Reliability of removal of selected pollutants in different technological solutions of household wastewater treatment plants

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Abstract

The reliability of removal of selected contaminants in three technological solutions of the household sewage treatment plants was analysed in this paper. The reliability of the sewage treatment plant with activated sludge, sprinkled biological deposit and hybrid reactor (activated sludge and immersed trickling filter) was analyzed. The analysis was performed using the Weibull method for basic indicators of impurities, BOD₅, COD and total suspended solids. The technological reliability of the active sludge treatment plant was 70% for BOD₅, 87% for COD and 66% for total suspended solids. In the sewage treatment plant with a biological deposit, the reliability values determined were: 30% (BOD₅), 60% (COD) and 67% (total suspended solids). In a treatment plant with a hybrid reactor, 30% of the BOD₅ and COD limit values were exceeded, while 30% of the total suspended solids were exceeded. The reliability levels are significantly lower than the acceptable levels proposed in the literature, which means that the wastewater discharged from the analysed wastewater treatment plants often exceeds the limit values of indicators specified in currently valid in Poland Regulation of the Minister of Environment for object to 2000 population equivalent.

Key words: BOD₅, COD, household wastewater treatment plants, technological reliability, total suspended solids

INTRODUCTION

Household wastewater treatment plants have in recent years become a common element of sanitary infrastructure in rural areas, especially in their part, where the development of a traditional sewage system is not justified for economic or technical reasons [BLAŻEJEWSKI 2005; OBARSKA-PEMPKOWIAK et al. 2015; PAWELEK, BUGAJSKI 2017; PIASECKI, JURASZ 2015; ŚWIERK 2016]. They are a good alternative to the hitherto used septic tanks, the exploitation of which is connected with many problems, mainly of an economic and ecological nature [KAROLINCKAZ et al. 2015]. As a result, the number of septic tanks has been steadily decreasing, with a simultaneous increase in the number of household wastewater treatment plants. According to the Central Statistical Office (Pol. Główny Urząd Statystyczny – GUS) data [2016] the number of non-return tanks in 2015 amounted to 2,136 thousand, which means a decrease by 2.6% compared to 2014. In the same period, the number of household wastewater treatment plants increased by 11.9%, to ca. 203,000 [GUS 2016]. Among the many solutions offered on the market of household wastewater treatment plants we can mention systems with infiltration drainage, sand filters, constructed wetland treatment plants and technological systems using conventional methods of sewage treatment – biological deposits, activated sludge and treatment plants with hybrid reactor [BLAŻEJEWSKI 2005; HEIDRICH et al. 2008, 2013; IGNATOWICZ, PUCHLIK 2015; SKRZYPIEC et al. 2017].

Usually, the amount of wastewater flowing out of household sewage treatment plants is small, however,
According to the study of [still] 3 household wastewater treatment plants, differentiated due to the applied technology of pollutants removing from wastewater: 1) a treatment plant with activated sludge, 2) a treatment plant with biological deposit, 3) a treatment plant with hybrid reactor (activated sludge and biological deposit).

**Object No. 1.** The household wastewater treatment plant with activated sludge type BIOPAN operates in Branica Radzyńska and has a flow capacity of 0.9 m³·d⁻¹. The population equivalent for this object is 6. It is made of PEHD polyethylene panels. It consists of a 1.34 m diameter cylinder with a depth of 1.55 m and a sealed bottom, divided into four chambers with vertical and inclined walls and covered with a tightly sealed cover (Fig. 1). The domestic wastewater flowing out of the residential building is fed directly into the I chamber of the wastewater treatment plant (no classical septic tank) where the thicker contaminants (grills) are separated. They then flow into the second anaerobic chamber, where under oxidized conditions a denitrification process takes place, and then they flow into the III chamber with activated sludge, in which the nitrification process takes place due to intensive mixing and aeration. After a certain time of contact, the mixture of old and newly formed microbial cells flows with the wastewater to the IV chamber – a secondary settling tank, where the sediment is separated from the treated sewage. Purified wastewater is discharged to the ground by drainage system [PASTUSZAK 2004].

