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Effect of wastewater temperature and concentration of organic compounds on the efficiency of ammonium nitrogen removal in a household treatment plant servicing a school building

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Abstract: The aim of this study was to determine the impact of the temperature of wastewater in a biological reactor with activated sludge and the $BOD_5/N\text{-}NH_4$ ratio in the influent to the treatment plant on nitrification efficiency and the concentration of ammonium nitrogen in treated wastewater. Tests were carried out in a household wastewater treatment plant which collects and treats sewage from a school building and a teacher's house. During the 3-year study, large fluctuations in the sewage temperature in bioreactor were noted which was closely related to the ambient temperature. There were also large fluctuations in the concentration of organic matter and the concentration of ammonium nitrogen in inflowing sewage. The influence of wastewater temperature in the bioreactor and the $BOD_5/N\text{-}NH_4$ ratio on the concentration of ammonium nitrogen in treated wastewater was determined using Pearson's linear correlation. A statistical analysis showed that a 1°C decrease in the temperature of wastewater in the bioreactor increased the concentration of ammonium nitrogen in treated wastewater by 2.64 $mgN\text{-}NH_4 \cdot L^{-1}$. Moreover, it was found that nitrification depended on the ratio of BOD_5 to the concentration of ammonium nitrogen in wastewater flowing into the bioreactor. An increase in the $BOD_5/N\text{-}NH_4$ ratio by 1 value led to a 5.41 $mgN\text{-}NH_4 \cdot L^{-1}$ decrease in the concentration of ammonium nitrogen.

Introduction

Over the recent years, more and more collective sewage systems have been built in rural areas in Poland. However, due to the specific layout of villages and substantial height differences in mountainous areas in the southern part of the country, the construction of collective sewage systems is unprofitable, and household wastewater treatment plants are built instead (Obarska-Pempkowiak et al. 2015, Pawełek 2016). According to current data of the Central Statistical Office (GUS 2017), there are nearly 217,000 household wastewater treatment plants in Poland and, as data from recent years show, there is an upward trend in the construction of such facilities. The trend indicator shows that in a few years' time, there may be around 500,000 treatment plants of this type in rural communes in Poland. It is crucial then, from the ecological point of view, that the technologies used in household wastewater treatment plants should be highly efficient, i.e. these plants should treat sewage in accordance with specific requirements. Unfortunately, when choosing a household wastewater treatment plant, often the only criterion investors use is the economic one, i.e. the price of the facility, an approach that is obviously faulty. Widespread use of household wastewater treatment plants which are "treatment plants" in name only, as they are technologically inefficient and do not meet relevant requirements, is bound to lead to degradation of the environment, in particular, the pollution of surface and ground waters and soil (Jóźwiakowski et al. 2014, Jucherski and Walczowski 2001, Nowak and Wawryca 2015). Currently, the technological systems used in household wastewater treatment plants employ various different solutions depending on many factors, i.e. the surface area of the property, the possibility of discharging treated effluent to land or a watercourse, groundwater level etc. (Pawełek and Bugajski 2017). The choice of the type of household wastewater treatment plant should be preceded by a thorough analysis of the above-mentioned conditions, and additionally should take into account technical and operation-related guidelines (Chmielowski 2016, Jawecki et al. 2016, Jóźwiakowski et al. 2015, Pawęska and Kuczewski 2013). Because land properties in rural communes surrounding large cities occupy small areas, household wastewater treatment plants with activated sludge are becoming more and more popular. These facilities have both advantages and disadvantages. Their main asset is that they take up little space; the main downside is that the technology is sensitive to variability in the quantity and quality of the influent and the temperature of wastewater in the biological reactor (Andreottola et al. 2000, Bugajski and Kaczor 2008, Manassra 2006). The results presented in this paper are contribution to the discussion about the efficiency of household wastewater treatment plants with biological reactor with activated sludge.

