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MODELLING OF CARBON AND NITROGEN COMPOUNDS REMOVAL FROM DOMESTIC WASTEWATER IN A MODERNIZED BIOLOGICAL REACTOR

Upgrading concepts for the Bioblok MU200a wastewater treatment plant have been presented. The main goals were to achieve an effective nitrogen removal and reduce energy demand. The reference version has been presented, followed by two retrofitting options: introduction of intermittent aeration for alternating aerobic and anoxic conditions, additionally including a retrofitting option to a hybrid technology that combines advantages of activated sludge and biofilm. To design and assess both variants, the ASM3 model was used, running on the Simba# simulator. A rather complex biofilm model, necessary for the hybrid concept, was bypassed by installing a separate activated sludge process differing in terms of sludge age and disposal of its excess sludge to the reactor. In this way, favorable technological parameters for efficient wastewater treatment could be assessed. Both upgrading concepts can be recommended for their satisfactory treatment effectiveness, feasibility in existing plants and considerable energy savings. The significance of the modelled effects was statistically confirmed by two-tailed Student's *t*-test.

1. INTRODUCTION

Effective municipal wastewater treatment is considered to be of paramount importance in the developed world and it is becoming widespread in developing nations as well. Therefore, upgrading existing wastewater treatment plants (WWTPs) has also become an important issue because of the large number of currently operating facilities and in view of increasingly stringent discharge requirements imposed on WWTPs. For some plants, the upgrading objectives can be achieved simply by modifying the way those plants are being operated. For other plants, extensive process modifications may be necessary to meet the treatment requirements, or the plant capacity may have to be

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substantially reduced. Daigger et al. [1] distinguished the following methods for WWTP retrofitting and plant upgrading:

- improved operation and maintenance,
- instrumentation and control,
- new liquid processing technologies,
- new solids processing technologies.

Another option, not mentioned here, but often inevitable, is connected with the installation of additional treatment volume, partly in combination with one of the above-mentioned solutions.

Activated sludge systems are the most common technology for domestic and industrial wastewater treatment. They are characterised by the growth of suspended biomass in the activated sludge tank and its separation from the treated wastewater by sedimentation of the biomass. The achievable biomass concentration in these systems is strongly related to the sedimentation process and typically limited to 3–5 g/m^3. There exist different approaches to enhance the biomass concentration, e.g., membrane bioreactors, improved settling technologies, or the provision of additional growth surface in the activated sludge tank. The latter decouples partly the available biomass from the limiting sedimentation process. Since suspended and biofilm growth take place simultaneously, those systems are called hybrid reactors. Generally, we may distinguish between freely floating small biofilm carriers (e.g., the Kaldnes process) and fixed biofilm systems. Although many studies investigated the improvement of treatment efficiency in hybrid bioreactors, its exact quantification is disputable [2]. Especially for the design phase, a reliable and rather simple modelling approach is desirable.

In Poland and several other east East European countries, wastewater treatment formerly was focused on COD and TSS removal. An often applied technology was the Bioblok reactor. Bioblok plants were designed to provide biological treatment of municipal wastewater and wastewater characterized by a similar composition and properties to municipal sewage. It is a completely mixed low-loaded activated sludge system and provides treatment consisting in the removal of organic matter and suspended solids. The achievable treatment efficiency with respect to both these parameters is 95%. In this study, the Bioblok plant to be modernized is type MU200a. The basic technological parameters are provided in Table 1 and technological schemes are given in Fig. 1.

The originally constructed plant consists of two completely mixed activated sludge aeration tanks, each with a single mechanical, energy inefficient, surface aerator followed by two square in-plant secondary clarifiers. The plant was designed without primary clarification. In Bioblok MU200a sludge recirculation was provided by submerged pumps, suspended from winches in each of the clarifiers. Return sludge was pumped to the aeration tanks directly under aerators and subsequently mixed with incoming wastewater. The recirculation system was set at a constant rate (recycle ratio) during normal flow conditions.

