Biodegradability of industrial textile wastewater – batch tests
Katarzyna Paździor, Anna Klepacz-Smółka, Julita Wrębiak, Ewa Liwarska-Bizukojć and Stanisław Ledakowicz

ABSTRACT
Following new trends we applied oxygen uptake rate (OUR) tests as well as long-term tests (in two batch bioreactors systems) in order to assess the biodegradability of textile wastewater. Effluents coming from a dyeing factory were divided into two streams which differed in inorganic and organic contaminants loads. Usefulness of the stream division was proved. Biodegradation of the low-loaded stream led to over 97% reduction of biochemical oxygen demand (BOD₅) together with 80% reduction of chemical oxygen demand (COD) and total organic carbon (TOC). Most of the controlled parameter values were below the levels allowed by legislation for influents to surface water, whereas the high-loaded stream was so contaminated with recalcitrant organic compounds that despite the reduction of BOD₅ by over 95%, COD, TOC, total nitrogen and total phosphorus levels exceeded permissible values. OUR tests were aimed at determination of the following kinetic parameters: maximum specific growth rate (μ_max), half-saturation constant, hydrolysis constant and decay coefficient for activated sludge biomass for both types of textile wastewater studied. The values of kinetic parameters will be applied in activated sludge models used for prediction and optimisation of biological treatment of textile wastewater.

Key words | anaerobic/aerobic treatment, kinetic parameters, oxygen uptake rate (OUR) tests, sequencing batch reactors (SBR), textile wastewater

INTRODUCTION
There is a constant progress in technologies, new machines and chemicals used in a textile industry. However, this sector still generates huge amounts of wastewater which introduces into the environment high loads of contaminations – dyes, textile auxiliaries and other chemicals (De Jager et al. 2014). The main goal of the textile wastewater treatment is to close the water cycle within the factories. It is a very difficult task demanding integrated usage of different technologies. Often biodegradation is coupled with chemical (e.g. electrochemical advanced oxidation (Ganzenko et al. 2014), ozone oxidation (Iaconi 2012)) or physico-chemical processes (e.g. filtration (Kang et al. 2012), nanofiltration (Zuriaga-Agusti et al. 2010)).

Among the many processes which can be applied to textile wastewater treatment, the biological one is recognised as environmentally friendly and ecological (Imran et al. 2015). However, it has also specific limits. It can be used for mineralisation of biodegradable compounds only. Moreover, microorganisms are sensitive to toxic compounds (Ganzenko et al. 2014). In the literature dealing with this topic still new papers concerning biological treatment are appearing (e.g. Aksu et al. 2015; Santos & Boaventura 2015). Some researchers used one type of bacteria (Franciscon et al. 2012) or fungi species (Pakshirajan & Kheria 2012; Aksu et al. 2015). Others implemented indigenous biomass such as activated sludge (Kang et al. 2012; De Jager et al. 2014; Santos & Boaventura 2015), bacteria–yeast consortium (Kurade et al. 2012) or biofilm (Lotito et al. 2012). As complete degradation of azo dyes demands anaerobic and afterwards aerobic conditions, many papers describe application of two-step biological treatment (Kang et al. 2012; De Jager et al. 2014) or sequencing batch reactors (SBR) (Lotito et al. 2012; Santos & Boaventura 2015). Previously, most of the publications concentrated on simulated wastewater treatment. Nowadays, real textile wastewater treatment is more frequently investigated (Kang et al. 2012;
Kurade et al. 2012; Lotito et al. 2012; Pakshirajan & Kheria 2012; De Jager et al. 2014; Aksu et al. 2015), as the industrial wastewater contains the whole spectrum of chemicals used within the dyeing mill.

Since 1856 (Perkin’s discovery of first synthetic dye mauve) several million coloured compounds have been discovered, and ca. 15,000 have had practical applications over time (Zollinger 2005). A little more than half of the whole production of colourants is dedicated to the textile industry. Among them there are dyes and pigments which are divided into many classes, mainly in terms of chemical structure and purpose of application (substrate). The choice of colourant is dictated by practical considerations: the type of fibre, fashion (market demand), application (dyeing/printing) and required technology (apparatus and know-how). The main production of the textile factories is based on cellulose fibres, mostly cotton and viscose. Nowadays, they are dyed mainly by reactive dyes (Imran et al. 2015). These dyes have several advantages such as relatively easy synthesis, wide range of colours, bright tints, permanent connection to fibres and good staining resistance. Unfortunately, despite many advantages they have also several disadvantages. First of all they have low ‘exhaustion’ from the bath – about 50 to 90% (Khan et al. 2013). That means that as much as half of the used dye may pass into wastewater. Additionally, binding of the reactive dyes to fibres demands significant amounts of electrolytes such as NaCl or Na₂SO₄, a strongly basic reaction and surfactants. The wastewater from reactive dyeing is characterised by high salinity and colour, high pH values, surfactants presence, high chemical oxygen demand (COD) values and low biochemical oxygen demand (BOD₅) values.

