.; Talcott, R.M. The Use of Ultrafiltration Membrane for Activated Sludge Separation. Proceedings of the 24th Annual Purdue Industrial Waste Conference, West Lafayette, **1969**, pp 1300-1310.

4. Enegess, D.; Togna, A. P.; Sutton, P. M. Membrane separation applications to biosystems for wastewater treatment. Filtration & Separation **2003**, 40 (1), 14–17. https://doi.org/10.1016/s0015-1882(03)80092-7

5. Yamamoto, K.; Hiasa, M.; Mahmood, T.; Matsuo, T. Direct Solid-Liquid Separation Using Hollow Fiber Membrane in an Activated Sludge Aeration Tank. Water Science and Technology **1989**, 21 (4-5), 43–54. https://doi.org/10.2166/wst.1989.0209

6. Alnaizy, R.; Abdel-Jabbar, N.; Aidan, A.; Abachi, N. Modeling and dynamic analysis of a membrane bioreactor with backwash scheduling. Desalination and Water Treatment **2012**, 41 (1-3), 186–194. https://doi.org/10.1080/19443994.2012.664713

7. Aidan, A.; Abdel-Jabbar, N.; Ibrahim, T. H.; Nenov, V.; Mjalli, F. Neural network modeling and optimization of scheduling backwash for membrane bioreactor. Clean Technologies and Environmental Policy **2007**, 10 (4), 389–395. https://doi.org/10.1007/s10098-007-0129-0

8. Albasi, C.; Bessiere, Y.; Desclaux, S.; Remigy, J. C. Filtration of biological sludge by immersed hollow-fiber membranes: influence of initial permeability choice of operating conditions. Desalination **2002**, 146 (1-3), 427–431. https://doi.org/10.1016/s0011-9164(02)00527-1

9. Hashino, M.; Katagiri, T.; Kubota, N.; Ohmukai, Y.; Maruyama, T.; Matsuyama, H. Effect of surface roughness of hollow fiber membranes with gear-shaped structure on membrane fouling by sodium alginate. Journal of Membrane Science **2011**, 366 (1-2), 389–397. https://doi.org/10.1016/j.memsci.2010.10.025

10. Bouhabila, E. Fouling characterisation in membrane bioreactors. Separation and Purification Technology **2001**, 22-23 (1-2), 123–132. https://doi.org/10.1016/s1383-5866(00)00156-8

11. Hirani, Z. M.; DeCarolis, J. F.; Adham, S. S.; Jacangelo, J. G. Peak flux performance and microbial removal by selected membrane bioreactor systems. Water Research **2010**, 44 (8), 2431–2440. https://doi.org/10.1016/j.watres.2010.01.003

12. Ivanovic, I.; Leiknes, T. Impact of aeration rates on particle colloidal fraction in the biofilm

membrane bioreactor (BF-MBR). Desalination **2008**, 231 (1-3), 182–190. https://doi.org/10.1016/j.desal.2007.11.046

13. Jiang, T.; Kennedy, M. D.; van der Meer, W. G. J.; Vanrolleghem, P. A.; Schippers, J. C. The role of blocking and cake filtration in MBR fouling. Desalination **2003**, 157 (1-3), 335–343. https://doi.org/10.1016/s0011-9164(03)00414-4

14. Jiang, T.; Kennedy, M. D.; Guinzbourg, B. F.; Vanrolleghem, P. A.; Schippers, J. C. Optimising the operation of a MBR pilot plant by quantitative analysis of the membrane fouling mechanism. Water Science and Technology **2005**, 51 (6-7), 19–25. https://doi.org/10.2166/wst.2005.0617

15. Ngo, H.-H.; Guo, W. Membrane fouling control and enhanced phosphorus removal in an aerated submerged membrane bioreactor using modified green bioflocculant. Bioresource Technology **2009**, 100 (18), 4289–4291. https://doi.org/10.1016/j.biortech.2009.03.057

