PILOT-SCALE STUDIES ON MAINSTREAM DEAMMONIFICATION AT THE WSCHÓD WWTP IN GDAŃSK

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IWAMA project aims at improving wastewater management in the Baltic Sea Region by developing the capacity of the wastewater treatment operators and implementing pilot investments to increase the energy efficiency and advance the sludge handling.

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INTRODUCTION

The objective of this research was to investigate the feasibility of applying the deammonification concept in the mainstream treatment process. Deammonification is a two-step biological process that converts the ammonia present in wastewater to nitrogen gas. In the first step ammonia-oxidizing bacteria (AOB) aerobically convert half of the influent ammonia to nitrite. In the second step, anammox bacteria oxidize the remaining ammonia using nitrite to produce nitrogen. Deammonification provides a more efficient nitrogen removal pathway compared to conventional nitrification/denitrification. Due to shortcut in the nitrogen cycle significantly less aeration energy is needed to oxidize ammonia. Moreover, no organic carbon is needed since the process is completely autotrophic (Metcalf & Eddy *et al*., 2014). Therefore, deammonification is an attractive and cost-effective process for the treatment of wastewater with unfavourable COD/N ratio without using an external carbon source. Mainstream treatment with deammonification maximizes energy recovery from wastewater by directing more organic carbon to anaerobic treatment from which more biogas can be captured and utilized in a combined heat and power plant (CHP) to generate renewable power. The possibility of saving energy for aeration and recovering a high fraction of organic carbon with mainstream deammonification is seen as the key to achieve the ultimate in the energy balance positive wastewater treatment plant.

Deammonification has been widely applied at wastewater treatment plants (WWTPs) as a cost effective process to treat sidestreams with high ammonia load. Applying the deammonification process in the mainstream, however, still presents a challenge. Major barriers in this application include low temperature, low nitrogen concentration, variable nitrogen loads, high COD/N ratio, stringent effluent quality requirements and long-term process stability (Laureni *et al*., 2016; Trojanowicz *et al*., 2016).

