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The changes of nitrogen content during sewage treatment: A study of a two-stages wastewater treatment plant

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Abstract: The paper relates to the changes in the content of various nitrogen forms, i.e. total nitrogen (TN), Kjeldahl nitrogen (TKN), ammonium nitrogen (NH_4-N), nitrite nitrogen (NO_2-N), nitrate nitrogen (NO_3-N) and organic nitrogen (ON) at the subsequent operation stages of a mechanical-biological wastewater treatment plant (WWTP). The obtained results indicate the correctness of nitrogen compounds transformations at the subsequent stages of sewage treatment; they are considered as typical for two-stages WWTPs, operating in the activated sludge technology. The analysis of multi-year data and the analysis for particular months show that nitrogen compounds in the form of NO_3-N and NO_2-N, were characterised by the greatest variability. Both the classical analysis of the nitrogen compounds content in each month of the year and the analysis using control cards prove that in the months characterised by a low temperature or by the impact of meltwater or rainwater, disturbances in the nitrification and denitrification processes can be expected, and thus, lower efficiency of nitrogen removal (winter months, the period between winter and spring, summer months). Knowledge on the transformation of nitrogen compounds at the subsequent stages of treatment can be useful both to improve the efficiency of the currently used processes and to model new solutions, which is particularly important in the case of biogenic compounds reduction.

Keywords: ammonium nitrogen, biological treatment, Kjeldahl nitrogen, mechanical treatment, nitrate nitrogen, nitrite nitrogen, organic nitrogen, sewage, total nitrogen

INTRODUCTION

Groundwater and surface water resources are constantly exposed to pollution with nitrogen compounds, the source of which may be fertilisers used in agriculture, untreated waste from industry, animal husbandry or households and insufficiently treated sewage (Rahimi, Modin and Mijakovic, 2020). Discharged sewage into the natural environment, in which significant amounts of nitrogen compounds are still present, is primarily threat to the environment, contributing to the eutrophication of surface waters, which disturbs the ecological balance of water ecosystems. It should be borne in mind that nitrogen in drinking water in high concentrations, e.g. in form of nitrates, can be harmful for human health, as well as toxins that are released from phytoplankton blooms (Capodaglio, Hlavínek and Raboni, 2015; Vries de, 2021). Due to the threat posed by the presence of nitrogen in the natural environment, ensuring the efficiency of nitrogen removal processes is one of the challenges faced by wastewater treatment plants. The importance of this problem is the reason why the permissible nitrogen content in sewage after treatment processes, along with other pollutant indicators, is legally regulated in many countries (Preisner, Neverova-Dziopak and Kowalewski, 2020). The Polish Regulation (Rozporządzenie, 2019) determines that the total nitrogen content in treated sewage should not exceed 30.0 mg·dm^{-3} in the case of wastewater treatment plants with a population equivalent (p.e.) of less than 2,000, for WWTPs with a p.e. of 2,000–99,999 is 15.0 mg·dm^{-3} and 10.0 mg·dm^{-3} is for WWTPs with p.e. over 100,000.

The structure of nitrogen compounds in sewage is as follows (Sperling von, 2007): total nitrogen (TN) is the sum of Kjeldahl nitrogen (TKN), nitrite nitrogen (NO_2-N) and nitrate nitrogen (NO_3-N); in turn, TKN, is the sum of ammonium nitrogen (NH_4-N) and organic nitrogen (ON). Raw sewage inflowing to the WWTP contains nitrogen mainly in the form of NH_4-N and ON. Other forms of nitrogen including in TN, i.e. NO_3-N and NO_2-N, are trace amounts in raw sewage (Sperling von, 2007). The conversion of organic forms of nitrogen into ammonium compounds through the ammonification process takes place already during the flow of sewage through the sewage network. It is therefore important to bear in mind what Qteishat, Myszograj and Suchowska-Kisielewicz (2011) underscores, in fact, sewage treatment processes do not start with the inflow of sewage into the WWTP, but already at the stage of their flow through the sewage network.

The classification of nitrogen compounds removal methods used in WWTPs includes biological, chemical and mechanical processes. As Zhou *et al.* (2023) shows, each of these processes has some advantages and disadvantages, however, biological methods are considered as the most effective, while the chemical methods, are the least effective. High efficiency of biological nitrogen removal processes is extremely important in the context of protection of water resources. Hence, constantly developed new criteria for the design of biological reactors, which are an improvement of the existing ones, as well as the proposed new treatment technologies by denitrification, is especially valuable (Du *et al.*, 2015; Capodaglio, Hlavínek and Raboni, 2016). The search for the answer to the question, of which biological processes can be considered as the best for removing nitrogen from sewage can be found, for example, in the paper of McCarty (2018), in which the author compares conventional and unconventional nitrogen removal techniques. At present, biological treatment processes using activated sludge technology are the main methods for municipal and industrial sewage treatment (Capodaglio, Hlavínek and Raboni, 2015). Biological sewage treatment using activated sludge technology is a gradual process that requires appropriate conditions in biological reactors to be considered as effective. Its efficiency depends primarily on the growth and activity of microorganisms in the activated sludge, which in turn is affected by pH, temperature, sludge retention time, carbon to nitrogen ratio, hydraulic retention time and dissolved oxygen content (Zhou *et al.*, 2023). As a result of nitrification, which takes place in the first under aerobic conditions, NH_4-N is oxidised to NO_2-N and then to NO_3-N with the participation of autotrophic bacteria. Then, during denitrification process taking place in hypoxic conditions, nitrates (NO_3-N) are reduced with the use of heterotrophic bacteria to gaseous nitrogen (N_2) (Qasim, 1999).