The aim of this study was to determine the impact of the temperature of wastewater in a biological reactor with activated sludge and the BOD_5/N-NH_4 ratio in the influent to the concentration of ammonium nitrogen in treated wastewater. The results obtained in the study can help calibrate automated software for measuring the age of sludge in activated-sludge biological reactors of household wastewater treatment plants. In addition, the results provide data on the nitrification efficiency of household wastewater treatment plants operating in the climatic conditions of southern Poland.

Material and methods

Experimental facility

The investigated wastewater treatment plant is located in Ibramowice, district (powiat) of Proszowice in the Lesser Poland Province (aka Małopolska Voivodeship) (50°15'N, 20°16'E). At the time of the experiments, the treatment plant was used to treat domestic sewage from a school building which accommodated about 120 students. Additionally, the plant collected sewage from a teacher's house which was inhabited permanently by six people. The maximum design flow capacity of the facility was 5.0 $m^3 \cdot d^{-1}$ and the assumed PE = 30. During the research period, the treatment plant was hydraulically underloaded, as the actual average daily sewage inflow was Q = 0.81 $m^3 \cdot d^{-1}$ and the actual PE (Population Equivalent) was 3.

Raw sewage from the school building and the teacher's house was gravitationally drained via a DN = 150 mm duct into the first chamber of the initial settling tank (1). The technological line of the treatment plant consisted of a two-chamber septic tank (1) with an active volume of 13.5 m^3, which had been used as a "cesspool" before the treatment plant was installed and was later modernized to be used as the mechanical treatment part of the facility. In accordance with the design specifications, wastewater retention time in the septic tank should have been 2–3 days. However, because inflow of sewage was lower than the system had been designed to handle, wastewater was retained in the tank for nearly 17 days. From the initial settling tank, wastewater got through openings in the partition wall into the retention tank (2), where it was held for some time and from where it was pumped to the biological reactor (3) (an aeration chamber with a volume of about 1.9 m^3) using a BIOX 200/8 Nocchi pump with a power of 900 W and a capacity up to 9.0 $m^3 \cdot h^{-1}$. The biological part of the facility consisted of a biological flow reactor with activated sludge, aerated with a fine bubble membrane diffuser. The last chamber of the technological line of the treatment plant was a secondary settling tank (4), from which treated wastewater was discharged into a nearby watercourse (no name). Part of the sludge from the bioreactor was recirculated to the initial settling tank (external recirculation), and another part was recirculated to the biological reactor (internal recirculation). A schematic of the technological system is shown in Figure 1.

Analytical and statistical methods

During the research period from January 2011 to December 2013, 42 samples were collected from mechanically treated sewage and effluent from the secondary settling tank. Sewage samples were collected once a month and during the summer months (July and August) twice a month. The samples were analyzed in accordance with the recommended reference methods (APHA 1992 and APHA 2005). Samples of mechanically treated sewage were collected from the retention chamber (2) and the secondary settling tank (4).

Organic and biogenic compounds in the samples were analyzed according to the following methods (quoted in Siwiec et al. 2012) recommended by the ordinance of the Polish Minister of the Environment (2006; 2009; 2014):

- BOD_5 was measured by the dilution method using a WTW OxiTop 538 portable meter PN-EN 1899-1:2002; PN-EN 25814:1999,
- Ammonium nitrogen was measured by the spectrophotometric method according to PN-ISO 7150-1.

In the analytical part of paper the statistical analysis with the Pearson's linear correlation coefficient has been done. The main goal of this was to present the influence of the temperature of the atmospheric air on the temperature of sewage in the bioreactor, and temperature of sewage in the bioreactor on the