**Object No. 2.** The household wastewater treatment plant with biological deposit is located in Brzegi, in the municipality of Siedliszcze near Chełm. The task of the treatment plant is to neutralize domestic wastewater from a multi-family residential building. The hydraulic load of the treatment plant is about 4.5 m³·d⁻¹. The population equivalent calculated on the basis of the average of BOD₅ load in raw wastewater is 50. The facility consists of a primary settling tank and biological deposit integrated with the secondary settling tank. The system uses a natural process of biological oxidation of contaminants on the sprinkled bed for wastewater treatment. After mechanical treatment in the precipitator, gravitational wastewater flows to the pumping zone in the bottom well under the biological deposit, from where they are lifted and flattened on the surface of the deposit by the sprinkler system. The deposit is filled with plastic fittings with high hydraulic permeability and a highly developed active surface. During periods of low flow, some treated wastewater can be recirculated, thus improving the efficiency of the deposit [MARZEC, JÓŹWIAKOWSKI 2006]. The treated wastewater is discharged to the drainage ditch.

**Object No. 3.** Wastewater treatment plant with hybrid reactor is located in Dys (lubelskie province). It is used for treatment of domestic wastewater from two houses inhabited by five people. The maximum throughput capacity of the treatment plant amounts to 1.0 m³·d⁻¹. The population equivalent for this object is 6 [JÓŹWIAKOWSKI et al. 2012; MARZEC 2016].

The tank of the wastewater treatment plant is made of concrete. It consists of four chambers with the total active capacity of 5.57 m³ [JÓŹWIAKOWSKI et al. 2012]. The first two chambers are primary settling tanks ($V_{cz} = 3.36$ m³$^3$), the third chamber ($V_{cz} = 1.57$ m³$^3$) is the hybrid reactor operating based on activated sludge and immersed trickling filter system, and the fourth chamber ($V_{cz} = 0.64$ m³$^3$) contains a secondary settling tank (Fig. 2). In the primary settling tank solids are separated and the accumulated sludge is initially fermented. From the second chamber of the primary settling tank wastewater flows into the hybrid reactor where it is cleaned by means of the biological activated sludge method (suspended biomass) and immersed trickling filter (settled biomass). Suspended solids are separated and the accumulated sludge is initially fermented.
Reliability of removal of selected pollutants in different technological solutions

13.1. Reliability was determined from cumulative distribution to empirical data was assessed by Hollander–Proschan test for the significant level of 0.05. The reliability function was calculated as a complement to the cumulative distribution function using the Equation 1:

\[
R(x) = 1 - F(x)
\]

where: \(x\) = indicator of the concentration of pollutants in treated wastewater.

The analysis has been carried out using Statistica 13.1. Reliability was determined from cumulative distribution plots, taking into the limit values of indicators for wastewater treatment plants of <2000 p.e. [Rozporządzenie MŚ… 2014]. The results have been interpreted on the basis of the guidelines proposed by ANDRAKA and DZIENIS [2003].

RESULTS AND DISCUSSION

Raw wastewater flowing into particular objects included in the assessment showed quite large differences in terms of physico-chemical properties. The lowest content of organic pollutants and total suspended solids was recorded in object No. 3 (treatment plant with hybrid reactor). During the whole research period the mean value of basic indicators was: for \(\text{BOD}_5\) – 393 mg O\(_2\)·dm\(^{-3}\), \(\text{COD}\) – 724 mg O\(_2\)·dm\(^{-3}\), and for total suspended solids – 140 mg·dm\(^{-3}\). In object No. 1 (treatment plant with activated sludge) the values of parameters in raw wastewater were at a slightly higher level: \(\text{BOD}_5\) – 521 mg O\(_2\)·dm\(^{-3}\), \(\text{COD}\) – 780 mg O\(_2\)·dm\(^{-3}\), total suspended solids – 427 mg·dm\(^{-3}\). In the described cases, the composition of treated wastewater did not differ significantly from the composition of typical domestic wastewater [HEIDRICH 1998; HEIDRICH et al. 2008]. Values significantly deviating from typical values were found in wastewater treated in a treatment plant with biological deposit (object No. 2). The average size of \(\text{BOD}_5\) was 666 mg O\(_2\)·dm\(^{-3}\), \(\text{COD}\) – 1017 mg O\(_2\)·dm\(^{-3}\), and total suspended solids – 563 mg·dm\(^{-3}\). The household equipment with water and wastewater systems, inhabitants habits and their material situation have a decisive influence on the quality of raw wastewater flowing to particular facilities. Objects No. 1 and 3 serve individual households, while object No. 2 operates in a communal building, inhabited mainly by unemployed persons, which may significantly affect the level of water consumption and thus the concentration of pollutants in wastewater.