The wastewater generated in the dyeing factory consists of several baths for:

- textile washing;
- bleaching (in the case of light colours);
- acidification;
- rinse;
- dyeing;
- rinse;
- acidification;
- washing after dyeing;
- several rinses;
- neutralisation.

Some of the above-mentioned baths generate wastewater which can be described as biodegradable (e.g. baths for washing, acidification, most rinses) – low to neutral pH, BOD₅:COD ratio between 0.3 and 0.9, and non-toxic to activated sludge. However, others contain so much inorganic salts and refractory organic compounds (e.g. bath from dyeing) that their biodegradation is very difficult or even impossible – pH above 10, BOD₅:COD ratio below 0.1, and toxic to activated sludge (Wrębiak et al. 2014).

Oxygen uptake rate (OUR) tests are a good tool for wastewater characterisation. They enable fast assessment of the effects of both complex media and certain chemical substances on the biomass activity (Arslan-Alaton et al. 2006). OUR tests are used also for a determination of the kinetic parameters – mainly the organic matter removal by aerobic heterotrophic biomass (Liwarska-Bizukojc et al. 2008). Although the textile wastewater is very complex and variable, a very few papers concerning OUR tests for this kind of wastewater may be found in the literature (Germirli-Babuna et al. 1998; Arslan-Alaton et al. 2006).

This paper describes the results of experiments in which susceptibility for biodegradation of textile wastewater was investigated. The real wastewater from a dyeing factory was divided into two streams and both of them were subjected to long-term biological treatment in a single SBR reactor and an anaerobic/aerobic batch reactors system. What is more, the kinetic parameters describing biological treatment of these two types of wastewater were determined with the use of respirometric tests.

MATERIALS AND METHODS

Tested material

Experimental studies were performed for textile wastewater coming from one of the Polish dyeing factories. The wastewater was divided into two streams. The first stream contained mostly effluents from the rinses after washing and dyeing (apart from the first rinse after dyeing). The second one consisted mainly of the effluents from the washing, bleaching and dyeing.

OUR tests

The experimental set-up and procedures used in the OUR tests were described previously by Liwarska-Bizukojc et al. (2008). There was the only one difference – the temperature was maintained at 25 °C instead of 20 °C as was used previously. Three types of OUR tests were conducted. These were tests at high ratio of substrate to biomass \( S(0)/X(0) = 5.5 \pm 0.5 \text{ mg COD/mg SS} \); SS: suspended solids) and at low ratio of substrate to biomass \( S(0)/X(0) = 0.65 \pm 0.04 \text{ mg COD/mg SS} \) and
the test with activated sludge only. The first type of tests were aimed at the determination of Monod equation parameters (maximum specific growth rate and half-saturation constant), the second one was performed in order to determine the value of the hydrolysis constant and finally the third one was aimed at the measurement of the decay constant for activated sludge microorganisms. Biomass used in the OUR tests was taken from the textile wastewater treatment plant, while the substrate was the low- and high-loaded stream of wastewater from the dyeing factory under study.

Long-term tests

The main experiments were conducted in a single SBR reactor and in a system consisting of two reactors in sequence – first anaerobic and second aerobic. Very similar equipment was used in previous experiments described by Pazdźior et al. (2009). However, there are some significant differences. The working volume of all bioreactors was changed. The SBR had a working volume of 1.5 dm³, both the anaerobic and aerobic reactors 0.8 dm³, and the transition tank 0.5 dm³. All experiments were conducted at 30 °C. Due to the fact that the dyeing effluents are hot, 30 °C is the mean temperature observed in the industrial textile wastewater treatment plant.

All bioreactors were inoculated with the activated sludge taken from the above-mentioned wastewater treatment plant. The single SBR reactor was working in a 12 h cycle (30 min sedimentation, 38 min drawing, 72 min filling, 11 h 40 min mixing, 8 h aeration), while the two bioreactors system had a 6 h cycle (30 min sedimentation, 38 min drawing, 38 min filling, almost 5 h mixing or aeration). Both systems were operated with hydraulic retention time (HRT) of 24 h for the low-loaded stream and 48 h for the high-loaded one in order to keep the organic loading rate (OLR) in the similar ranges for different streams (between 0.21 and 0.67 kgCOD·m⁻³·d⁻¹).