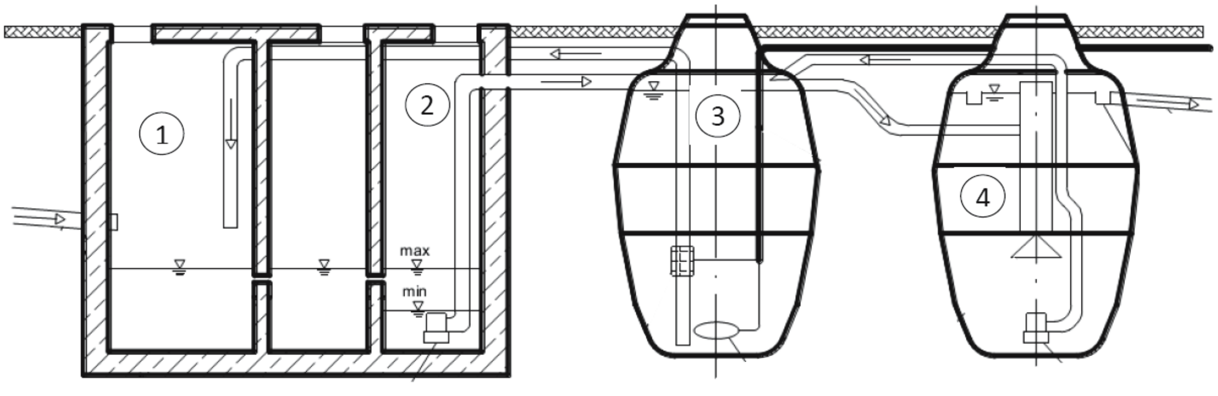

Fig. 1. Schematic of the household wastewater treatment plant; 1 – two-chamber septic tank, 2 – retention tank with pump, 3 – bioreactor, 4 – secondary settling tank

concentration of ammonium nitrogen in treated wastewater. At the end of the analysis the influence of relation between BOD_5 and $N\text{-}NH_4$ in inflow sewage to the concentration of ammonium nitrogen on the outflow of sewage was presented. The correlation coefficient was interpreted according to the Stanisz (2006) guidelines on the significant level $\alpha=0.05$. According to the analysis of partial correlation, the strength of two independent variables was determined (temperature of sewage in the bioreactor and the ratio between BOD_5 to $N\text{-}NH_4$ in the inflow sewage), and dependent variable (concentration of ammonium nitrogen on the outflow of sewage). This part of analysis has been done with STATISTICAL 8.

Results and discussion

In the initial part of the analysis, pollution parameters were determined in mechanically treated wastewater and in the effluent from the treatment plant. In addition, the ranges of air temperatures and wastewater temperatures in the bioreactor were ascertained. Characteristic values of the analyzed parameters are given in Table 1. The values of BOD_5 in raw sewage ranged from 68.4 to 418.6 $mgO_2 \cdot L^{-1}$ and, as indicated by the coefficient of variation Cv = 0.37, showed medium variability (according to the scale proposed by Mucha 1994). The median and mean values of BOD_5 in raw sewage were 179.9 and 192.0 $mgO_2 \cdot L^{-1}$, respectively. The corresponding values in mechanically treated sewage were typical of domestic sewage flowing from an initial settling tank (Canter and Knox 1995, Chmielowski and Bugajski 2008, Gizińska-Górna et al. 2015, Kuczewski 1993). The concentrations of ammonium nitrogen $N\text{-}NH_4$ in raw sewage ranged from 25.6 to 120.6 $mgN\text{-}NH_4 \cdot L^{-1}$ and, as indicated by the coefficient of variation Cv = 0.37, showed medium variability (according to the scale proposed by Mucha 1994). High concentrations of ammonium nitrogen in inflowing sewage result from a high proportion of urine coming from school toilets. The concentrations of ammonium nitrogen in mechanically treated wastewater were similar to those recorded by Richards (2016) and Nourmohammadi et al. (2013).

