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Solving wastewater treatment problems caused by carbon source shortage by through oxygen penetration and using N- and P-deficient food-industrial wastewater

Thesis book

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1. INTRODUCTION, AIMS AND SCOPE

In order to adhere to the directives of the European Union, Hungary's important tasks include environmental protection and natural values preservation. Special attention is paid to water sources protection, preservation and improvement, including modernization and optimization of the existing wastewater treatment plants.

Previous design rules based on population equivalent have to be reviewed in many cases, as social habits have changed, and the amount of water used also varies significantly in each area. Specifying the quantity and quality of the wastewater is absolutely necessary during wastewater treatment plant design. It is essential to review and modernize the existing and operating wastewater treatment plants due to these very significant differences and changes.

Increasing efficiency in a cost-effective way is greatly enhanced by the fact that the rapid development of biotechnology has opened up new opportunities for ensuring selective advantage of various microorganisms and biodegradation processes. In addition to the carbon source shortage (low C:N ratio), which is often very specific of domestic wastewater, is particularly important using most of the available carbon sources for denitrification and, if possible, for enhanced biological phosphorus removal. The situation is more unfavorable in anaerobic digestion of the biomass generated in wastewater treatment plants and in fact its co-treatment with food industry waste. These processes increase further the nitrogen load in returning flows, and results in lower C:N ratios.

The amounts and proportions of carbon, nitrogen and phosphorus sources in the incoming wastewater significantly impact the microorganisms and the removal efficiency of the pollutants.

Goals of the study:

- to eliminate shortage of organic carbon sources and ‘low S - low DO’ conditions (low substrate and dissolved oxygen concentration in the non-aerated reactors) to improve the efficiency of biological phosphorus and nitrogen removal
- to develop successful technological applications to improve biological phosphorus and nitrogen removal
- to examine and verify cost-effective operational solutions by mathematical simulation calculations and by lab-scale as well as full-scale on-site measurements
- to minimize oxygen penetration through water surface in non-aerated reactors that adversely affects the efficiency of biological phosphorus and nitrogen removal (denitrification).

2. BACKGROUND

It is globally proven and accepted that staged non-aerated (anaerobic, anoxic) bioreactor arrangement can be effectively used in biological nutrient removal activated sludge systems (Chudoba et al., 1973a; Jobbágy et al., 1999). Research also demonstrate that anaerobic/anoxic selectors make a significant contribution to keeping the Sludge Volume Index (SVI) low by maintaining oxygen- and nitrate-free environment for the growth of Phosphorus Accumulating Organisms (PAOs), as evidenced by our research team performing one of the first three full-scale certifications in Europe (Parker et al., 2004). Even maintaining low dissolved oxygen concentrations in anoxic selectors is detrimental for denitrification processes and may cause kinetic inhibition (Plósz et al., 2003) that may favor filamentous microorganisms. Furthermore, these basins can be easily diluted, resulting in an environment of low substrate concentrations. This condition is even more unfavorable for sludge sedimentation in the case of high nitrate recirculation rate and already low inflow of readily biodegradable Chemical Oxygen Demand (rbCOD) (Wanner & Jobbágy, 2014). In order to avoid kinetic inhibition and metabolic advantage, it is necessary to exclude as much incoming dissolved oxygen as possible (Jobbágy et al., 2000). At the same time, surveys (Tardy et al., 2012) reflect that in Hungary, similarly to international data, the amount of readily biodegradable carbon source available in the influent decreases, while the influent NH_4-N concentration rises in many cases.

On the other hand, in addition to municipal wastewater, industrial wastewater is also subject to strict limit values, as laid down in the channel regulation. This forces many industrial facilities to build costly pre-treatment plants. In addition to the investment costs, addition of any required amounts of N- and P-sources will increase the operating costs, especially for some food processing plants. At the same time, carbon source deficiencies are common in municipal wastewater treatment plants where available carbon source is insufficient for denitrification and anaerobic P-release being the first step in biological P-removal. Therefore, additional carbon source may need to be added. To replace the expensive methanol, a number of alternative additional carbon sources have been experimented with so far, including waste materials with a high organic content (Hu et al., 2018; Xiong et al., 2020). However, it has not been examined whether, where appropriate, combined treatment of industrial and municipal wastewater would be more effective.