Detailed knowledge about the share of particular fractions of nitrogen in sewage, e.g. according to El Sheikh *et al.* (2016), the knowledge about the TKN, allows for a more accurate estimation of biological pollutants degradability than the commonly used Kjeldahl nitrogen/five-day biochemical oxygen demand ratio (TKN/BOD_5), which is particularly useful for WWTPs operation modelling. According to Wąsik *et al.* (2017), the control of inorganic nitrogen content in sewage in the form of NH_4-N, not only TN, is important too; for example, Slovakia is the country where limited value for ammonium nitrogen in sewage is determined.

Undoubtedly, a continuous monitoring of biogenic compounds removing processes, as well as the knowledge about the course of these processes and the knowledge about the nitrogen compounds transformations at the subsequent treatment stages, is very important for proper operation of each WWTP. Therefore, in this study, a detailed analysis of changes in the content of a different nitrogen forms, i.e. TN, TKN, NO_2-N, NO_3-N, NH_4-N and ON at the next treatment stages of mechanical-biological WWTP was performed. The knowledge about the transformations of nitrogen compounds at the subsequent treatment stages and the changes of nitrogen fractions content allows not only assessing the reliability of WWTP operation. In this way, a data set constituting the basis for, either modelling a new nitrogen removal processes, or to improve the efficiency of those currently used, is provided.

MATERIALS AND METHODS

CASE STUDY

The measurements of nitrogen compounds were conducted in mechanical-biological WWTP "Wielopole", located in one of the largest cities of the southern Poland. Subjected WWTP with a design capacity of 180,000 p.e. (these data refers to the 2020; in 2013, it was 120,000 p.e.), serves the area of the city along with the neighbouring municipalities. The area of this agglomeration is sewered by a combined and separate sewage system, working mainly as gravitational sewage system. In the period 2013–2020, a separate sewage system was successively expanded, what is evidenced by the data presented below. In 2013, the total length of the sewage system (excluding rainwater drainage network) was 349 km (including combined sewage system – 76 km, sanitary sewage system – 273 km). In 2020, the total length of the sewage system was already 610 km (including combined sewage system – 76 km, sanitary sewage system – 534 km). In 2013, less than 85,000 people used the agglomeration's sewage system and in 2020 – by over 20,000 more inhabitants. In 2013, over 49,000 inhabitants used septic tanks and in 2020, it was only about 5,000 residents. In turn, individual sewage treatment systems, i.e. household treatment plants, were used by almost 1,150 inhabitants (2013); in 2020, the number of household treatment plants users was more than twice as low.

The analysed WWTP purifies domestic and industrial sewage. In 2013, the hydraulic capacity of the object, expressed by the maximum daily flow was 42,200 $m^3 \cdot d^{-1}$; in 2020, it was 33,000 $m^3 \cdot d^{-1}$. Raw sewage inflowing to the WWTP, along with sewage delivered to the discharge station, at first, are subjected to a mechanical treatment on two automatic screens, then in two parallel grit chambers, where fats are also separated, and in the final stage of a mechanical treatment, in two radial primary settling tanks. Next, biological treatment using activated sludge technology takes place in two reactors with separate anaerobic, hypoxic and aerobic zones. The clarified outflow of treated sewage from the secondary settling tanks located at the end of the technological line of the WWTP is directed to the river.

RESEARCH DATA HANDLING AND STATISTICAL ANALYSIS

The materials for this study were provided by the operator of the facility; these included the results of the quality of raw sewage and sewage after mechanical and biological treatment. The results come from the measurements carried out in the period 2013–2020 for the following nitrogen forms: total nitrogen (TN), Kjeldahl nitrogen (TKN), nitrate nitrogen (NO_3-N), nitrite nitrogen (NO_2-N), ammonium nitrogen (NH_4-N) and organic nitrogen (ON). The number of measurements' data for each form of nitrogen in the eight-year research period was approximately 545. There was no division of the research period for dry weather and wet weather; sewage composition was tested together for both weather conditions. For sewage from three treatment stages, descriptive statistics were determined; these included minimum (Min.), average (μ), maximum (Max.), standard deviation (σ), coefficient of variation (*CV*), kurtosis (*Kurt*) and skewness (*Sk*). Based on the average values, the changes in the content of nitrogen compounds after the subsequent stages of sewage treatment in particular years and months were analysed. Based on the average values for the multi-year period, the share of a different nitrogen forms was calculated. In the last stage, based on the measurements of TN in sewage after biological treatment, the stability of nitrogen compounds removal processes was assessed using control cards. To be able to use a control cards, the examined random variables should be characterised by a normal distribution. The normality of variables' distribution was verified using the Shapiro–Wilk test (Shapiro and Wilk, 1965). Since the examined random variables were not characterised by a normal distribution, they were normalised by logarithmic. During the control cards elaboration, the three sigma rule for the normal distribution $N(\mu, \sigma)$ was followed. Therefore, the boundaries of the control lines, warning lines, helping lines and the central line were determined from the dependences as Krzanowski and Wałęga (2006) and Młyński, Chmielowski (2017) describe:

– upper control line (*UCL*):

$$UCL = \mu + 3\sigma \tag{1}$$

– upper warning line (*UWL*):

$$UWL = \mu + 2\sigma \tag{2}$$

– upper helping line (*UHL*):

$$UHL = \mu + 1\sigma \tag{3}$$

– central line (*CL*):

$$CL = \mu \tag{4}$$

– lower helping line (*LHL*):

$$LHL = \mu - 1\sigma \tag{5}$$

– lower warning line (*LWL*):

$$LWL = \mu - 2\sigma \tag{6}$$

– lower control line (*LCL*):

$$LCL = \mu - 3\sigma \tag{7}$$

where: μ = average (mg·dm^{-3}), σ = standard deviation (mg·dm^{-3}).

The following results (Andraka, 2005), may indicate the disruption or lack of stability of the nitrogen removing processes:

– one point outside the *UCL* or *LCL*,
– two of three subsequent points outside the *UWL* or *LWL*,
– four of five subsequent points outside the *UHL* or *LHL*,
– eight subsequent points on one side of the *CL*.

RESULTS AND DISCUSSION

THE CHANGES OF THE NITROGEN FORMS CONTENT AT THE SUBSEQUENT TREATMENT STAGES IN THE PERIOD 2013–2020

As it can be seen in the Figure 1, between 2013 and 2020, the content of a different nitrogen forms at the subsequent treatment stages in particular years, remained at a relatively equal level. The average content of total nitrogen (TN) determined for the multi-year period 2013–2020 at the subsequent treatment stages changed from 66.8 mg·dm^{-3} in raw sewage, through 64.8 mg·dm^{-3} in mechanically treated sewage (that gives a 3% of TN reduction in mechanical treatment), and finally, to 7.8 mg·dm^{-3} in biologically treated sewage (Tab. 1) (that gives a further 88% of TN reduction in biological treatment); 7.80 mg·dm^{-3} in treated sewage meets the requirements of Rozporządzenie (2019) about the permissible TN content in sewage discharged from WWTP to the natural environment, i.e. 10.0 mg·dm^{-3}. The values of coefficient of variation (*CV*) at all treatment stages were not only very similar to each other, but also reached values indicating a low variability of total nitrogen content in sewage. The values of kurtosis (*Kurt*) show that biologically treated sewage was characterised by the greatest concentration of TN content values around the average value. The skewness calculated additionally for biologically treated sewage (*Sk* = 0.47) indicates the results concentrated below the average TN content (Tab. 1).

Since the Kjeldahl nitrogen (TKN), along with the nitrate nitrogen (NO_3-N) and nitrite nitrogen (NO_2-N) is the part of the total nitrogen (TN), the changes in the content of these nitrogen forms also were analysed. The content of TKN formed by ammonium nitrogen (NH_4-N) and organic nitrogen (ON) in raw sewage is dominant; in the analysed case, TKN constituted a 99% of total nitrogen (TN) (Fig. 2a). Mechanical treatment processes did not significantly affect the changes in TKN content, but the share of nitrogen forms that are the part of TKN was changed: first of all, the share of NH_4-N increased by nearly 6%, while the share of ON, decreased by nearly 6% (Fig. 2a, b). Only biological treatment processes ensured high reduction of TKN, by significantly reducing the content of NH_4-N to the level at which, it was only about 6% of TN (Fig. 2c). In the last stage of the treatment, NH_4-N was transformed into NO_3-N, after which, NO_3-N was as much as 50% of TN content (Fig. 2c). Sewage treatment processes at the analysed two-stages WWTP ensured in the period 2013–2020 a decrease in the content of NH_4-N (average from 38.4 to 0.5 mg·dm^{-3}) and ON (average from 27.8 to 3.3 mg·dm^{-3}) and an increase in the content of NO_3-N (average from 0.5 to 3.9 mg·dm^{-3}). The content of NO_2-N at all treatment stages remained at a relatively even level (average 0.10–0.14 mg·dm^{-3}) – Table 1. In addition, it was observed that the changes of TKN content, described by the *CV*, *Kurt*, *Sk* parameters, at the subsequent treatment stages, had a similar