Because one of the goals of the study was to investigate the effect of wastewater temperature in the bioreactor on the efficiency of removal of ammonium nitrogen, in the first place analyzed the range of variability of wastewater temperature in the bioreactor in the aspect of variability of temperature of atmospheric air. The influence of atmospheric air temperature on wastewater temperature in the bioreactor was determined by Pearson's linear correlation. During the research period, the average wastewater temperature in the biological reactor was 11.7°C (median 11.8°C). The minimum temperature of sewage ranged between 7–8°C in January–February, and the maximum temperature ranged between 17–18°C in July–August. The coefficient of variation of wastewater temperature in the biological reactor was Cv = 0.28, which means there was medium variability in this parameter according to the scale proposed by Mucha (1994). The temperature of atmospheric air on the days on which wastewater samples were collected ranged from -6.1 to +21.9°C.

In the next stage of the study, the influence of air temperature on the temperature of wastewater in the biological reactor was analyzed. Using data on average daily air temperatures and average daily wastewater temperatures, a statistical analysis of Pearson's linear correlation was carried out, the purpose of which was to determine the strength of the relationship between the two variables, where air temperature was the independent variable and wastewater temperature in the biological reactor was the dependent variable. It was found that the correlation between air temperature and wastewater temperature was $r_{xy} = 0.92$, which was an almost certain correlation, according to the scale proposed by Stanisz (2006). The correlation was statistically significant at $\alpha = 0.05$. The value of the t-statistic was 0.0876. The equation describing the regression line shown in Figure 2 indicates that a 1°C change in air temperature changes the temperature of wastewater in the bioreactor by 0.35°C.

In the analyzed case, the R^2 determination coefficient indicates that the influence of air temperature explains 84% of the variability of sewage temperature in the bioreactor as shown in Figure 2.

In the next stage of the study, the influence of wastewater temperature in the biological reactor on the efficiency of ammonium nitrogen removal was determined. This was done by examining the correlation between the concentration of ammonium nitrogen in treated wastewater and the temperature of sewage in the biological reactor. The correlation was found to be high (according to Stanisz's scale, 2006) at $r_{xy} = -0.62$ as shown in Figure 3. It was statistically significant at

Table 1. Statistical characteristics of indicators of contaminant concentration in influent and treated wastewater

Parameter	Type of wastewater	Statistics					
		Average	Median	Min.	Max.	Standard deviation	Coefficient of variation
BOD_5 [$mg \cdot L^{-1}$]	influent	192.0	179.9	68.4	418.6	71.9	0.37
	treated	32.0	30.7	12.0	81.3	14.2	0.44
$N\text{-}NH_4$ [$mg \cdot L^{-1}$]	influent	62.9	59.5	25.6	120.6	23.4	0.37
	treated	17.3	26.5	4.3	68.9	13.5	0.78
Wastewater temperature [°C]	bioreactor	11.7	11.8	6.5	18.0	3.2	0.28
Air temperature [°C]	–	9.3	10.4	-6.1	21.9	8.4	0.90

a significance level of α = 0.05; the value of the t-statistic was 0.0049. The equation for the regression line given in Fig. 3 shows that a 1°C increase in wastewater temperature in the bioreactor caused a decrease in the concentration of ammonium nitrogen in treated wastewater of 2.64 $mgN\text{-}NH_4 \cdot L^{-1}$ The concentrations of ammonium nitrogen in treated wastewater ranged from 4.3 to 68.9 $mgN\text{-}NH_4 \cdot L^{-1}$, with a mean of 17.3 $mgN\text{-}NH_4 \cdot L^{-1}$. The results regarding the effect of wastewater temperature on the efficiency of ammonium nitrogen removal are similar to the results obtained by Liu et al. (2018), Ma et al. (2009) and Nourmohammadi et al. (2013).