Table 1

Technological data of the Bioblok MU200a plant

Part of the system	Parameter	Values	
		Nominal	Range
Basic parameters	plant design capacity, m^3/day	200	
	population equivalent, inhabitants	1320	
	oxygen transfer rate, kg O_2/h	10 (×2)	
	reactor volume, m^3	200	
Aeration tank	sludge load, kg BOD_5/(kg_{DW}·day)	0.1	0.02–0.15
	sludge concentration, kg/m^3	4	≤6
	aeration time, h	24	20–30
	sludge production, kg/kg BOD_5	0.7	0.1–0.7
	oxygenation rate,	2.5	≥2
Sedimentation tank[a]	settler volume, m^3	50	
	flow time for: Q_{hmed}, h; Q_{hmax}, h	4; 1.5	3–4; ≥1.5
	hydraulic load for: Q_{hmed}, m/h; Q_{hmax}, m/h	0.8; 1.4	≤0.8; ≤1.5

[a]Q_{hmed} – average hourly flow, Q_{hmax} – maximum hourly flow.

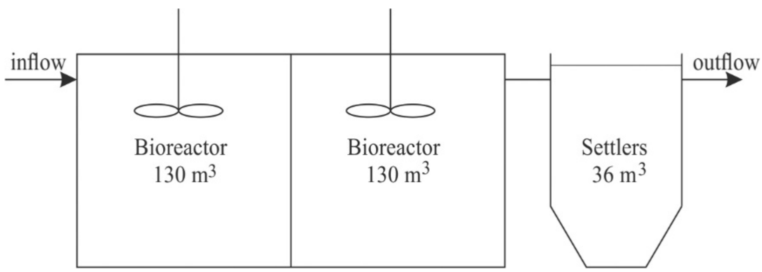

Fig. 1. Scheme of Bioblok MU200a

The Bioblok is an old technology of municipal wastewater purification. At the time when the system was designed, no effluent control for nitrogen and phosphorous was required. For this reason, it has become obvious that the Bioblok plants must be improved in order to meet today's standards with regard to nutrient removal efficiency and energy consumption or replaced with more advanced technologies.

The aim of this study was to demonstrate that modernisation of the old system by simple and cost efficient measures is feasible. Particularly it should be tested if the provision of floating biofilm carriers may facilitate reliable nitrification. By changing the continuous aeration system to intermittent aeration, both denitrification and energy savings shall be achieved. This demands an optimised control of aerated and non-aerated periods.

2. MODELLING OF BIOLOGICAL AND HYBRID REACTORS

Mathematical modelling of the activated sludge process provides a powerful tool for plant design, optimization, training, controller design and research [3]. The International Water Association (IWA) task group has been developing activated sludge models (ASMs) for over 20 years. Despite some limitations, the most often used IWA models ASM1, ASM2 and ASM3 have proved to be reliable tools for modelling carbon oxidation, nitrification, denitrification and biological phosphorus removal processes [4] and as such they have become popular not only among researchers, but also for designers and plant operators.

ASM1 was primarily developed for municipal activated sludge plants to describe the removal of organic carbon compounds and nitrogen [5]. In 1995, the Activated Sludge Model No. 2 has been published. This model included nitrogen removal and biological phosphorus removal. The ASM2 model was expanded in 1999 into the ASM2d model, where the denitrifying activity of PAOs was included. The ASM3 model is based on the ASM1 model but replaces the decay-hydrolysis-growth cycle by a direct endogenous respiration and introduces the imperative formation of internal storage products before enabling growth of heterotrophs [6, 7]. Based on these models, many modifications have been created. Many authors have simplified the reference models or introduced changes to, e.g., better describe simultaneous processes, intermittent aeration and hybrid systems.