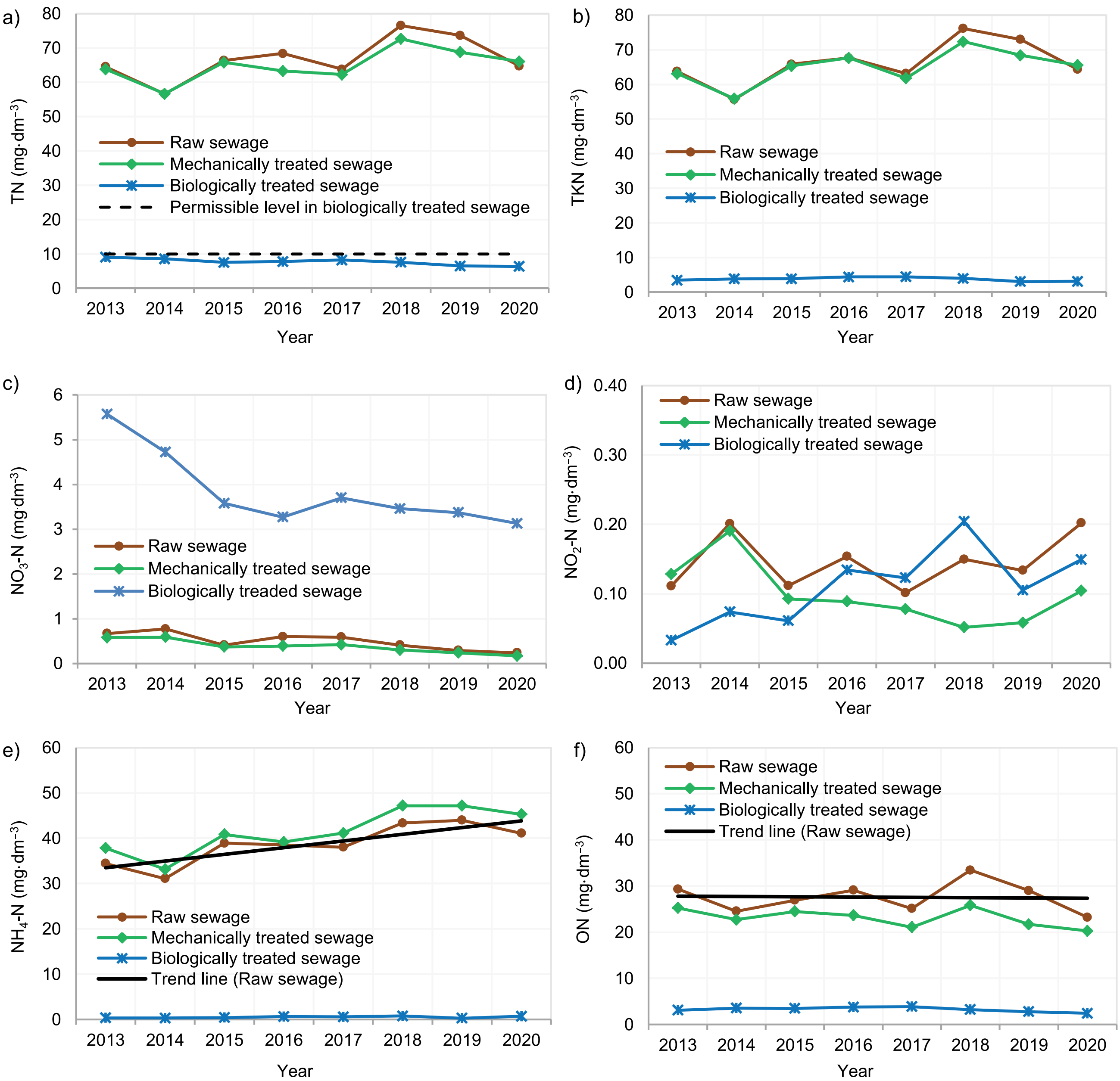

Fig. 1. The changes of the nitrogen forms content in raw sewage and in sewage after mechanical and biological treatment in each year of the period 2013–2020 (average yearly values): a) total nitrogen (TN), b) Kjeldahl nitrogen (TKN), c) nitrate nitrogen (NO_3-N), d) nitrite nitrogen (NO_2-N), e) ammonium nitrogen (NH_4-N), f) organic nitrogen (ON); source: own study

Table 1. Descriptive statistics for a different nitrogen forms in raw sewage and in sewage after mechanical and biological treatment in the period 2013–2020

Nitrogen forms	Min.	*μ*	Max.	*σ*	*CV*	*Kurt*	*Sk*
	(mg·dm^{-3})				(–)		
Raw sewage							
TN	20.10	66.78	108.86	16.23	0.24	–0.05	–0.09
TKN	11.32	66.15	108.30	16.47	0.25	0.02	–0.14
NO_3-N	0.01	0.51	8.48	0.54	1.07	96.43	7.87
NO_2-N	0.0005	0.14	0.83	0.17	1.15	1.72	1.38
NH_4-N	5.03	38.43	83.84	10.45	0.27	0.63	–0.19
ON	1.90	27.80	81.59	11.01	0.40	1.68	0.70