Next, the effect of the ratio of organic carbon, expressed as BOD_5, to ammonium nitrogen in wastewater flowing into the biological reactor on the concentration of ammonium nitrogen in treated sewage was established. As shown by pilot (laboratory) studies as well as studies conducted in existing collective treatment plants, there is a close relationship between the availability of organic matter to the microorganisms inhabiting activated sludge and the course of nitrification, (Bugajski and Woźniak-Vecchie 2011, Pelaz et al. 2018, Ruscalleda Beylier et al. 2011). The present analysis of the impact of the $BOD_5/N\text{-}NH_4$ ratio in the influent on the concentration of ammonium nitrogen in treated sewage showed that there was a high correlation (according to Stanisz's scale, 2006) between these variables at r_{xy} = -0.50 as shown in Figure 4. The correlation was statistically significant at a significance level of α = 0.05, and the value of the t-statistic was 0.0000. The equation describing the regression line shown in Fig. 6 that indicates increase in the $BOD_5/N\text{-}NH_4$ by 1 ratio in sewage flowing into the bioreactor led to a decrease in the concentration of ammonium nitrogen in treated wastewater of 5.41 $mgN\text{-}NH_4 \cdot L^{-1}$.

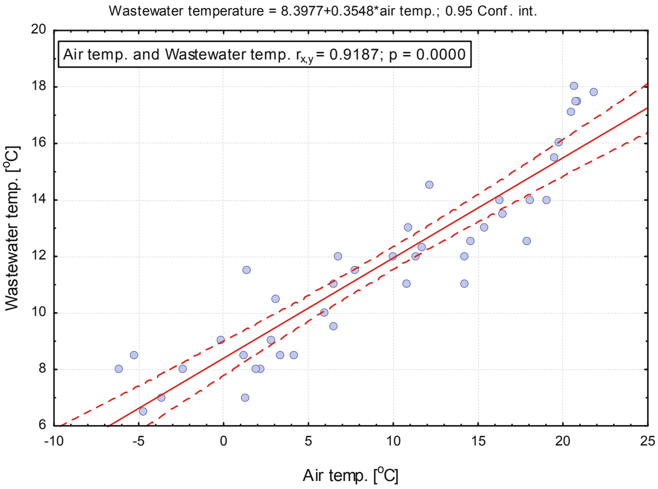

Fig. 2. Scatter plot with a regression line and a 95% confidence level for the effect of air temperature on wastewater temperature in the bioreactor

The analysis demonstrated that the efficiency of nitrification in the biological reactor was affected by two independent factors. To determine the effect of the two factors (independent variables) acting simultaneously, partial correlation analysis was performed for three variables. The purpose of this analysis was to determine the magnitude of the effect of the two independent variables: wastewater temperature in the biological reactor and the $BOD_5/N\text{-}NH_4$ ratio in sewage flowing into the biological reactor on the dependent variable of concentration of ammonium nitrogen in treated wastewater. Partial correlation analysis showed that the temperature of wastewater in the bioreactor had a greater effect on the concentration of ammonium nitrogen in treated wastewater (R_c = 0.56) than did the $BOD_5/N\text{-}NH_4$ ratio in sewage flowing into the biological reactor (R_c = 0.42). The significance of the calculated correlation coefficients was tested using Student's t-test at a significance level of α = 0.05. In both cases, the relationships were found to be significant. Detailed results of multiple regression analysis of the analyzed relationships are shown in Table 2.

Based on the results of partial correlation, the nomogram shown in Figure 5 was developed. The nomogram can be used to predict the concentration of ammonium nitrogen in treated wastewater on the basis of wastewater temperature (the Y axis) and the $BOD_5/N\text{-}NH_4$ ratio in inflowing sewage (the X axis). The model can be described by the following equation: $N\text{-}NH_4$_effluent=56.247 – 2.2 · wastewater temp. – 3.7559·$BOD_5/N\text{-}NH_4$.