Exemplary modifications of the ASM1 model include the introduction of a MBBR reactor [8–10], intermittent aeration [11], ammonia inhibition [12], and a hybrid reactor with intermittent aeration, two-stage nitrification and denitrification and inhibition [13]. In ASM2d the attached biomass system was introduced [14] and in ASM3 it was two-stage nitrification and denitrification [15]. Popular commercial simulators for ASM models include ASIM (Switzerland), BioWin (Canada), GPS-X (Canada), SIMBA (Germany), STOAT (UK) and West (Belgium).

In this paper, the ASM3 model, running on Simba# was used to simulate the upgrading options for the Bioblok system. Model parameters were selected according to the recommendations of The Central European Simulation Research Group (Hochschulsimulationsgruppe – HSG). The sedimentation process at the secondary clarifier was modelled using a 3-layer model with a variable sludge layer.

3. EXPERIMENTAL PROCEDURES

As reference, the original configuration of the Bioblok process was set up and is used to assess change in performance and the economic benefits arising from the proposed Bioblok retrofits. As input flow, and load a characteristic daily time series of connected 1320 inhabitants was created using the approach given by Langergrabe et al. [16].

Two retrofit scenarios were considered here. In the first case it was assumed that the plant served for the original designed number of users (personal equivalent $PE = 1320$). Nitrogen removal is to be achieved by a change in the plant control strategy, namely by introducing intermittent aeration that creates conditions for simultaneous nitrification and denitrification (SND) in the same reactor.

The second scenario assumed that the number of inhabitants within the service area increased (personal equivalent $PE = 2500$). In order to meet the challenge of larger wastewater volumes and pollutant loads, additional biomass in the process is required. The possibility of retrofitting to a hybrid technology was investigated. Introduction of free floating plastic media into the activated sludge bioreactor was proposed (fill 20%) in order to increase the biomass content and improve effluent quality. Such a solution known as integrated fixed film and activated sludge has gained worldwide popularity as a simple solution for upgrading existing overloaded systems. Technological parameters for the reference, first and second scenarios are provided in Table 2.

Table 2

Technical parameters for the reference, first and second scenario

Parameter	Reference scenario	First scenario	Second scenario
Wastewater flow, m^3/day	200	200	380
Sludge retention time, day	17	11	–
Nominal hydraulic retention time, h	28	28	19
Actual hydraulic retention time, h	13	16	12
Reactor fill fraction, %	–	–	20
Carriers specific surface area, m^2/m^3	–	–	100
COD loading rate, g COD/($g_{DW}\cdot$d)	0.21	0.24	0.16
Dissolved oxygen concentration, mg O_2/dm^3	1	2	2
Recycle ratio, %	90	70	75
Aeration cycle length, t_N/t_D	24/0	1.2/0.8	1.2/0.8
Aeration period, %	–	60	60
Non-aeration period, %	–	40	40
COD, mg O_2/dm^3	804	804	1200
TSS, mg/dm^3	402	402	603
TN, mg N/dm^3	73	73	110

The original Bioblok system WAS equipped with surface aerators (AP 1000 type) which are robust but not energy efficient. The retrofitting options are simulated with energy efficient pressure aeration. For a correct comparison of energy consumption, the original Bioblok plant was also simulated with pressure aeration. The significance of the modelled changes was statistically tested.

4. RESULTS OF SIMULATION

For simulations, the SIMBA# software was used implementing the equations of the ASM3. Treated wastewater has to comply with Polish effluent standards (Table 3).

Table 3

Polish effluent standards (regulation of the Minister of the Environment)

PE	BOD_5 [mg O_2/dm^3]	COD [mg O_2/dm^3]	TSS [mg N/dm^3]	Total N [mg N/dm^3]
<2000	40	150	50	30
<10 000	25	125	35	15

4.1. REFERENCE SCENARIO

The simulation scheme in the reference scenario was built of blocks corresponding to different units of the activated sludge system and its control.