cont. Tab. 1

Nitrogen forms	Min.	μ	Max.	σ	*CV*	*Kurt*	*Sk*
	(mg·dm^{-3})				(–)		
Mechanically treated sewage							
TN	16.08	64.79	127.97	15.02	0.23	0.60	–0.14
TKN	15.80	64.29	127.70	15.19	0.24	0.66	–0.18
NO_3-N	0.01	0.40	7.72	0.47	1.18	127.69	9.46
NO_2-N	0.0003	0.10	1.63	0.19	1.92	16.42	3.46
NH_4-N	8.08	41.12	76.33	10.83	0.26	0.47	–0.29
ON	0.39	23.36	83.09	9.48	0.41	5.06	0.96
Biologically treated sewage							
TN	1.78	7.80	16.99	1.95	0.25	1.01	0.47
TKN	0.80	3.80	9.37	1.50	0.39	1.05	0.92
NO_3-N	0.68	3.92	10.02	1.33	0.34	2.04	0.88
NO_2-N	0.0012	0.10	4.28	0.21	1.99	267.71	14.24
NH_4-N	0.01	0.50	4.98	0.54	1.10	22.57	4.06
ON	0.36	3.31	9.02	1.38	0.42	1.28	0.91

Explanations: Min. = minimum, μ = average, Max. = maximum, σ = standard deviation, *CV* = coefficient of variation, *Kurt* = kurtosis, *Sk* = skewness, TN = total nitrogen, TKN = Kjeldahl nitrogen, NO_3-N = nitrate nitrogen, NO_2-N = nitrite nitrogen, NH_4-N = ammonium nitrogen, ON = organic nitrogen.
Source: own study.

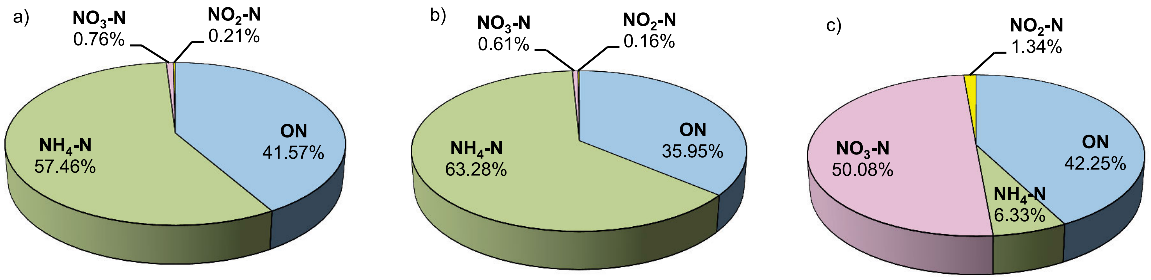

Fig. 2. The share of a different nitrogen forms (based on the average values for the multi-year period 2013–2020) in: a) raw sewage, b) mechanically treated sewage, c) biologically treated sewage; source: own study

trends as the changes of TN contents, as was presented in Table 1 or in Figure 1. The *CV* determined for NH_4-N, indicate that its content in raw sewage and in mechanically treated sewage was characterised by average variability, in sewage after biological treatment – it was a very strong variability; in turn, contents of ON at all treatment stages were characterised by variability tending towards strong. However, when analysing the NO_3-N and NO_2-N, in both cases, at all treatment stages, their contents were characterised by very high variability (*CV* > 1.0), with the exception of NO_3-N after biological treatment, for which the determined *CV* value of 0.3 indicates average variability (Tab. 1). Other descriptive statistics, i.e. *Kurt* and *Sk* for NH_4-N, ON, NO_3-N and NO_2-N presented in Table 1 should be interpreted in accordance with the assumption that the higher kurtosis, the greater number of measurement data is concentrated around the average. Positive skewness indicates a majority of values below the average; skewness less than zero indicates a majority of values above the average. Very similar results of TN, NH_4-N, NO_3-N, NO_2-N and ON in raw sewage and in biologically treated sewage are presented in the paper of Wąsik *et al.* (2017).

MONTHLY CHANGES OF THE NITROGEN FORMS CONTENT AT THE SUBSEQUENT TREATMENT STAGES

Content of TN in raw sewage varied from 58.5 mg·dm^{-3} (May) to 74.8 mg·dm^{-3} (January) – Figure 3a. The average TN contents in biologically treated sewage calculated for multi-year period show slight differences in particular months; all of them were around 8.0 mg·dm^{-3}, so that meets with the requirements of Rozporządzenie (2019). In the case of TKN (Fig. 3b) and NH_4-N included in TKN (Fig. 3e), a similar course over the months was observed as in the case of TN (Fig. 3a). Off all months, the maximum content of TN, TKN and NH_4-N in raw sewage and in mechanically treated sewage was in January; the lowest content for TN, TKN and NH_4-N was in May, except of NH_4-N in raw sewage. Also in the case of ON (Fig. 3f), a slight variability was observed in the sewage from the first two stages of treatment (similar to TN, TKN, NH_4-N, *CV* < 0.1); the only one difference was maximum ON content, that did not fall on January, but in August. The *CV* determined for NH_4-N (Fig. 3e) indicate that while its variability in raw sewage and in mechanically treated sewage can be considered as low, in particular months, NH_4-N in biologically