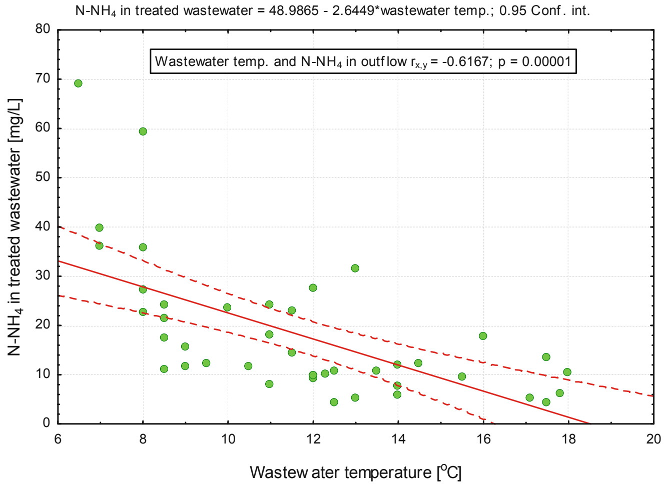

Fig. 3. Scatter plot with a regression line and a 95% confidence level for the effect of wastewater temperature on ammonium nitrogen in treated wastewater

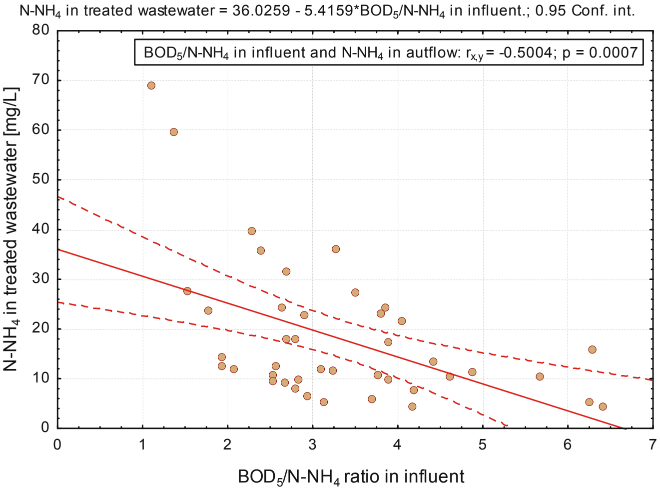

Fig. 4. Scatter plot with a regression line and a 95% confidence level for the effect of $BOD_5/N\text{-}NH_4$ ratio in influent and ammonium nitrogen in treated wastewater

Table 2. Results of multiple regression analysis of the effect of temperature of wastewater flowing into the bioreactor and $BOD_5/N\text{-}NH_4$ ratio on concentration of ammonium nitrogen in treated wastewater

Statistic	Group size	Partial correlation coefficient	Coefficient of determination	Standard deviation of variable	Arithmetic mean of variable	Value of the t-statistic testing significance R	Value of the t-test at α = 0.05
Correlation \ Statistic	N	R_c	R^2	S	SR	t	$t\alpha_{kr}$
$N\text{-}NH_4$ concentration	42	0.56	0.09	13.5	17.3	-4.28	0.000117
Wastewater temperature in bioreactor				3.2	11.7		
$N\text{-}NH_4$ concentration	42	0.42	0.09	13.5	17.3	-2.89	0.006172
$BOD_5/N\text{-}NH_4$ ratio				1.3	3.3		