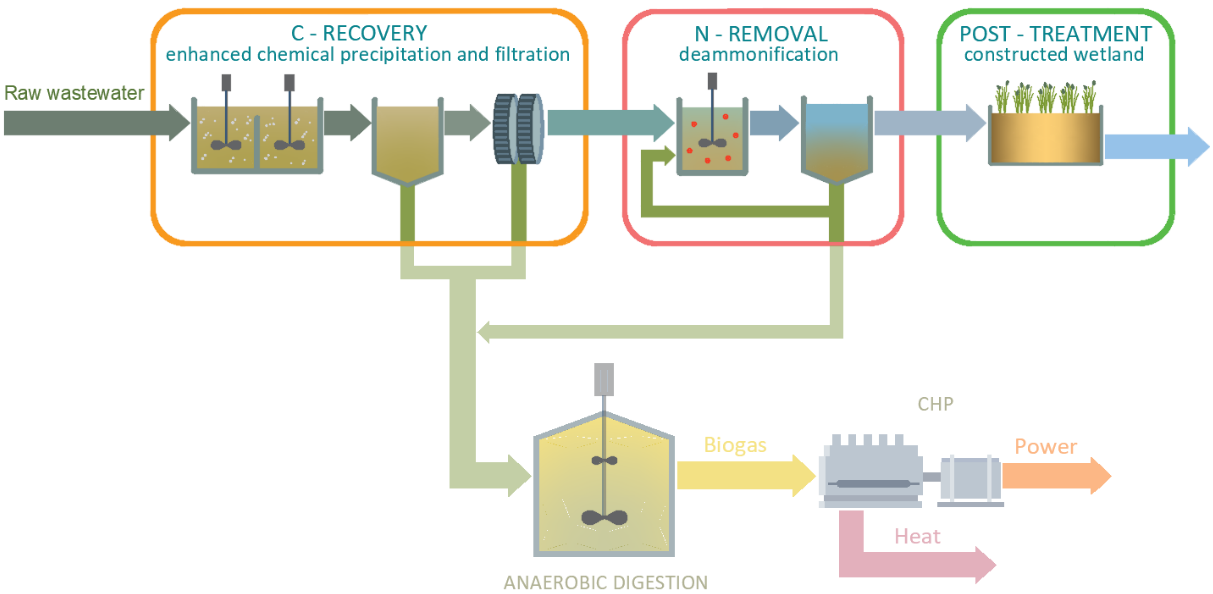

Fig. 1 Mainstream deammonification concept tested at the Wschód WWTP in Gdańsk

This report presents the results of pilot testing deammonification concept that was conducted at the Wschód WWTP in Gdańsk over a period of one-year (see Figure 1). The proposed innovative technology concept is based on organic carbon recovery using enhanced chemical precipitation, nitrogen removal with deammonification process and post-treatment in a two-stage constructed wetland (CW). Removal efficiency of organic compounds and nutrients were observed after each step of the wastewater treatment process. The effect of COD/N ratio and temperature variations on nitrogen removal were investigated, with particular attention to the efficiency and resilience to low temperature of deammonification. To measure the activity of different groups of bacteria, a series of microbial activity tests were performed, including specific anammox activity (SAA), oxygen uptake rate (OUR) and nitrate utilisation rate (NUR).

MATERIALS AND METHODS

Pilot-scale plant

The pilot plant used in this research has been designed and constructed to enable long-term testing innovative technology concept that combines low energy consumption and cost-effective processes of wastewater treatment, including coagulation/flocculation/sedimentation (CFS), deammonification and wetland treatment. All appliances, except for constructed wetland tanks, have been mounted within a 20-foot mobile shipping container that can be easily transported as a contained unit (see Figure 2).

The examined wastewater treatment system included primary, secondary and tertiary treatment steps. The physical-chemical primary treatment consisted of a two-stage flocculation tank and a primary sedimentation tank. The secondary treatment constituted a hybrid moving bed biofilm reactor (HMBBR) of the volume 720 litres (see Figure 3), followed by a secondary sedimentation tank. The reactor was inoculated with anammox bacteria immobilized on AnoxKaldnes K5 plastic carriers from the Sjölunda WWTP in Malmö and suspended growth activated sludge from the Wschód WWTP in Gdańsk.

Fig. 2 View of the pilot plant located at the Wschód WWTP.

The K5 carriers constituted 40% of the reactor total volume. The final post-treatment for further removal of the remaining organic matter and nutrients was demonstrated by a hybrid constructed wetland (CW) system consisted of horizontal flow constructed wetland (HFCW) and vertical flow constructed wetland (VFCW). The process being tested was monitored remotely with WTW in-line instruments for measuring concentration of solids, NH_4-N, NO_3-N, NO_2-N, dissolved oxygen (DO), pH, conductivity and oxidation reduction potential (ORP). Process temperature, DO and pH in the HMBBR were automatically regulated within the desired set-points by means of advanced PLC control system.

Fig. 3 View of the HMBBR reactor equipped with in-line instruments

Study site

The pilot studies were conducted at the Wschód WWTP, which is one of the largest facilities located upon the Baltic Sea. The average influent flow rate to the plant is 98,000 m^3/d and the pollutant load corresponds to 760,000 population equivalents (PE). The primary treatment line includes screens, aerated grit chambers and primary settling tanks. The secondary treatment line consists of six bioreactors and twelve circular secondary clarifiers operated in parallel. Configuration of the bioreactors is based on the Anaerobic/Anoxic/Oxic (A^2/O) system.

Analytical methods

Performance of the examined CFS-HMBBR-CW system was monitored using grab sampling as well as the WTW in-line probes. Depending on the study period grab samples were collected once or twice a week. The wastewater samples were examined for total COD (TCOD), soluble COD (SCOD), total nitrogen (TN), NH_4-N, NO_3-N, NO_2-N, total phosphorus (TP), PO_4-P, total suspended solids (TSS) and volatile suspended solids (VSS). The wastewater parameters were measured using WTW cuvette tests and WTW photoLab® 7600 UV/VIS spectrophotometer. TSS and VSS were determined according to the standard methods. The samples for determining SCOD were prepared according to the rapid physical-chemical method of Mamais *et al*. (1993).

RESULTS

Start-up of the pilot plant began in October 2017. Continuous operation of the plant with regular physico-chemical analyses of collected wastewater samples started in November 2017. The entire study time included the study period 1 aimed at testing the efficiency of mainstream deammonification operated in the HMBBR system and the study period 2 focused on evaluating the overall efficiency of the pilot system consisted of chemical precipitation, deammonification and wetland treatment.