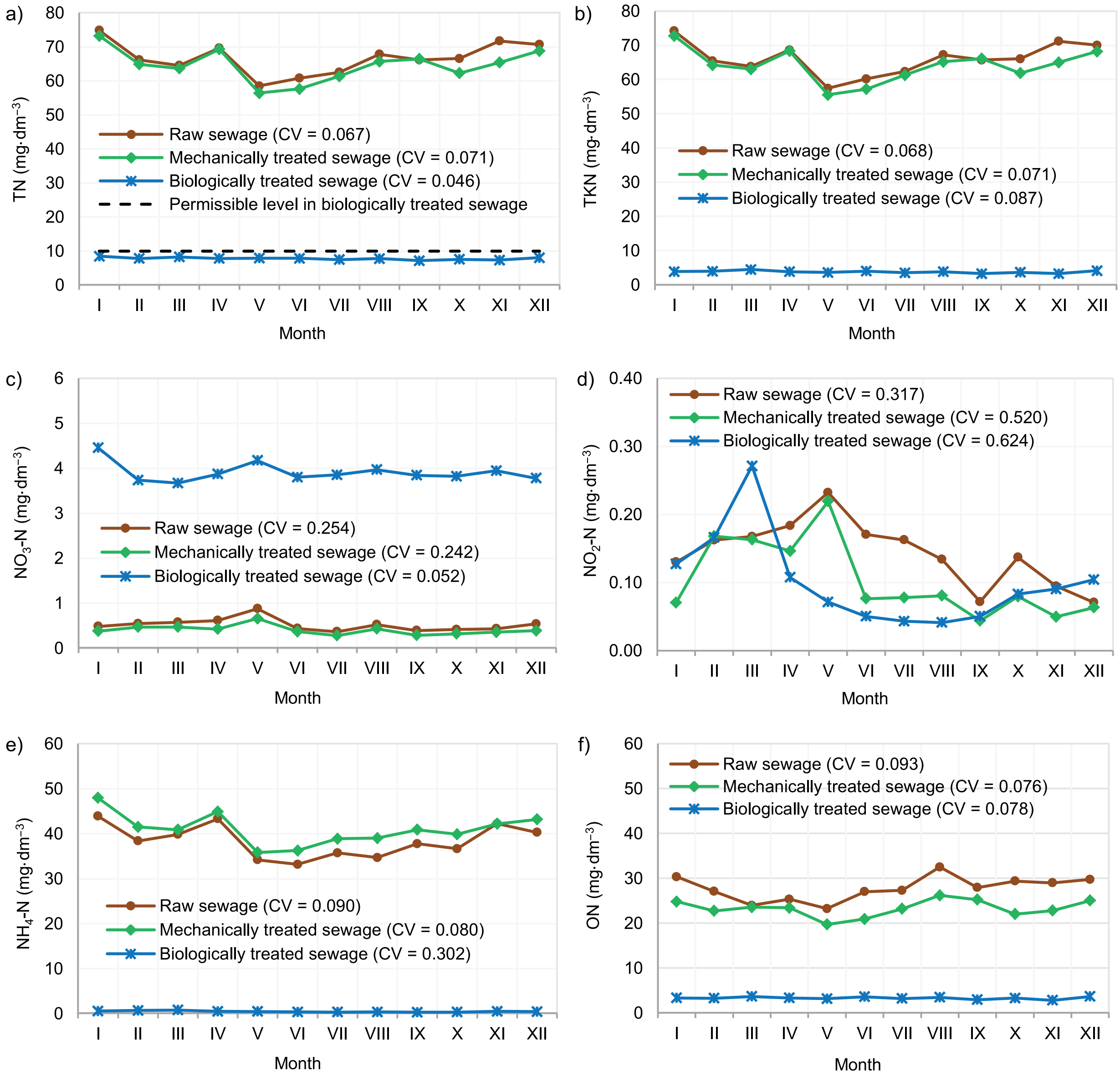

Fig. 3. The changes of the nitrogen forms content in raw sewage and in sewage after mechanical and biological treatment in particular months (average monthly values for the multi-year period 2013–2020): a) total nitrogen (TN), b) Kjeldahl nitrogen (TKN), c) nitrate nitrogen (NO_3-N), d) nitrite nitrogen (NO_2-N), e) ammonium nitrogen (NH_4-N), f) organic nitrogen (ON); *CV* = coefficient of variation; source: own study

treated sewage was characterised by greater variability; according to the classification of the *CV* coefficient, it was average variability. The observations for NO_3-N (Fig. 3c) and NO_2-N (Fig. 3d) are different than the other nitrogen forms. In both cases, over the months, their clearly greater variability compared to other forms of nitrogen in raw sewage and in mechanically treated sewage (average variability) was observed, with the maximum content in May. However, while the content of NO_3-N in sewage after biological treatment in particular months remained at a relatively even level (Fig. 3c), in the case of NO_2-N (Fig. 3d), differences in particular months were clearly noticeable: from the highest value in March, gradually decreasing in the next months, to the minimum in July and August (strong variability). In general, it was observed that the highest content each of the nitrogen forms in biologically treated sewage, i.e. the lowest efficiency of nitrogen removal biological processes, occurred in the winter months and in the period between winter and spring (January/March). In the next chapter of this paper, the analysis by using control cards will show the disruption of treatment processes in those periods of the year, that are associated with low temperature and with the inflow of meltwater or rainwater.