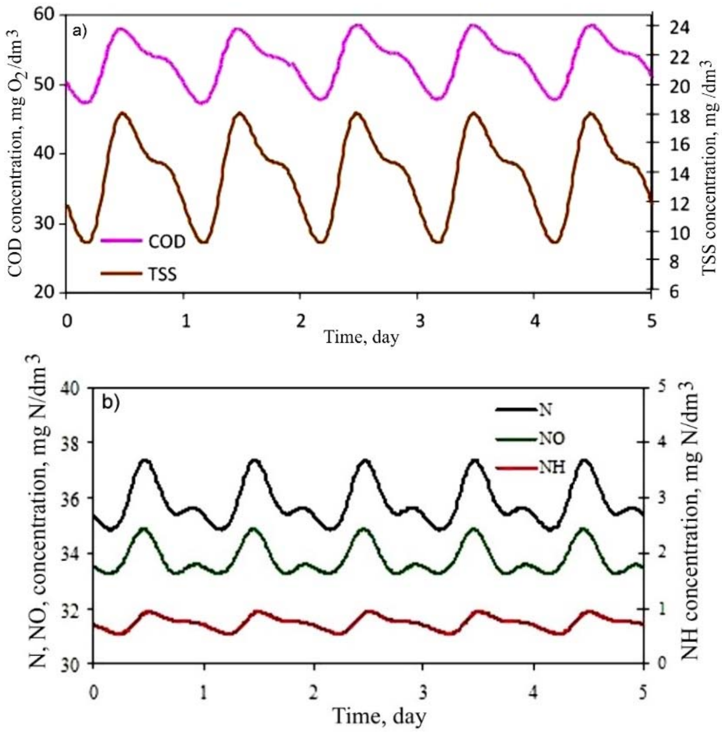

Fig. 2. Concentrations of pollutants in purified wastewater in the reference scenario: a) COD and total suspended solids, b) fractions of nitrogen; N – N_{tot}, NH – ($NH_4^+ + NH_3$), NO – ($NO_2^- + NO_3^-$)

In the data, daily dry weather was assumed. COD fractionation is accomplished by assuming the default Simba pattern that corresponds to the recommendations of the Central European Researchers' Simulation Group [3, 5]. Technological parameters are given in Table 2.

Figure 2 shows effluent concentrations of investigated pollutants. Because the Bioblok MU200a was originally designed to provide treatment for removal of organic matter and suspended solids, it provides satisfactory treatment for COD and SS removal. Due to the high aerobic sludge retention time, complete nitrification is achieved. However, since this system does not include denitrification, the effluent does not meet the criteria for total nitrogen concentration.

4.2. SCENARIO 1. INTERMITTENTLY AERATED ACTIVATED SLUDGE PROCESS

In the first scenario, intermittent aeration was applied to obtain sequentially nitrification and denitrification in the same tank. The time series of inflow is the same as for the reference scenario (Table 2). Provided that the COD/N ratio is not a limiting factor, the efficiency of nitrogen removal in an intermittently aerated activated sludge process depends mainly on two parameters: the t_N/t_D (aeration and non-aeration period) ratio and cycle length t_C (sum of t_N and t_D). Generally, an optimum aeration control could be achieved by online measurement of ammonia and nitrate levels. However, for economic reasons, mostly a simple time control is used and must be optimised in the process. In the simulation, different strategies varying in lengths of nitrification and denitrification were tested. The optimal range of the cycle length (t_C) was determined as 0.5 h and the ratio t_N/t_D as 1.5.

However, due to the total N concentration in the effluent and correct operation of the blowers [17], the optimal value of the t_N/t_D ratio was determined as 1.2 h and 0.8 h for aeration and non-aeration periods, respectively. Figure 3 presents dynamics of O_2 concentrations during a 12 h period.