Study period 1
Testing nitrogen removal efficiency in the pilot HMBBR system

Evaluation of the pilot HMBBR system for TN removal was conducted over a period of 150 days, from 7 November 2017 to 5 April 2018. The reactor was supplied with real primary effluent from the Wschód WWTP pre-treated in the pilot CFS system using liquid iron(III) sulphate as the coagulant at dosage of 33 – 91 g/m^3. Influent flow rate to the HMBBR system and return activated sludge flow rate were both fixed at 15 L/h to maintain hydraulic retention time (HRT) at a constant level of 24 hours. The temperature in the reactor was automatically controlled to keep the desired set points. The temperature was gradually decreasing from 30 °C to 13.5 °C, by 1.5 °C each 1-4 weeks depending on the biomass acclimation and observed nitrogen removal efficiency. Similarly mixed liquor suspended solids (MLSS) concentration in the reactor was regulated in the range of 620 – 1,580 mg/L and adjusted on an ongoing basis according to the measured TN removal efficiency.

Table 1 Operating parameters of the HMBBR system

Parameter	Unit	Value
Inflow rate	L/h	15.0
	L/d	360
Process temperature	°C	13.5 – 30
HRT in HMBBR	h	24
N loading rate of HMBBR	g N/(m^3·d)	37 – 71
RAS flowrate (% inflow rate)	%	100
Filling with K5 carriers	%	40
Total surface area of anammox biofilm	m^2	240
Aeration on/off	min/min	20/40
DO concentration in aeration phase	mg O_2/L	0.50 – 1.50
MLSS concentration	mg/L	620 – 1,580

The HMBBR was aerated intermittently 20/40 min aeration on/off time. Dissolved oxygen (DO) concentration was kept at the desired set points between 0.50 and 1.50 mg O_2/L by means of the PLC control system linked with air valve and oxygen probe. To favour anammox process pH was automatically controlled and maintained at constant value of 7.5 using hydroxide sodium and hydrochloric acid. Operating parameters of the HMBBR system during the study period 1 are summarised in Table 1.

The average concentration of TCOD and TN in the wastewater inflow to the HMBBR system over the entire study period 1 equalled 373 ± 48 mg COD/L and 99 ± 16 mg N/L, respectively. SCOD in the inflow amounted to 241 ± 33 mg SCOD/L and constituted 65% of TCOD. The average influent TCOD/TN ratio was 3.9 ± 0.8.

The highest TN removal efficiency from 93% to 98% were recorded at the process temperature of 30 °C. Gradual decreasing the temperature to 13.5 °C during 127 days resulted in lowering the removal efficiency to the value of 69 – 73%. TN removal rates varied in a wide range from 28 to 63 g N/(m^3·d) depending on the temperature in the reactor. The concentration of NO_2-N in the HMBBR remained at very low levels, i.e. below 0.70 mg N/L, regardless of temperature. The measured removal efficiency of TN at different temperatures during the study period 2 is illustrated in Figure 4.

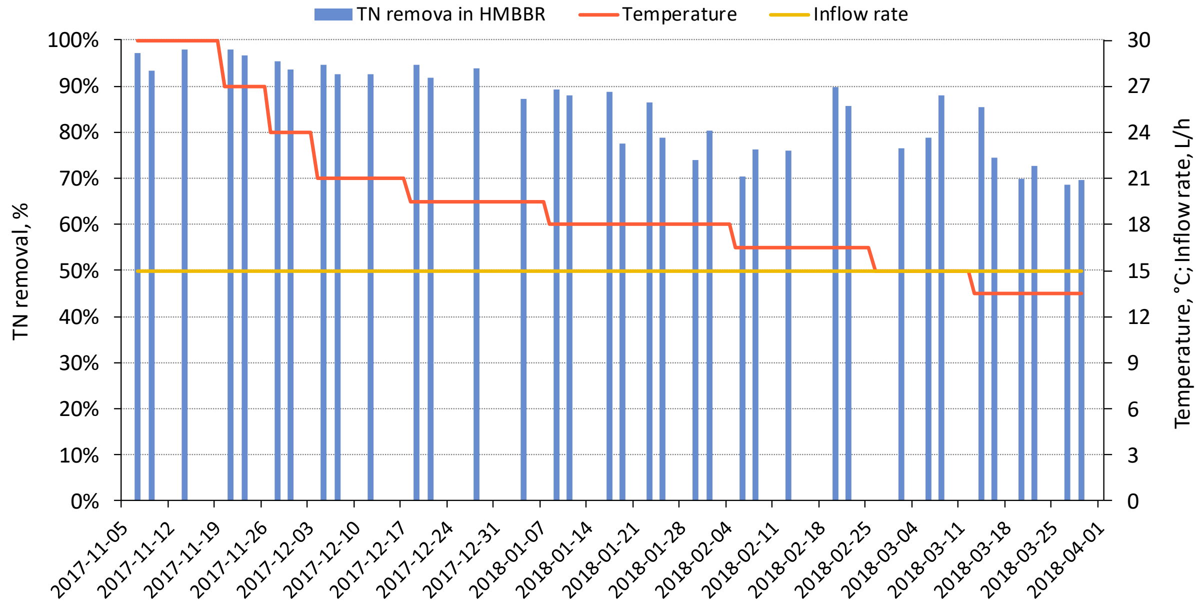

Fig. 4 Graphical presentation of the efficiency of TN removal in the pilot HMBBR during the study period 1