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Jobbágy A., Garai G., Farkas F., Sevella B. and Oszoly T. 1999. Enhanced nitrogen removal at the Northpest wastewater treatment plant. Proc. 8th IAWQ Conference on Design, Operation and Economics of Large Wastewater Treatment Plants, Budapest, Hungary, September 6-9, 255-262.

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Plósz B.Gy., Jobbágy A. and Grady C.P.L. Jr. 2003. Factors influencing deterioration of denitrification by oxygen entering an anoxic reactor through the surface. *Water Research*, **37**(4), 853-863.

Tardy G.M., Bakos V. and Jobbágy A. 2012. Conditions and technologies of biological wastewater treatment in Hungary. Water Science and Technology, 65(9), 1676-1683.

Wanner J. and Jobbágy A. 2014. Activated sludge solids separation. In: Activated Sludge – 100 Years and Counting (D. Jenkins & J. Wanner, eds). IWA Publishing, Glasgow, UK, pp. 171-194.

Xiong R., Yu X., Zhang Y., Peng Z., Yu L., Cheng L. and Li T. 2020. Comparison of agricultural wastes and synthetic macromolecules as solid carbon source in treating low carbon nitrogen wastewater. *Science of The Total Environment*, **739**, 139954.

3. METHODOLOGY

The purpose of my doctoral study was to investigate the causes of carbon deficiency in the influent wastewater to be treated, which is an internationally increasingly significant problem, and to find possible solutions. In contrast to general research practice, my goal was to verify the direct use of laboratory measurement results and simulation calculations for existing full-scale wastewater treatment plants.

In the examined cases, the research consisted of the following sub-activities:

- Evaluation and statistical analysis of the data provided by operators.
- Investigation of the problems at the given wastewater treatment plant (e.g. periodic decrease of nitrification and denitrification efficiency, insufficient aeration, sludge sedimentation problems, etc.), cause determination and possible solution development.
- Carrying out on-site profile measurements for better transparency of bioreactions and collection of input parameters for mathematical simulation calculations.
- Examination of proposed changes on a laboratory (e.g. batch) scale and/or full-scale (onsite) by setting up appropriate measurement strategy.

The highest possible availability of readily biodegradable carbon source in the influent, utilized for denitrification and anaerobic phosphorus release, is particularly important due to the reasons mentioned earlier. Therefore, I paid special attention to the following:

- Efficient treatment options development for N- and P-deficient food-industrial and C-deficient municipal wastewater.
- Utilization of readily biodegradable carbon source (rbCOD) during denitrification and biological P-removal.
- To develop solutions for minimizing the metabolic and kinetic inhibition of dissolved oxygen returning from recirculation streams and oxygen entrainment at the water surface.

4. RESULTS

4.1. Results obtained during the examination of the combined treatment of dairy and municipal wastewater at the Törökbálint Wastewater Treatment Plant

- Temporarily reduced N-removal efficiency of the wastewater treatment plant could not be directly attributed to a potentially toxic effect of industrial wastewater. Moreover, it has been proven that dairy wastewater contains readily biodegradable C-source, which benefits denitrification efficiency.
- The data measured and the simulation results showed that at a total COD concentration of less than 650-700 mg/l entering the municipal wastewater treatment plant additional carbon source dosage is required in order to maintain the denitrification efficiency at unchanged nitrogen load (influent BOD_5/NH_4-N ratio <6). Furthermore, no biological excess P-removal is possible.
- Contrary to general trends, according to which the construction of an industrial pre-treatment plant is justified, in order to achieve safe and efficient denitrification, the combined treatment of dairy wastewater with municipal wastewater is advantageous at the given wastewater treatment plant. In the given case, the co-treatment with the dairy wastewater is more expedient, since with its introduction the average influent total COD concentration is 783 mg/l (BOD_5/NH_4-N ratio: 6.47 and COD/TKN ratio: 8.96), which no longer requires additional carbon dosing.