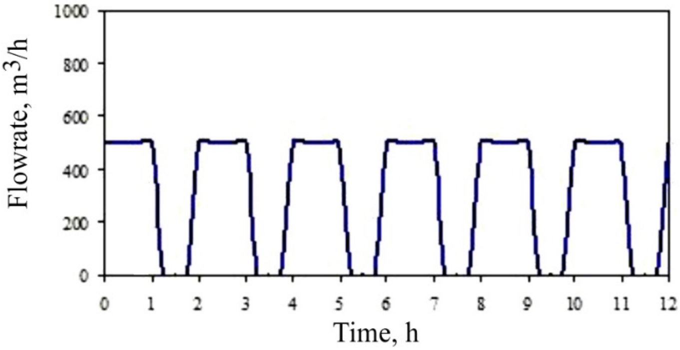

Fig. 3. Dynamics of O_2 in the intermittently aerated Bioblok reactor

With the intermittent aeration, total N concentrations could be heavily reduced, while ammonia concentration would only moderately increase to 1.2 mg/dm^3 (Fig. 4).

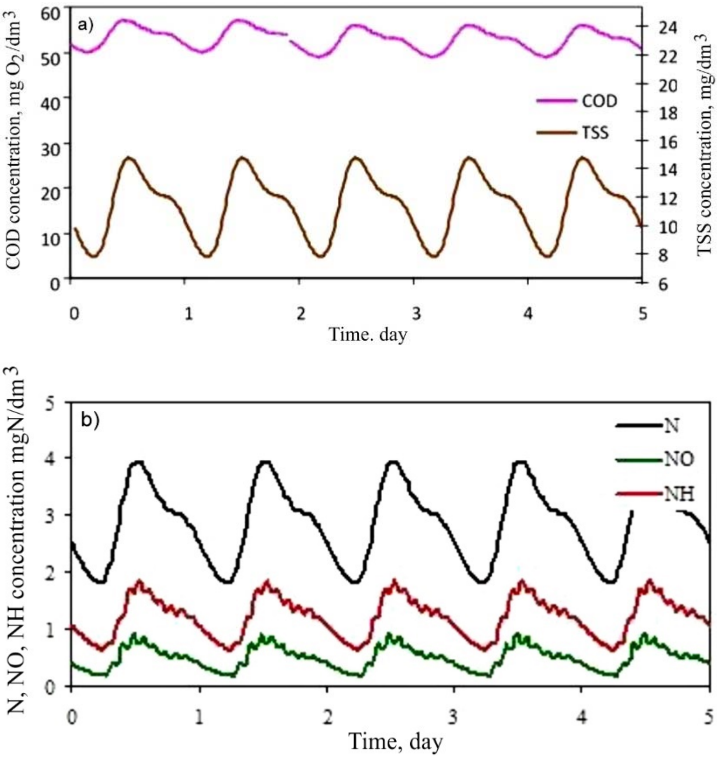

Fig. 4. Concentrations of pollutants in purified wastewater in the first scenario:
a) COD and total suspended solids, b) fractions of nitrogen;
N – N_{tot}, NH – ($NH_4^+ + NH_3$), NO – ($NO_2^- + NO_3^-$)

Thus, a rather simple change in aeration control towards an intermittently aerated Bioblok reactor produces effluent that meets the discharge criteria required for sewage facilities serving for larger populations of inhabitants (*PE* > 100 000).

4.3. SCENARIO 2. INTERMITTENTLY AERATED HYBRID REACTOR

The second scenario in this study assumed the application of a hybrid technology in order to adapt the Bioblok plant to treat wastewater characterized by higher nitrogen and organic loadings. In this process, biomass carriers were introduced into the activated sludge system, filling of 20% of the reactor volume.

The K3 biofilm carriers [18] were made of polyethylene (density 0.95 g/cm^3) and shaped like small cylinders (25 mm in diameter, 12 mm long). The effective biofilm surface area of the K3 carriers is 500 m^2/m^3. For the assumed surface organic loading rate of 5 g BOD/($m^2 \cdot d$), the required media surface area is about 20 000 m^2. With a given specific surface of the carrier of 500 m^2/m^3, 400 m^3 of carrier are needed.