Analytical methods

The influents and effluents from the bioreactors were analysed twice a week. The following analyses were conducted:

- pH (WTW meter Multi 720);
- conductivity (WTW meter Multi 720);
- colour: spectrophotometric analysis (according to PN-EN ISO 7887:2002);
- BOD₅ (dilution method, standard method – APHA 1992);
- COD (standard dichromate method, spectrophotometer DR 5000, Hach-Lange);
- total organic carbon (TOC) (analyser IL550TOC-TN, Hach-Lange);
- total nitrogen (TN; the sum of organic and inorganic nitrogen compounds) (analyser IL550TOC-TN, Hach-Lange);
- total phosphorus (TP) (spectrophotometer DR 5000, Hach-Lange).

The following parameters were determined for the wastewater in the bioreactor:

- redox potential (SenTix ORP electrode connected to WTW pH-meter);
- pH (WTW pH-meter);
- dissolved oxygen (CellOX 325 electrode connected to Multilevel 1);
- dry matter (total suspended solids) and organic dry matter content (volatile suspended solids (VSS)) in the suspension according to Standard Methods (APHA 1992).

Colour removal was calculated on the basis of wastewater absorbance before and after biodegradation at three wavelengths – 436, 525 and 620 nm.

RESULTS

Characteristics of the treated wastewater

The wastewater was taken from the dyeing factory – several times during half a year. The first stream was characterised by lower loads of organic and inorganic compounds

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### Table 1 | Main characteristics of the treated wastewater

<table>
<thead>
<tr>
<th></th>
<th>First stream</th>
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<th>Second stream</th>
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</tr>
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<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>Standard deviation</td>
<td>Mean</td>
<td>Standard deviation</td>
</tr>
<tr>
<td>pH (–)</td>
<td>8.71</td>
<td>0.64</td>
<td>9.22</td>
<td>0.45</td>
</tr>
<tr>
<td>Conductivity (mS·cm⁻¹)</td>
<td>2.96</td>
<td>0.51</td>
<td>15.93</td>
<td>2.68</td>
</tr>
<tr>
<td>BOD₅ (mgO₂·dm⁻³)</td>
<td>248</td>
<td>77</td>
<td>239</td>
<td>141</td>
</tr>
<tr>
<td>COD (mgO₂·dm⁻³)</td>
<td>577</td>
<td>183</td>
<td>994</td>
<td>218</td>
</tr>
<tr>
<td>BOD₅:COD (–)</td>
<td>0.44</td>
<td>0.11</td>
<td>0.24</td>
<td>0.13</td>
</tr>
<tr>
<td>TOC (mgC·dm⁻³)</td>
<td>205</td>
<td>69</td>
<td>265</td>
<td>80</td>
</tr>
<tr>
<td>TN (mgN·dm⁻³)</td>
<td>10.02</td>
<td>4.25</td>
<td>33.4</td>
<td>19.2</td>
</tr>
<tr>
<td>TP (mgP·dm⁻³)</td>
<td>4.48</td>
<td>2.04</td>
<td>3.38</td>
<td>0.55</td>
</tr>
<tr>
<td>BOD₅:TN (–)</td>
<td>27</td>
<td>6.82</td>
<td>8.2</td>
<td>4.1</td>
</tr>
<tr>
<td>BOD₅:TP (–)</td>
<td>58</td>
<td>11.50</td>
<td>32</td>
<td>2.8</td>
</tr>
</tbody>
</table>
TP (mgP·dm⁻³) and TN (mgN·dm⁻³). The BOD₅:TP ratio was below 100 and BOD₅/COD (mgO₂·dm⁻³) was 8.97 ± 0.37 (525 nm) for the second stream, which is around 100:5:1 (Zhidong et al. 2009). The first stream was characterised by BOD₅:TN ratio above 20. That means that the addition of nitrogen might be necessary during this stream’s biodegradation.

However, Sherrard & Schroeder (1976) stated that optimal BOD₅:TN ratio for the industrial wastewater depends on the sludge age and varies between 100:5:4 and 194:5:4. BOD₅:TP ratio for the first stream is below 100. It means that phosphorus will be not completely embedded biomass and specific processes will be necessary for the phosphorus removal.

In contrast, the BOD₅:TN ratio for the second stream was strongly below 20. It can be stated that the nitrogen will be not completely embedded in biomass and specific processes will be necessary for nitrogen removal, e.g. nitrification and denitrification. Similarly to the first stream, the BOD₅:TP ratio was below 100 – specific processes will be necessary for the phosphorus removal also for this stream.