4.2. Results of the research on exclusion of oxygen entrainment at the water surface in the non-aerated reactors of the Szeged Wastewater Treatment Plant

- Investigation of the specific growth rate of filamentous/floc-forming microorganisms showed that if the organic matter concentration in the influent wastewater is particularly low, then in the selector system a sufficiently large substrate concentration gradient cannot develop. As a result, floc-forming microorganisms may lose their expected growth advantage over filaments.

- The so-called ‘low DO’ condition was found in the range of 0.04-0.2 mg/l dissolved oxygen concentration. At such low dissolved oxygen levels, even at higher substrate concentration values, filamentous microorganisms may benefit, which may lead to the filamentous bulking of the activated sludge biomass.
- The ‘low S - low DO’ conditions detected in non-aerated basins significantly affect the efficiency of denitrification and biological excess P-removal as well as the composition of activated sludge flocs. In addition to the available carbon source the dissolved oxygen concentration depends on the process temperature.
- In order to minimize oxygen entrainment at the water surface in non-aerated reactors (anaerobic/anoxic selectors), it is recommended to cover non-aerated reactors with a special floating seal.

4.3. Results obtained during the comparative study of two differently operated trains on the North-Pest Wastewater Treatment Plant

- Intermittent aeration of aerated basins may result in significant reduction in effluent total nitrogen (TN) and energy (aeration) consumption (therefore resulting in cost savings) in certain parts of the year.
- Based on mathematical simulation calculations, as the temperature decreases, it is necessary to increase the length of the aerated periods on the New Line for achieving efficient nitrification. However, increasing aeration time may decrease denitrification efficiency.
- Mathematical simulation of the Old Line also showed that the plant was underloaded and excluding one of the treatment sub-trains and/or reducing the sludge concentration would not cause deterioration in the effluent. Based on this observation, and due to the positive result of intermittent aeration in the operation of the New Line, intermittent aeration was also introduced in the Old Line.
- At low dissolved oxygen and low dissolved carbon concentrations measured in aerated and non-aerated zones suggest that so-called ‘low S - low DO’ conditions may occur mainly during the winter period in intentionally anoxic or anaerobic basins, when available readily biodegradable carbon was not converted to anaerobic P-release or denitrification but reacted with metabolically easier to utilize oxygen rather than nitrate.

4.4. Results of the investigation of significantly increased N-load returning to the biological system from anaerobic digestion at the North-Pest Wastewater Treatment Plant

- Simulation calculations showed that in many cases readily biodegradable carbon was insufficient to maintain denitrification with returning supernatant. Supply of an additional carbon source may be necessary to keep the effluent total nitrogen (TN) concentration constant.

- In pre-denitrification, the C-source of wastewater is much better utilized, as some of it will certainly run out along with oxygen in the alternatively aerated basins.
- Methanol demand may be reduced by utilizing the influent carbon source as much as possible in the pre-anoxic zone by increasing nitrate recirculation.

4.5. Results obtained during the examination of non-aerated anaerobic/anoxic reactors covered with the special seal cover at the North-Pest Wastewater Treatment Plant