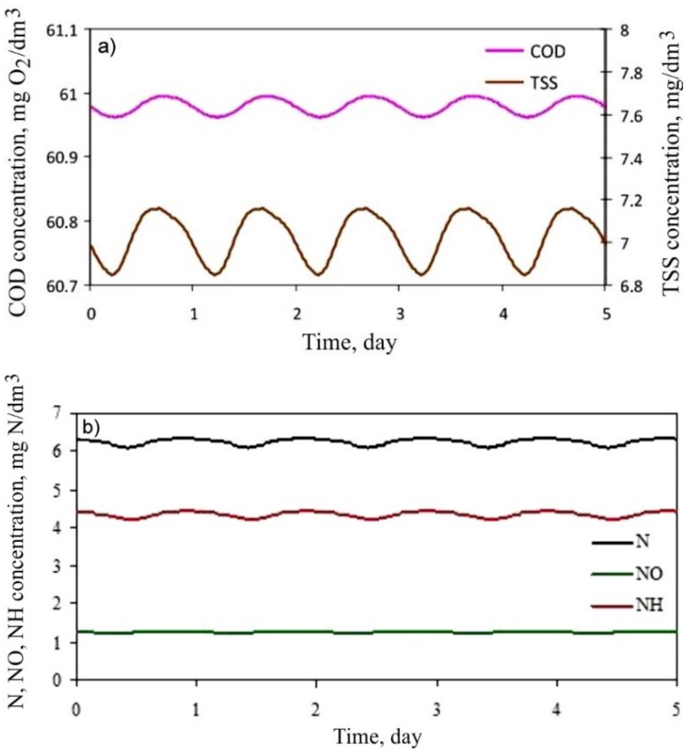

Fig. 5. Concentrations of pollutants in purified wastewater in the second scenario: a) COD and total suspended solids, b) fractions of nitrogen; N – N_{tot}, NH – (NH_4^+ + NH_3), NO – (NO_2^- + NO_3^-)

Introduction of an attached growth system generally demands a parallel modelling of suspended biomass and biofilms, including their interaction (e.g., attachment, detachment, concurrence for substrate). Especially biofilm modelling, including surface, thickness development and diffusional transport is rather complex [19–22]. To avoid the necessity of biofilm modelling, we assumed here that due to a sufficient turbulence in the reactor, the attached biofilms remain thin. In this way, diffusional transport may be neglected. The reactor was split into two virtual reactors: 80% for suspended growth and 20% for attached growth. The biomass of attached growth is retained by an ideal secondary clarifier. The detachment of surface sludge produced in the biofilm is controlled with a virtual surplus sludge removal, maintaining the biofilm biomass on a constant level. This level is assessed by assuming an equal activity of suspended and attached biomass, expressed as the food to microorganism ratio (F/M ratio) of 0.2 g COD/(g DW·day). The input module for the second scenario is generated in the same way as the first scenario, but for a higher number of inhabitants (Table 2).