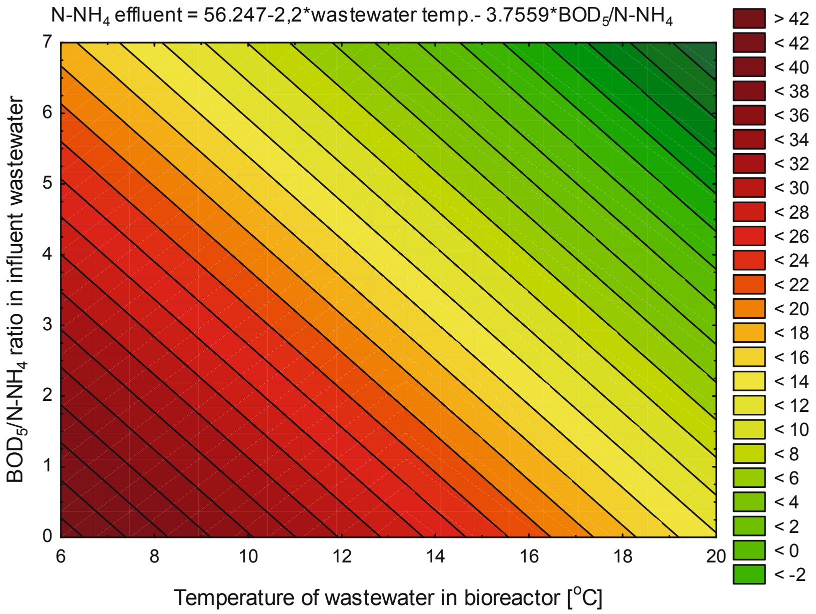

Fig. 5. Nomogram for predicting concentration of wastewater in the bioreactor and $BOD_5/N\text{-}NH_4$ ratio in influent wastewate

Conclusion

The analysis showed that the hydraulic underloading of the tested wastewater treatment plant with activated sludge increased the retention time of wastewater in the biological reactor, which meant that air temperature started to affect wastewater temperature. During the research period, the temperatures of wastewater in the biological reactor ranged from 6.5 to 18.0°C. In addition, large variations in the $BOD_5/N\text{-}NH_4$ ratio were observed in the range from 1.1 to 6.4. The high variability in the content of organic pollutants in the influent relative to the concentration of ammonium nitrogen had an impact on the course of nitrification, and ultimately led to fluctuations in the content of ammonium nitrogen in treated wastewater in the range from 4.3 to 68.9 $mgN\text{-}NH_4 \cdot L^{-1}$. Overall, the analysis demonstrated that the household wastewater treatment plant with activated sludge was sensitive to the analyzed factors. In order to minimize their impact, the quantity of influent sewage should be increased, which would shorten the retention time, and thus the cooling time of sewage in the winter. This would also reduce the time of sedimentation of organic suspended solids in the primary settling tank, which would decrease fluctuations in the concentration of organic compounds in the wastewater flowing into the biological reactor. These measures would increase the efficiency of removal of nitrogen compounds from treated wastewater.

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Wpływ temperatury ścieków oraz związków organicznych na skuteczność usuwania azotu amonowego w przydomowej oczyszczalni przy budynku szkolnym

Streszczenie: Celem pracy było określenie wpływu temperatury ścieków w reaktorze biologicznym z osadem czynnym oraz stosunku $BZT_5/N\text{-}NH_4$ w ściekach dopływających do oczyszczalni na skuteczność procesu nitryfikacji i stężenia azotu amonowego w ściekach oczyszczonych. Badania prowadzono w przydomowej oczyszczalni, do której odpływają ścieki z budynku szkolnego oraz domu nauczyciela. W okresie 3-letnich badań odnotowano duże wahania temperatury ścieków w bioreaktorze co było ściśle związane z temperaturą otoczenia. Stwierdzono również duże wahania stężenia materii organicznej oraz stężenia azotu amonowego w ściekach dopływających. Analizę wpływu temperatury ścieków w bioreaktorze oraz stosunku $BZT_5/N\text{-}NH_4$ na stężenie azotu amonowego w ściekach oczyszczonych określono za pomocą korelacji liniowej Persona. W wyniku przeprowadzonej analizy statystycznej stwierdzono, że wraz obniżeniem temperatury ścieków w bioreaktorze o 1°C następuje zwiększenie stężenia azotu amonowego w ściekach oczyszczonych o 2,64 $mgN\text{-}NH_4 \cdot L^{-1}$. Ponadto stwierdza się, że proces nitryfikacji zależny jest od stosunku BZT_5 do stężenia azotu amonowego w ściekach dopływających do bioreaktora. Wraz ze wzrostem zależności $BZT_5/N\text{-}NH_4$ o 1 maleje stężenie stężenia azotu amonowego o 5,41 $mgN\text{-}NH_4 \cdot L^{-1}$.