In order to assess the reliability of operation of selected types of WWTPs, the results of tests of treated wastewater discharged from these facilities into the environment were used. The basic statistical parameters characterising their quality are listed in Table 1.

In all cases, the average values of indicators are close to the levels specified in the Regulation of the Minister of Environment [Rozporządzenie MŚ… 2014] as acceptable. In a treatment plant with a biological deposit, the average \(\text{BOD}_5\) value at the outflow was more than twice the normative value (Tab. 1).

In addition, the data presented can be used to conclude that the results are very varied and vary widely between their sets. Basic statistical analysis may indicate the occurrence of disturbances in the operation of the investigated objects and their instability.

Further analysis included a verification of the hypothesis that empirical data could be described by the Weibull distribution. The results of the Hollander–Proschan test with the estimated parameters are presented in Table 2.
Table 1. Basic statistics for the indicator values in the treated wastewater

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Number of samples</th>
<th>Mean</th>
<th>Median</th>
<th>Minimum</th>
<th>Maximum</th>
<th>Standard deviation</th>
<th>Coefficient of variation</th>
</tr>
</thead>
<tbody>
<tr>
<td>BOD₅</td>
<td>20</td>
<td>31.8</td>
<td>26.0</td>
<td>4.7</td>
<td>95.0</td>
<td>23.1</td>
<td>72.4</td>
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<tr>
<td>COD</td>
<td>20</td>
<td>108.2</td>
<td>107.0</td>
<td>29.0</td>
<td>200.0</td>
<td>37.6</td>
<td>34.7</td>
</tr>
<tr>
<td>TSS</td>
<td>20</td>
<td>51.5</td>
<td>26.0</td>
<td>2.0</td>
<td>227.0</td>
<td>64.6</td>
<td>125.4</td>
</tr>
</tbody>
</table>

Object No. 2

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Number of samples</th>
<th>Mean</th>
<th>Median</th>
<th>Minimum</th>
<th>Maximum</th>
<th>Standard deviation</th>
<th>Coefficient of variation</th>
</tr>
</thead>
<tbody>
<tr>
<td>BOD₅</td>
<td>20</td>
<td>86.2</td>
<td>56.3</td>
<td>33.0</td>
<td>398.0</td>
<td>88.6</td>
<td>102.7</td>
</tr>
<tr>
<td>COD</td>
<td>20</td>
<td>135.6</td>
<td>125.0</td>
<td>35.0</td>
<td>350.0</td>
<td>66.1</td>
<td>48.8</td>
</tr>
<tr>
<td>TSS</td>
<td>20</td>
<td>41.2</td>
<td>28.0</td>
<td>5.0</td>
<td>111.0</td>
<td>29.2</td>
<td>70.8</td>
</tr>
</tbody>
</table>

Object No. 3

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<th>Parameter</th>
<th>Number of samples</th>
<th>Mean</th>
<th>Median</th>
<th>Minimum</th>
<th>Maximum</th>
<th>Standard deviation</th>
<th>Coefficient of variation</th>
</tr>
</thead>
<tbody>
<tr>
<td>BOD₅</td>
<td>20</td>
<td>34.6</td>
<td>27.5</td>
<td>4.0</td>
<td>90.0</td>
<td>27.0</td>
<td>78.0</td>
</tr>
<tr>
<td>COD</td>
<td>20</td>
<td>128.5</td>
<td>103.0</td>
<td>28.0</td>
<td>350.0</td>
<td>88.9</td>
<td>69.2</td>
</tr>
<tr>
<td>TSS</td>
<td>20</td>
<td>37.8</td>
<td>26.2</td>
<td>2.0</td>
<td>103.0</td>
<td>33.8</td>
<td>89.3</td>
</tr>
</tbody>
</table>

Source: own study.