THE ASSESSMENT OF THE STABILITY OF NITROGEN REMOVAL BIOLOGICAL PROCESSES BY USING CONTROL CARDS

The control cards as tools for assessing the stability of sewage treatment processes have already been used many times in different studies (Krzanowski and Wałęga, 2006; Krzanowski, Wałęga and Paśmionka, 2008; Górka, 2015; Młyński and Chmielowski, 2017; Wąsik *et al.*, 2017; Śliz, 2018; Śliz and Bugajski, 2022). The validity of using the control cards for the investigation of the effectiveness of nitrogen processes removal was stated, for example, by Wąsik *et al.* (2017).

In this paper, the control cards showed that in the analysed WWTP, in the eight-year research period, there were periods in which one can talk about the lack of stability of the processes of removing nitrogen compounds. In 2013 (Fig. 4a), 2014 (Fig. 4b), 2016 (Fig. 4d), 2018 (Fig. 4f) and in 2020 (Fig. 4h), at least eight next points on one side of the central line, indicate the lack of

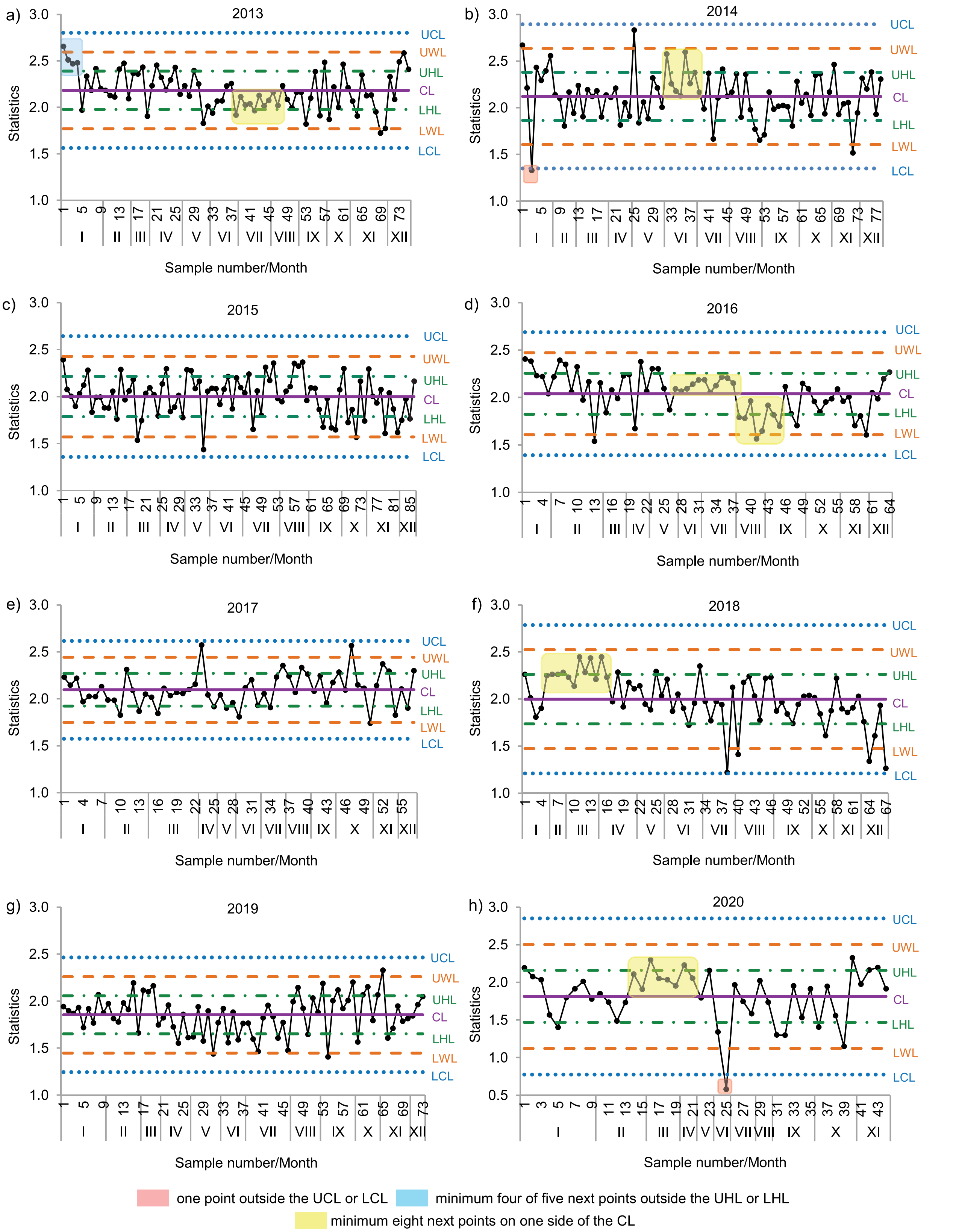

Fig. 4. Control cards for total nitrogen content in biologically treated sewage in each year of the period 2013–2020; *UCL* = upper control line, *UWL* = upper warning line, *UHL* = upper helping line, *CL* = central line, *LHL* = lower helping line, *LWL* = lower warning line, *LCL* = lower control line; source: own study