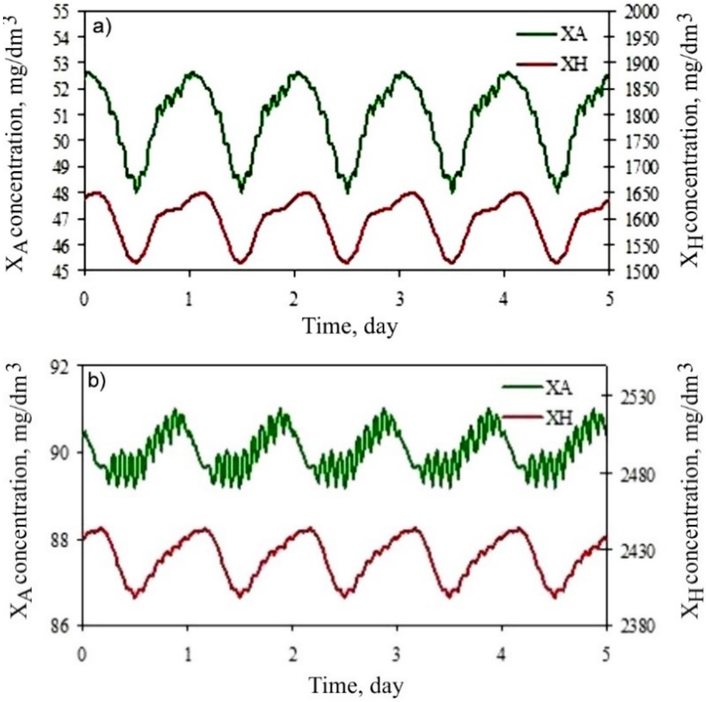

Fig. 6. Distribution of autotrophic (X_A) and heterotrophic (X_H) biomass in the second scenario: a) in the activated sludge compartment, b) in the biofilm compartment

Figure 5 presents concentrations of pollutants in purified wastewater during the monitoring period after about 50 days necessary to reach the maximal activity of microorganisms. Compared to the results of the first scenario, the system was more resistant to variations in inflow, since the attached biomass is fixed in the reactor. In consequence, the pattern of the effluent concentrations is less pronounced. In the hybrid Bioblok reactor, microorganisms are found in the liquid sludge and on the carriers. According to results presented by Paul et al. [23], over 90% of the autotrophic activity was found over the support material.

A similar regularity was observed with the simplified hybrid reactor model, developed in this study. However, the difference between suspended and attached growth is less distinct. Distribution of autotrophic and heterotrophic biomass in an activated sludge and biofilm compartment is presented in Fig. 6. Since the simplified model approach is not able to describe biofilm processes adequately, the often reported selective promotion of slowly growing biomass may therefore only partly described. To achieve this goal, the activity of the biofilm must be slower or a model with different biomass layers has to be used. Nonetheless, the model provides plausible results and facilitates a quantitative assessment of hybrid systems performance. Energy consumption for the original and modernised Bioblok plant, for both surface aerators and blowers were also calculated. The results are shown in Fig. 7.

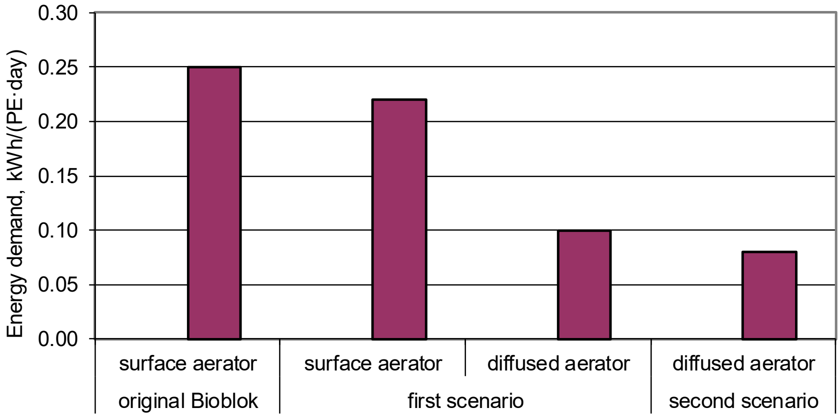

Fig. 7. Energy consumption in the Bioblok plant for the tested options

When maintaining surface aeration, the energy savings with intermittent aeration are evident, but rather small. An alteration to submersed pressure aeration reduces the energy demand by more than 50%. In the second scenario with much higher respiration rates due to the increased biomass, the energy demand is further decreased. Treatment efficiency levels in the reference, first and second scenarios are shown in Table 4.

Table 4

Treatment efficiency in all scenarios

Parameter	Reference scenario	First scenario	Second scenario
Average treatment efficiency, %			
COD	93.4	93.3	94.6
TSS	96.6	97.2	98.8
TN	50.9	96.0	94.3
Biomass concentration, g/m^3	3800	3300	2800
Return sludge concentration, g/m^3	7800	7730	7850
Excess sludge flow, m^3/day	4.8	6	–

In summary, modernization provided by the first variant will bring primarily improvements in terms of nitrogen and suspended matter removal. The second option would allow stable system operation when the influent load is increasing over the design capacity. Intermittent aeration and a change in the aeration system ensures a significant reduction in energy consumption.