Table 2. Parameters of the Weibull distribution and the Hollander–Proschan goodness-of-fit test

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Parameters of Weibull distribution</th>
<th>Hollander–Proschan goodness-of-fit test</th>
</tr>
</thead>
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<tr>
<td></td>
<td>location</td>
<td>shape</td>
</tr>
<tr>
<td>Object No. 1</td>
<td>BOD₅</td>
<td>1.2222</td>
</tr>
<tr>
<td></td>
<td>COD</td>
<td>-5.0000</td>
</tr>
<tr>
<td></td>
<td>TSS</td>
<td>1.1667</td>
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<tr>
<td>Object No. 2</td>
<td>BOD₅</td>
<td>32.5760</td>
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<td></td>
<td>COD</td>
<td>5.0000</td>
</tr>
<tr>
<td></td>
<td>TSS</td>
<td>1.2576</td>
</tr>
<tr>
<td>Object No. 3</td>
<td>BOD₅</td>
<td>2.9343</td>
</tr>
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<td></td>
<td>COD</td>
<td>22.2220</td>
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<tr>
<td></td>
<td>TSS</td>
<td>0.0175</td>
</tr>
</tbody>
</table>

Symbols: stat – value of the test statistic, p – significance level of the test; when p ≤ 0.05 the distribution of data is not Weibull distribution.

Source: own study.

Reliability analysis was performed separately for each facility and wastewater quality indicator. The results of the analysis are shown in Figures 3–5.

In the wastewater treatment plant with activated sludge (object No. 1) it was found that the permissible BOD₅ size was exceeded in 30% of the samples (Fig. 3). On this basis, it can be estimated that in 110 days of the year, wastewater with an above-normative concentration of organic pollutants, expressed as BOD₅. In the case of COD, the reliability level found was 87%, which means that for 48 days per year the rate in treated wastewater exceeded the acceptable level. Reliability of the wastewater treatment plant with activated sludge for total suspended solids removal was 66%. The limit value was exceeded in 34% of the wastewater samples, which corresponds to 124 days a year. BUGAJSKI et al. [2012] in his study of the wastewater treatment plant with active sludge Bio-compact BCT S-12 determined its process reliability at 68% for BOD₅, 88% for COD and 62% for total suspended solids.

The analysis shows that the treatment plant with activated sludge operates at a very low level of reliability and does not guarantee stable results and quality of treated wastewater in accordance with the applicable regulations. According to the guidelines proposed by ANDRAKA and DZIENIS [2003] the minimum level of reliability for wastewater treatment plants with an p.e. < 2000 should be 97.27%, with the operator's risk of the treatment plant at a level of α = 0.05. Therefore,
the permissible value of indicators in 9 days per year can be exceeded.

In wastewater treatment plant with a biological depos-
it, 70% of the BOD₅ limit value was found to be ex-
ceded. It follows that the period of faulty operation of the treatment plant for disposal of BOD₅ was 256
days per year. In 40% of the wastewater samples
treated, the amount of COD exceeded 150 mg·dm⁻³
normalized value (Fig. 4). This means that 146 days
of the year did not meet the requirements specified for

this indicator in the Regulation of the Minister of the Environment [Rozporządzenie MŚ… 2014]. Reliabi-
licity of the sewage treatment plant in the scope of total suspended solids removal was about 67%. As in the
case of other indicators, it is much lower than the value
proposed by ANDRAKA and DZIENIS [2003]. For comparison, the reliability wastewater treatment plant
type of RetroFAST (with aerated biological filter) was
85% (BOD₅), 89% (COD) and 92% (total suspended
solids) respectively [WAŁĘGA et al. 2008].
In a wastewater treatment plant with a hybrid reactor, the limit values BOD₅ and COD were exceeded in 33% of the treated wastewater samples (Fig. 5). It follows that for around 121 days a year, the effluents flowing from object No. 3 did not meet the legal requirements for these indicators. The reliability of the total suspended solids removal in a treatment plant with a hybrid reactor was 72%, which means that the limit in 28% of cases was exceeded (Fig. 5). As a general rule, it can be concluded that in 103 days a year, the total suspended solids content in treated wastewater exceeded the limit value.