16. Rosenberger, S.; Krüger, U.; Witzig, R.; Manz, W.; Szewzyk, U.; Kraume, M. Performance of a bioreactor with submerged membranes for aerobic treatment of municipal waste water. Water Research **2002**, 36 (2), 413–420. https://doi.org/10.1016/s0043-1354(01)00223-8

17. Schoeberl, P.; Brik, M.; Bertoni, M.; Braun, R.; Fuchs, W. Optimization of operational parameters for a submerged membrane bioreactor treating dyehouse wastewater. Separation and Purification Technology **2005**, 44 (1), 61–68. https://doi.org/10.1016/j.seppur.2004.12.004

18. Smith, P.; Vigneswaran, S.; Ngo, H.; Benaim, R.; Nguyen, H. Design of a generic control system for optimising back flush durations in a submerged membrane hybrid reactor. Journal of Membrane Science **2005**, 255 (1-2), 99–106. https://doi.org/10.1016/j.memsci.2005.01.026

19. Srijaroonrat, P.; Julien, E.; Aurelle, Y. Unstable secondary oil/water emulsion treatment using ultrafiltration: fouling control by backflushing. Journal of Membrane Science **1999**, 159 (1-2), 11–20. https://doi.org/10.1016/s0376-7388(99)00044-7

20. Villarroel, R.; Delgado, S.; González, E.; Morales, M. Physical cleaning initiation controlled by transmembrane pressure set-point in a submerged membrane bioreactor. Separation and Purification Technology **2013**, 104, 55–63. https://doi.org/10.1016/j.seppur.2012.10.047

21. Yigit, N. O.; Civelekoglu, G.; Harman, I.; Koseoglu, H.; Kitis, M. Effects of various backwash scenarios on membrane fouling in a membrane bioreactor. Desalination **2009**, 237 (1-3), 346–356. https://doi.org/10.1016/j.desal.2008.01.026

ОПТИМІЗАЦІЯ ТЕХНОЛОГІЇ ОЧИЩЕННЯ СТІЧНИХ ВОД З ВИКОРИСТАННЯМ МЕМБРАННОГО БІОРЕАКТОРА

Кириченко К.С.[1], Саблій Л.А.[1]

[1]Національний технічний університет України «Київський політехнічний інститут імені Ігоря Сікорського», Україна;

kyrychenko.kyryll@lll.kpi.ua, larisasabliy@ukr.net

Зростаючі екологічні виклики, пов'язані з підвищеним вмістом амонійного азоту в міських стічних водах, а також посилення нормативних вимог до скидів, зумовлюють необхідність упровадження ефективних технологій очищення. У цьому дослідженні проведено оптимізацію експлуатаційних параметрів мембранного біореактора для очищення стічних вод із фокусом на досягнення балансу між ефективністю та економічністю роботи. Мембранний біореактор має переваги над традиційними методами завдяки високій концентрації біомаси, покращеній якості очищення, компактності та можливості одночасної нітрифікації та денітрифікації. За допомогою програмного забезпечення GPS-X змодельовано 36 комбінацій тривалості фільтрації та промивання протягом 10 діб у динамічному режимі. Було оцінено вплив цих параметрів на основні показники ефективності: трансмембранний тиск, гідравлічне навантаження, гідравлічну проникність, ефективність видалення азоту та витрати води на промивання. Результати моделювання показали, що оптимальним є режим із тривалістю фільтрації 30 хвилин та промивання 180 секунд. За таких умов трансмембранний тиск знижувався до мінімуму (1,586 кПа), а концентрації амонійного та нітратного азоту у стоках ефективно зменшувались до 0,13 мг N/дм³ і 11,36 мг N/дм³ відповідно — значно нижче встановлених нормативних меж для скиду. Також досягнуто прийнятної гідравлічної проникності (0,3635 м³/(м²·кПа·доба)) та помірного споживання води (13,1 м³/добу), що сприяє зниженню витрат і довговічності мембран. Результати підтверджують ефективність мембранного біореактора як перспективної технології для муніципального очищення стічних вод в Україні.

Ключові слова: *біотехнологія, стічні води, біологічне очищення стічних вод, мембранний біореактор, оптимізація*