stability. In 2013, 2014 and 2016, the instability of processes occurred in the summer months (June–August), while in 2018 and 2020, in late winter and spring (February–April). In addition, the instability of the processes expressed by the occurrence of one measurement point outside the *LCL* was recorded in January 2014 (Fig. 4b) and in June 2020 (Fig. 4h). In turn, in January 2013, four next points outside the *UHL* (Fig. 4a) were noted. Despite the recorded periods in which disruption of nitrogen removal processes was found, it can be stated that the processes of biological sewage treatment ensured the required level of total nitrogen reduction, as indicated by the results analysed in the earlier part of this paper. It should be also noted that these disturbances, did not occur in all years of the 2013–2020 period, and in those years in which they were recorded, they occurred mainly in the summer and winter months. Based on this, it can be assumed that the disturbances of sewage treatment processes occurring in this period were affected by extreme temperatures or inflows of rainwater and snowmelt. Similar conclusions regarding to a periodic disturbances of nitrification and denitrification processes, related to the weather conditions typical for particular seasons (e.g. low temperature in winter, inflow of meltwater between winter and spring), are also drawn by Krzanowski and Wałęga (2006), Wąsik *et al.* (2017), and Śliz and Bugajski (2022) and based on the performed research using control cards. A decrease in the activity of nitrifying and denitrifying bacteria in reduced temperature was evidenced not only by Wąsik *et al.* (2017) (temperature <8–9°C), or similarly by Hwang and Oleszkiewicz (2008), but also by Gnida *et al.* (2016) (temperature <16°C). It is observed that the optimum temperature for the growth of bacteria involved in the process of nitrification and denitrification, and therefore, the highest efficiency of these processes, e.g. according to Zhang *et al.* (2019), is achieved at a temperature >18°C or according to Chen *et al.* (2018), at a temperature of 20–25°C.

CONCLUSIONS

A sufficiently high efficiency of nitrogen removal is one of the challenges faced by WWTPs operators. Creating appropriate conditions for the course of biological treatment processes is the key to achieving the required level of nitrogen reduction in treated sewage. To make this possible, it is extremely important to know the course of these processes. Because of this, in this paper, the analysis of the changes in the content of different forms of nitrogen at the subsequent stages of sewage treatment, beginning with the analysis of raw sewage, through the analysis of mechanically treated sewage, ending with biologically treated sewage was performed.

In the analysed multi-year period 2013–2020, mechanical treatment resulted in a 3% of total nitrogen reduction, and biological treatment, a further 88% of total nitrogen reduction. Conducted analysis showed that the share of a different forms of nitrogen Kjeldahl nitrogen (TKN), ammonium nitrogen (NH_4-N), nitrate nitrogen (NO_3-N), nitrite nitrogen (NO_2-N), and organic nitrogen (ON) changing at each stage of treatment, can be considered as typical for properly functioning WWTPs using activated sludge technology. Compared to biological treatment, mechanical treatment did not bring significant changes in the share of different nitrogen forms in total nitrogen (TN). The NH_4-N, constituting the largest part of TN in raw sewage (about 58%), in biologically treated sewage, it was only about 6%; as a result of biological processes, NH_4-N was converted into the NO_3-N, which constitutes as much as half of TN content in treated sewage. In turn, the share of ON at all three treatment stages, did not change significantly, always constituting about 40% of TN content. The variability of the content of TN, TKN, NH_4-N and ON in each month, in raw sewage, mechanically treated sewage and in biologically treated sewage, can be considered as small, in contrast to NO_3-N and NO_2-N. Particular in the case of NO_2-N, at all three treatment stages, a strong variability over the year was observed. Similarly, the coefficients of variation (*CV*) for NO_3-N and NO_2-N, determined based on the multi-year data, are the highest among all other analysed nitrogen compounds. Both the classical analysis of changes in the content of nitrogen forms in each month of the year and the analysis using control cards, indicate in which periods of the year, the nitrification and denitrification processes are exposed to disturbances, thus resulting in lower efficiency of nitrogen removal, and therefore, higher nitrogen content in sewage. As is reported by other analysed literature studies, this can be expected especially in the months with low temperature and in the periods of snowmelt or rainwater inflow. The results obtained in this paper confirm the reports of other authors. Namely, the lower efficiency of biological nitrogen removal compared to other periods of the year was observed in the winter months, in the period between winter and spring (January/March) and in the summer months.

To summarise, it can be stated that the detailed knowledge about the transformation of nitrogen compounds at the subsequent sewage treatment stages may be useful not only to assess the correctness of the course of biological treatment processes in similar facilities, but also to model a new processes or to improve the efficiency of the currently ones used. The results presented in this manuscript can become the basis for further development of scientific research in this direction.

CONFLICT OF INTERESTS

All authors declare that they have no conflict of interests.

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