Table 2 Wastewater characteristics and performance of the HMBBR system at the temperature of 13.5, 21 and 30 °C

Parameter	Unit	Average values ± SD, mg/L		% removal ± SD	Temperature (°C)
		Influent	Effluent		
TCOD	mg COD/L	373 ± 48	43 ± 8.9	93 ± 1.9	13.5 – 30
TN	mg N/L	98 ± 6.6	3.7 ± 2.0	96 ± 2.4	30
		93 ± 4.2	6.1 ± 1.0	93 ± 1.2	21
		84 ± 3.9	22 ± 5.3	73 ± 6.2	13.5
NH_4-N	mg N/L	69 ± 3.7	2.3 ± 2.1	97 ± 2.9	30
		64 ± 3.4	4.3 ± 0.5	93 ± 1.3	21
		73 ± 2.9	11 ± 3.3	84 ± 4.0	13.5
NO_3-N	mg N/L	–	0.3 ± 0.1	–	30
		–	0.9 ± 0.7	–	21
		–	10 ± 2.0	–	13.5
TP	mg P/L	8.7 ± 1.1	6.0 ± 0.9	31 ± 12	13.5 – 30

In the case of NO_3-N the effect of temperature on its concentration was observed. At higher temperatures (21 – 30 °C) the concentration of NO_3-N remained at low levels between 0.25 and 1.70 mg N/L, whereas at lower temperatures (13.5 – 19.5 °C) it was significantly higher and varied between 1.3 and 22.7 mg N/L. The average wastewater composition and the performance of the HMBBR at the temperature of 13.5 °C, 21 °C and 30 °C is shown in Table 2. It must be noted that at the maximum temperature of 30 °C the average concentration of DO needed to oxidize NH_4-N effectively during aeration phase was only 0.59 mg O_2/L. The lower process temperature the higher concentration of DO was required to oxidize NH_4-N. At the minimum temperature of 13.5 °C the average concentration of DO equalled 1.37 mg O_2/L.

Study period 2
Performance evaluation of the combined CFS-HMBBR-CW system

Evaluation of TN removal efficiency in the pilot combined CFS-HMBBR-CW system was conducted over a period of 215 days, from 6 April 2018 to 6 November 2018. The pilot system was fed with real primary effluent of the Wschód WWTP. Wastewater entering the HMBBR was pre-treated using CFS process at dosages of 48 – 57 g/m^3 of iron(III) sulphate. Performance of the HMBBR was evaluated under different influent flow rates between 15.0 and 22.2 L/h and at different process temperatures from 13.3 to 25.9 °C. Nitrogen loading rates of the reactor varied in the range of 40 – 75 g N/(m^3·d). The reactor was aerated intermittently 20–25/40 min aeration on/off time. Average DO concentration during aeration phase remained at the desired set points between 1.20 and 1.75 mg O_2/L. The effluent from the HMBBR system was treated in the HFCW followed by VFCW to remove the remaining organics and nutrients. Hydraulic loading rates of the HFCW and VFCW varied from 0.21 to 0.95 m^3/(m^2·d), depending on the amount of excess sludge withdrawn from the HMBBR. Operating parameters of the pilot CFS-HMBBR-CW system during the study period 2 are presented in Table 3.

Table 3 Operating parameters of the examined CFS-HMBBR-CW system

Parameter	Unit	Value
Inflow rate	L/h	15.0 – 22.2
	L/d	360 – 533
Process temperature	°C	13.5 – 25.9
Coagulant iron(III) sulphate dosage	mg/L	48 – 57
HRT in HMBBR	h	13 – 24
N loading rate of HMBBR	g N/(m^3·d)	40 – 75
RAS flowrate (% inflow rate)	%	83 – 200
Filling with K5 carriers	%	40
Total surface area of anammox biofilm	m^2	240
Aeration on/off	min/min	20 – 25/40
DO concentration in aeration phase	mg O_2/L	1.20 – 1.75
MLSS concentration in HMBBR	mg/L	750 – 1,520
Hydraulic loading rate of HF-CW	m^3/(m^2·d)	0.22 – 0.54
Hydraulic loading rate of VF-CW	m^3/(m^2·d)	0.21 – 0.52