- Dissolved oxygen concentration levels typical for 'low DO' conditions occur in open, non-aerated reactors (0.04-0.2 mg/l).
- It can be assumed from the results that the amount of readily biodegradable carbon expressed in dissolved COD has practically been consumed in the anoxic basin (<50 mg/l) to the typical value of other units of the system, and a significant decrease in dissolved COD has already been observed in the distribution chamber.
- Covering the non-aerated anoxic selectors of the New Line *Test* System with a special seal cover proved to be successful at the North-Pest Wastewater Treatment Plant.
- The use of the floating seal and thereby the exclusion of oxygen dissolving through the surface, favored PAOs as a result of utilization of carbon source unreacted with oxygen. The *Test* System proved to be more advantageous in terms of the first step of biological excess P-removal i.e. the nutrient uptake accompanied by P-release.
- Having excluded oxygen penetration through the open water surface, significantly high orthophosphate and dissolved COD concentration values were measured in the anaerobic/anoxic basin of the *Test* System regardless of the aerated or non-aerated operation mode of the main reactor. However, the results of P-release were often masked by (excessive) chemical dosing for chemical P-removal.
- Parallel applied laboratory experiments also demonstrated that samples from the on-site *Reference* and *Test* systems contained phosphorus accumulating microorganisms. The bioconversion processes of PAOs are significantly influenced by the amount of available organic carbon source and the design of the reactor (covered, open surface). The results, similarly to the onsite data, showed that oxygen penetration through the open water surface is not negligible and compromises the efficiency of biological excess P-removal.

5. NOVEL FINDINGS

1. In full-scale experiment I demonstrated that the combined treatment of N- and P-deficient but carbon-rich dairy wastewater and carbon-deficient but N- and P-rich municipal wastewater was significantly more expedient and cost-effective than the widespread and expensive separate treatment. With this solution, the costly addition of N and P during the treatment of dairy wastewater and the introduction of an additional carbon source into the carbon-deficient municipal wastewater can be avoided. I determined that in case of separate treatment of municipal and dairy wastewater the limited readily biodegradable chemical oxygen demand concentration entering the municipal wastewater treatment plant, would not be sufficient for efficient denitrification without dairy wastewater. [Papers II and VII]
2. I found that in most of the wastewater treatment plants the so-called ‘low S - low DO’ conditions may occur, which hinders biological P removal, possibly also denitrification, especially in the case of dilution with incoming wastewater (heavy rain, snowmelt, strong infiltration). This microaerophilic condition may significantly affect sedimentation characteristics of the sludge and may require chemical repression of filamentous microorganisms. I have pointed out that oxygen should be excluded to avoid these microaerophilic conditions. [Papers I, IV, VI, VIII and X]
3. In both laboratory- and full-scale experiments, I have pointed out that in addition to marginal organic carbon source availability, moreover deficiency without covering the water surface of non-aerated reactors with a special floating seal even a minimal amount of oxygen may hinder or even inhibit denitrification and the biological excess P-removal both kinetically and metabolically. The high released orthophosphate concentration and dissolved COD values detected in the Test system covered by a floating seal demonstrated that the microaerophilic condition caused by oxygen penetration through the open water surface could be avoided. As a result, I found that nitrate-nitrogen was no longer detectable in the seal-covered anaerobic/anoxic basins as it was completely consumed. Therefore, the P-release known as the first step of biological P-removal appeared to be more dominant. [Papers I, V and VIII]
4. I determined that an additional 60 mg/l of readily biodegradable organic carbon remained for further utilization due to the oxygen exclusion through seal-covering the open water surface. [Papers I, V and VIII]

6. APPLICABILITY IN PRACTICE

- A new approach was developed for the combined treatment of dairy wastewater with high, readily biodegradable carbon content, but N- and P-deficiency, and municipal wastewater with low carbon but high nutrient (N and P) content. As opposed to the construction of an industrial pre-treatment plant and the addition of costly N- and P-sources, an application has been developed where the combined treatment of the given dairy and municipal wastewater is more expedient and cost-effective.
- In 2013, the non-aerated reactors (anaerobic/anoxic selectors) of the North-Pest Wastewater Treatment Plant were covered by a special floating seal, developed as an internationally pioneered project at relatively low investment costs. Excluding oxygen penetration aims to use available readily biodegradable C-source more efficient for denitrification and P-release being the first step in biological P-removal.
- In order to solve problems encountered during the installation of the floating seal produced by the Karsai Plastic Engineering Holding Ltd. (Karsai Műanyagtechnikai Holding Zrt.) several modifications were made. The edge of the floating seal was slightly raised and weirs were formed. Frame bracing at the edges was also required to avoid breakages. The modifications made the seal more stable and allowed replacement of potentially damaged elements without dismantling the entire cover.