Summing up the research results, it can be concluded that the reliability of the wastewater treatment plants included in the tests for organic pollutants and suspended solids removal was very low. The reliability levels based on the limit values of pollution indicators differ significantly from those indicated in the literature [ANDRAKA, DZIENIS 2003]. It is worth noting that the analysed objects achieved in the research period quite high effectiveness of removing contaminants. For most of the indicators, the average effects were around 90%, but this did not ensure a stable quality of treated wastewater, in accordance with the national regulations. Many factors can affect this, including with the characteristics of raw wastewater, as well as the specificity of the analysed technological solutions. They are based on conventional methods of contaminant removal (activated sludge, biological deposit), which require the provision and maintenance of specific parameters and technological conditions. Fulfilling this in the case of household wastewater treatment plants can be difficult, as it requires users to constantly check the facilities, to identify disturbances and faults and to correct them. Moreover, in the event of a failure, a certain amount of time is needed to restore the wastewater treatment plant to normal operation. As an alternative to this type of solution, systems using semi-natural wastewater treatment methods can be used. They are simpler to operate and provide high efficiency and reliability. Studies by JUCHERSKI et al. [2017] indicate that the reliability of hybrid constructed wetland wastewater treatment plant can reach up to 100% for BOD₅ and COD and 92% for total suspended solids.

CONCLUSIONS

1. The reliability of BOD₅, COD and total suspended solids removal in all wastewater treatment plants under analysis was very low, usually within the range of 60 to 70%.
2. Low reliability of analysed objects is the result of many cases of exceeding the limit value of the tested indicators of pollutants.
3. The reliability levels set were significantly lower than those proposed in the literature.
4. Low reliability of pollutants removal in household wastewater treatment plants with activated sludge, biological deposit and hybrid reactor may be associated with the sensitivity of these systems to sudden changes in technological conditions and their inability to maintain them during operation.

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Niezawodność usuwania wybranych zanieczyszczeń w różnych rozwiązaniach technologicznych przydomowych oczyszczalni ścieków

STRESZCZENIE

W pracy przeanalizowano niezawodność usuwania wybranych zanieczyszczeń w trzech rozwiązaniach technologicznych przydomowych oczyszczalni ścieków: oczyszczalni z osadem czynnym, ze złożem biologicznym zraszanym oraz reaktorem hybrydowym (osad czynny i złoże biologiczne zanurzone). Analizę wykonano z wykorzystaniem metody Weibula w odniesieniu do podstawowych wskaźników zanieczyszczeń: BZT₅, ChZT i zawiesiny ogólnej. Niezawodność technologiczna oczyszczalni z osadem czynnym kształtowała się na poziomie 70% w przypadku BZT₅, 87% – ChZT i 66% – zawiesiny ogólnej. W oczyszczalni ścieków ze złożem biologicznym zraszanym wyznaczone wartości niezawodności wyniosły: 30% (BZT₅), 60% (ChZT) i 67% (zawiesina ogólna). W oczyszczalni z reaktorem hybrydowym przekroczenie dopuszczalnej wartości BZT₅ i ChZT miało miejsce w 30% przypadków, a zawiesiny ogólnej w 28%. Wyznaczone poziomy niezawodności są wyraźnie niższe od poziomów dopuszczalnych proponowanych w literaturze, co oznacza, że w ściekach oczyszczonych odpływających z analizowanych oczyszczalni często pojawiają się przekroczenia wartości granicznych wskaźników, określonych w aktualnie obowiązującym Rozporządzeniu Ministra Środowiska dla obiektów o wielkości poniżej 2000 RLM.

Słowa kluczowe: BZT₅, ChZT, niezawodność technologiczna, przydomowe oczyszczalnie ścieków, zawiesina ogólna