The average concentration of TCOD and TN in the wastewater after primary treatment in CFS system equalled 446 ± 45 mg COD/L and 90 ± 6.8 mg N/L, respectively. SCOD in the primary effluent amounted to 254 ± 25 mg SCOD/L, which constituted 57% of TCOD. After chemical precipitation the average ratio of TCOD/N in wastewater was decreased from 8.0 ± 0.7 to 5.0 ± 0.4.
The study results revealed high efficiency of COD and TN removal in the examined CFS-HMBBR-CW system. The removal efficiency of COD during CFS increased 1.5 times reaching the value of 60% compared to 41% observed in the full-scale primary treatment at the Wschód WWTP. Such increase in organic carbon recovery at the Wschód WWTP would enhance, in turn, biogas production by

approximately 70% in anaerobic digestion and therefore, adequately higher production of renewable energy in the CHP system.

Table 4 Wastewater characteristic and performance of the examined CFS-HMBBR-CW system

Parameter	Unit	Average values, mg/L				Removal efficiency	Requirements 91/271/EEC
		Influent	CFS effluent	HMBBR effluent	VFCW effluent	%	% removal[1)]
TCOD	mg COD/L	775 ± 72	446 ± 45	40 ± 6.0	28 ± 4.0	96 ± 0.5	75
TSS	mg/L	212 ± 39	69 ± 21	11 ± 3.8	3.4 ± 1.6	98 ± 0.8	90
TN	mg N/L	98 ± 8.4	90 ± 6.8	21 ± 10	16 ± 9.5	84 ± 9.4	70 – 80
TP	mg P/L	13 ± 2.1	12 ± 1.9	8.8 ± 1.4	7.3 ± 2.0	47 ± 11	80

[1)] Requirements for discharges from urban WWTPs of the size more than 100,000 PE.

At influent flow rates to the HMBBR system between 15.0 and 22.2 L/h, the measured removal efficiency of TN was high and averaged 84 ± 9%, while the minimum and maximum removal was 67% and 98%, respectively. The corresponding TN removal rates were similar as in the study period 1 and varied from 26 to 69 g N/(m^3·d), depending on the process temperature. Wastewater characteristics and performance of the pilot system, compared to the requirements of the Council Directive 91/271/EEC for discharges from urban WWTPs serving more than 100,000 PE, is summarised in Table 4.

At the minimum wastewater inflow rate of 15.0 L/h and temperature of 14.3 – 23.4 °C the measured removal efficiency of TN was high from 77% to 93%. Since the removal efficiency was 80 – 93% at temperature above 19 °C, the inflow rate to the HMBBR system was increased by 48% from 15.0 to 22.2 L/h. Despite significantly higher inflow rate TN removal efficiency still remained high between 77% and 98%. Lowering temperature in the reactor below 19.5 °C resulted in significant decreasing the efficiency to 67% which can be explained by hydraulic overloading of the system at lower temperature. In order to maintain high efficiency of TN removal (at least 70%) the influent flow rate was decreased from 22.2 L/h to the initial value of 15.0 L/h. In the final stage of the study period 2 the wastewater influent flow rate was increased again by 20% from 15.0 to 18.0 L/h. At this inflow rate and temperature of 17.0 – 19.0 °C the observed removal efficiency of TN varied from 69% to 78%. Figure 5 shows the effect of temperature fluctuations and hydraulic loading on the efficiency of TN removal in the tested pilot system.

The average removal efficiency of TP in the examined CFS-HMBBR-CW system was relatively poor, i.e. 47 ± 11%. The efficiency of TP removal in the CW system was decreasing in time, which most probably was associated with gradual depletion of sorption capacity of the filtration beds. Moreover, average hydraulic loading rates of the HFCW and VFCW were quite high, 0.40 ± 0.09 and 0.39 ± 0.08 $m^3/(m^2·d)$, respectively, which could limit adsorption of P on the surface of porous filtration media (Vymazal, 2007). High inflow rates reduced HRT, and in consequence, also reduced contact time of wastewater with the filtration media and with the biomass of bacteria that developed in the CW.

Similarly to the study period 1, TN was removed in the intermittently aerated HMBBR. Intermittent aeration with relatively low oxygen concentration (1.20 – 1.75 mg O_2/L) allows to reduce considerably aeration demand for TN removal in comparison to conventional nitrification and denitrification processes.