7. PUBLICATIONS

Basic publications of the thesis

Peer reviewed scientific papers in English

I. Jobbágy A., Weinpel T., Bakos V., Vánkos Zs. 2019. Use of floating seals to exclude oxygen penetration in non-aerated selectors. *Water Science and Technology*, **80**(2), 357-364. IF: 1.624 (2019), https://doi.org/10.2166/wst.2019.280

II. Weinpel T., Bakos V., Jobbágy A. 2018. Co-treatment of a Carbon Deficient Domestic Wastewater with a Dairy Process Effluent for a Cost-effective Global Solution. *Periodica Polytechnica Chemical Engineering*, **62**(4), 432-440. IF: 1.368 (5 year Impact Factor, 2019), https://doi.org/10.3311/PPch.12856

III. Weinpel T., Bakos V., Jobbágy A. 2013. Effects of increased influent nitrogen load on a part-time aerated activated sludge system. *Water Practice and Technology*, **8**(1), 18-26., https://doi.org/10.2166/wpt.2013.003

IV. Jobbágy A., Palkó Gy., Weinpel T., Makó M. 2012. Comparative studies on the differently operated trains of the North-Budapest Wastewater Treatment Plant. *Water Science and Technology*, **65**(10), 1801-1808. IF: 1.102 (2012), https://doi.org/10.2166/wst.2012.079

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V. Jobbágy A., Weinpel T., Bakos V. 2017. Excluding oxygen penetration from non-aerated selectors: application of float-seal, a new technology. *IWA Conference on Sustainable Wastewater Treatment and Resource Recovery Research, Planning, Design and Operation*, Chongqing, China, 7-10 Nov. Proc. pp. 176.

VI. Weinpel T., Jobbágy A. 2017. Low-S - low-DO conditions in the non-aerated reactors of Szeged Wastewater Treatment Plant. *IWA 9th Eastern European Young Water Professionals Conference*, Budapest, Hungary, 24-27 May. Proc. pp. 534-540.

VII. Weinpel T., Bakos V., Jobbágy A. 2016. Utilization of dairy wastewater as carbon source in a domestic activated sludge treatment plant. *IWA 8th Eastern European Young Water Professionals Conference*, Gdansk, Poland, 12-14 May, Book of full papers (Proc. pp. 780-787).

VIII. Jobbágy A., Weinpel T., Bakos V., Vánkos Zs. 2015. Factors potentially converting non-aerated selectors into „low-S – low-DO basins", effects of seal-covering. *IWA 12th Specialised Conference on Design, Operation and Economics of Large Wastewater Treatment Plants*, Prague, Czech Republic, 6-9 Sept. Proc. pp. 149-155.

IX. Weinpel T., Bakos V. 2012. Effects of increased influent load on a part-time aerated activated sludge system. *IWA 6th International Conference for Young Water Professionals Conference*, Budapest, Hungary, 10-13 July. Proc. CD, ID: IWA-9841 (ISBN: 978-963-87507-8-5).

X. Palkó Gy., Weinpel T., Makó M., Jobbágy A. 2011. Comparative studies on the differently operated trains of the North-Budapest Wastewater Treatment Plant. *IWA 11th Specialised Conference on Design, Operation and Economics of Large Wastewater Treatment Plants*, Budapest, Hungary, 4-8 September. Proc. pp. 281-288 (ISBN: 978-963-08-2207-7).