4.4. STATISTICAL VERIFICATION

The summary table (Table 5) summarizes information on effluent quality in the three plant operation scenarios. Low values of the coefficient of variation (defined as the ratio of the standard deviation to the mean one) in the second scenario prove the regularity observed in Fig. 5 and confirm a more stable performance of the hybrid reactor.

Table 5

Summary results of effluent quality

Parameter	Variant	Unit	COD	TN	SS
Maximum observed	reference scenario	mg/dm^3	57.9	37.4	18.0
	first scenario		57.1	4.0	14.8
	second scenario		61.0	6.3	7.1
Minimum observed	reference scenario		47.3	34.9	9.1
	first scenario		49.9	1.8	7.8
	second scenario		60.9	6.1	6.8
Mean	reference scenario		52.9	35.8	13.8
	first scenario		53.6	2.9	11.4
	second scenario		60.9	6.2	7.0
Coefficient of variation (CV)	reference scenario	%	6.37	2.14	20.13
	first scenario		4.23	23.58	19.22
	second scenario		0.02	1.15	1.54

In order to verify whether the treatment effectiveness differs significantly between particular scenarios, the effluent pollutant concentrations (COD, TN, TSS) were statistically compared by two-tailed Student's *t*-test for two samples with 97 replicates comparing the variances. We concluded that the variances do not differ significantly. The *t*-value was calculated using the formula and compared with the value from the reference table for the level of significance $\alpha = 0.05$.

Firstly, the *t*-test was performed for the results of the reference and the first scenario. The calculated values of *t* for TN and SS are higher than the tabulated value of *t*-critical at a 5% level of significance, therefore, we reject the null hypothesis and conclude, that effluent quality in the reference and first scenario differs significantly with regard to TN and SS concentration. It should be stressed here, that between the reference and the second scenario many variables exist including different input module and different means of treatment. Therefore, their omission from the statistical comparison of the reference and the second scenario seems justified.

5. CONCLUSIONS

A simplified approach for the hybrid reactor modelling provides plausible results of simulation, with different technological parameters. However, the approach must be further calibrated and validated using monitoring data, focusing on the available biomass and its activity in the attached growth system.

The assessment of two upgrade scenarios pointed out that the proposed approaches provide treatment in an efficient and cost-effective manner. For the numerous existing Bioblok plants in Poland, it is a simple method to ensure compliance with the Polish effluent standards.

- Introduction of intermittent aeration is a sufficient method to provide simultaneous nitrogen and organic matter removal in plants serving for originally designed personal equivalent. However, it must be ensured that aerobic retention time does not fall below the wash-off point for nitrifiers.
- In Poland, for the typical wastewater composition, the optimal ratio between aeration and non-aeration periods (t_N/t_D) was determined at 1.5. Cycle length can be reduced to 2 hours, due to the operation of the blower.
- The moving bed reactor is an effective technology to upgrade overloaded wastewater treatment plants. The Bioblok plant retrofitted to install the hybrid technology is capable of treating wastewater characterised by higher nitrogen and organic loads up to 200% of the original design capacity without any additional footprint or extra tank volume.
- The hybrid reactor turned out to be more stable than the system not equipped with the moving bed. The coefficient of variation (*CV*) in the first scenario amounts to 4.2% (COD), 23.6% (TN) and 19.2% (TSS); in the second scenario, the *CV* values are 0.02%, 1.15% and 1.54% for COD, TN and TSS, respectively. However, this effect is partly caused by the special method describing the biofilm as two separate reactors and will be less marked in reality.
- Modernisation based on the assumptions of the first scenario makes it possible to save up to 60% energy compared to the original plant. Retrofitting to hybrid technology serving a larger population of inhabitants provides energy savings of 43% compared to the original plant.
- The simulation results may be implemented in practice. Future studies should address the potential phosphorus removal in the Bioblok plants.

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