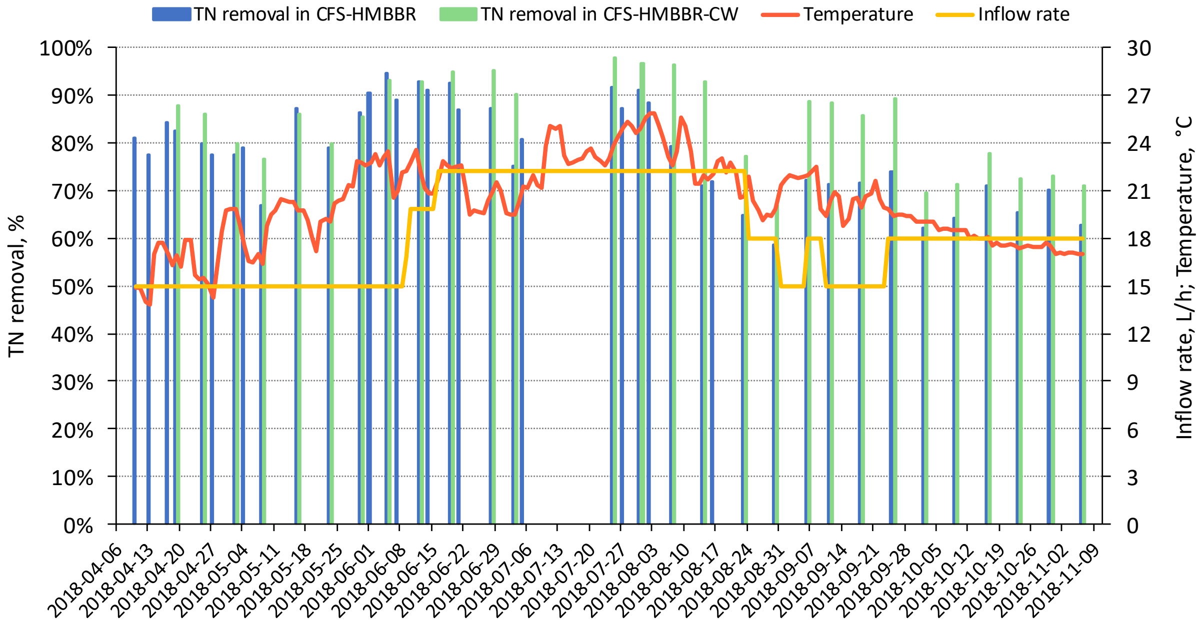

Fig. 5 Graphical presentation of the efficiency of TN removal during the study period 2

CONCLUSIONS

The following conclusions can be derived from this study:

- The obtained results showed the possibility of potential applying the combined CFS-HMBBR-CW system to remove TN and COD from the mainstream efficiently at low wastewater temperature and unfavourable COD/N ratio.
- The effluent from the pilot combined CFS-HMBBR-CW system based on deammonification meets the requirements of minimum percentage reduction of COD, TN and TSS set out in the urban wastewater treatment directive (91/271/EEC) for discharges from WWTPs serving more than 100,000 PE. The average removal of TN, COD and TSS equalled 84%, 96% and 98%, respectively.
- TP was relatively poorly removed in the examined wastewater treatment system with the average removal efficiency of 47 ± 11%. This might be improved by either further optimisation of chemical precipitation in the CFS system through selecting more effective coagulant, or enhancing chemical precipitation with dosing flocculant. Other option to improve phosphorus treatment performance is the implementation of reactive materials in the CW system. Materials with depleted sorption capacity of PO_4-P could be utilized as phosphate fertilizer.
- Mainstream treatment with the innovative CFS-HMBBR-CW system using deammonification maximizes energy recovery from wastewater by directing more organic carbon to anaerobic fermentation from which more biogas can be captured and utilized in a combined heat and power plant (CHP) to generate renewable power. Furthermore, it allows to reduce considerably aeration demand for biological nitrogen removal through intermittent aeration with low DO concentration. Energy savings for aeration and maximizing recovery of organic carbon is the key to achieve energy-positive wastewater treatment and sludge management.

  Organic carbon removal in the examined system can be at least twice higher compared to the conventional nitrification/denitrification system that is applied at the Wschód WWTP. Such high recovery of organic carbon at the Wschód WWTP would result in increasing biogas production by approximately 70%, which would make the plant energy-positive.

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