Platform presentations related to the scope of the doctoral thesis

Jobbágy A., Weinpel T., Bakos V. 2017. Excluding oxygen penetration from non-aerated selectors: application of float-seal, a new technology. *IWA Conference on Sustainable Wastewater Treatment and Resource Recovery Research, Planning, Design and Operation*, Chongqing, China, 7-10 Nov. Platform Presentation. Presenter: Andrea Jobbágy.

Weinpel T., Jobbágy A. 2017. Low-S - low-DO conditions in the non-aerated reactors of Szeged Wastewater Treatment Plant. *IWA 9th Eastern European Young Water Professionals Conference*, Budapest, Hungary, 24-27 May, Platform Presentation. Presenter: Tamás Weinpel.

Weinpel T., Jobbágy A. 2017. Low-S - low-DO körülmények kialakulása magyarországi nagyüzemi szennyvíztisztító telepek nem levegőztetett reaktoraiban. *Magyar Szennyvíztechnikai Szövetség, Dr. Dulovics Dezső Junior Szimpózium*, Budapest, 2017. március 22. Presenter: Tamás Weinpel.

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Weinpel T., Bakos V., Jobbágy A. 2014. Hatékony denitrifikálás lehetőségei szűkös C-forrás mellett. *Magyar Szennyvíztechnikai Szövetség, III. MASZESZ Junior Szimpózium*, Budapest, 2014. február 6. Presenter: Tamás Weinpel.

Weinpel T., Bakos V. 2012. Effects of increased influent load on a part-time aerated activated sludge system. *IWA 6th International Conference for Young Water Professionals Conference*, Budapest, Hungary, 10-13 July, Platform Presentation. Presenter: Tamás Weinpel.

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Weinpel T. 2011. Az Észak-Budapesti Szennyvíztisztító Telep eltérő technológiájú tápanyageltávolítási fokozatainak összehasonlító tanulmányozása. *Magyar Szennyvíztechnikai Szövetség, II. MASZESZ Junior Szimpózium*, Budapest, 2011. december 9. Presenter: Tamás Weinpel.

Weinpel T., Bakos V., Jobbágy A. 2011. Élelmiszeripari és kommunális szennyvíz együttes tisztításának lehetősége. *Magyar Kémikusok Egyesülete, Környezetvédelmi Analitikai és Technológiai Konferencia*, Sümeg, 2011. október 5-7. Presenter: Tamás Weinpel.

Palkó Gy., Weinpel T., Makó M., Jobbágy A. 2011. Comparative studies on the differently operated trains of the North-Budapest Wastewater Treatment Plant. *IWA 11th Specialised Conference on Design, Operation and Economics of Large Wastewater Treatment Plants*, Budapest, Hungary, 4-8 September, Platform Presentation. Presenter: Andrea Jobbágy.

Poster presentations related to the scope of the doctoral thesis

Weinpel T., Simon J., Vánkos Zs., Jobbágy A. 2014. Low S-low-DO bulking in an activated sludge system with anaerobic-anoxic selectors. *IWA Activated Sludge – 100 Years and Counting Conference*, Essen, Germany, Poster Presentation, 12-14 June.

Other co-authored platform presentations in English in the field of wastewater treatment, not directly related to the scope of the doctoral thesis

Tóth I., Rieger L., Schraa O., Bolgár A., Vánkos Zs., Weinpel T. 2018. Which process control strategy is right for you? Extensive assessment using process modeling and pilot-scale experiments for a fixed bed activated sludge system. *91st Annual Water Environment Federation Technical Exhibition and Conference, WEFTEC 2018*, New Orleans LA, United States, 29 Sept.- 3Oct., Proc. pp. 2904-2918. Presenter: Imre Tóth.

Other platform presentations in Hungarian in the field of wastewater treatment, not directly related to the scope of the doctoral thesis

Weinpel T. 2010. Nyers- és fölösiszap elvétel optimalizálása vegyipari szennyvíztisztító telepen. *Magyar Szennyvíztechnikai Szövetség, I. Junior Szimpózium*, Budapest, 2010. március 25. Presenter: Tamás Weinpel.