On the basis of the wastewater characteristics it is possible to state that the first stream (low-loaded) is more suitable for the biodegradation than the second one (high-loaded). However, in order to prove this statement as well as to find the best solution for the wastewater treatment, both streams were subjected to biodegradation.

### The biodegradation of the low-loaded stream

The biodegradation tests in batch reactors confirmed the good biodegradability of the low-loaded stream. The effluents from both systems fulfilled the requirements of the Polish legislation for the influents to surface water (Table 2). There were only two exceptions: TOC and TP values. The TOC mean value in the effluents slightly exceeded the allowed level (Table 2, Figure 1). The TP mean value was significantly above the permissible level. It was clear that this wastewater contained too much phosphorus for biomass needs. The biomass content estimated on the basis of VSS in the bioreactors was quite stable (1.8 to 2.7 gVSS·dm⁻³ in SBR, 1.9–3.5 gVSS·dm⁻³ in anaerobic reactor and 1.9–3 gVSS·dm⁻³ in aerobic reactor). As a result there was no surplus activated sludge removal.

Apart from the colour removal there were no significant differences in the results obtained from both reactor systems. The mean colour reduction in the SBR was between 42.9 ± 18.8 (525 nm) and 47.1 ± 16.4% (620 nm) while in the two reactors system it was between 62.3 ± 18.9 (436 nm) and 71.9 ± 12.5% (620 nm) – Figure 2.

The disperse, vat, direct and basic dyes can be adsorbed onto activated sludge or flocculated (Frijters et al. 2006). The bacterial degradation of reactive dyes, especially azo dyes, demands a sequence of processes. Firstly, in strongly reductive conditions – by redox potential below ~350 mV – double bonds (responsible for the colour of the dyes) can be broken. In this way aromatic amines are formed, which must be further mineralised under aerobic conditions (Khan et al. 2013).

### Table 2: Characteristics of the effluents after low-loaded stream biodegradation

<table>
<thead>
<tr>
<th></th>
<th>SBR</th>
<th>Two bioreactors</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Effluent</td>
<td>Removal (%)</td>
</tr>
<tr>
<td>pH (°)</td>
<td>8.96 ± 0.18</td>
<td>-</td>
</tr>
<tr>
<td>Conductivity (mS·cm⁻¹)</td>
<td>3.35 ± 0.37</td>
<td>-</td>
</tr>
<tr>
<td>BOD₅ (mgO₂·dm⁻³)</td>
<td>3.40 ± 5.34</td>
<td>97.7 ± 3.8</td>
</tr>
<tr>
<td>COD (mgO₂·dm⁻³)</td>
<td>77.15 ± 28.76</td>
<td>81.1 ± 7.5</td>
</tr>
<tr>
<td>BOD₅/COD (-)</td>
<td>0.03 ± 0.02</td>
<td>90.3 ± 2.2</td>
</tr>
<tr>
<td>TOC (mgC·dm⁻³)</td>
<td>27.54 ± 9.97</td>
<td>82.6 ± 6.8</td>
</tr>
<tr>
<td>TN (mgN·dm⁻³)</td>
<td>3.70 ± 1.10</td>
<td>53.9 ± 19.1</td>
</tr>
<tr>
<td>TP (mgP·dm⁻³)</td>
<td>3.60 ± 1.33</td>
<td>0</td>
</tr>
</tbody>
</table>
The main production of the dyeing factory which provided wastewater for the conducted experiments is based on cellulose fibres. Thus the treated wastewater contained mostly reactive dyes. In the anaerobic reactor strictly reducing conditions were observed – redox potential values varied between $-310$ and $-345$ mV, while in the SBR during anoxic phase they were between $-255$ and $-280$ mV. As a result higher colour removal was observed in the two-stage system.

Better colour removal was obtained by Zuriaga-Agusti et al. (2010) for simulated textile wastewater in an SBR reactor – above 70% removal of colour, whereas Lotito et al. (2012) treating real textile wastewater in a sequencing batch biofilter granular reactor obtained lower efficiency of decolorisation: $15.8 \pm 12.8\%$ for 426 nm, $21.0 \pm 14.5\%$ for 558 nm and $22.2 \pm 10.8\%$ for 660 nm.

Experiments were conducted for OLR between 0.33 and $0.69$ kgCOD·m$^{-3}$·d$^{-1}$. Both systems were very efficient in removal of the biodegradable organic compounds – the BOD$_5$ reductions were above 97% (Table 2). Generally, organic compounds were removed with high efficiency – about 80% for COD and TOC values (Table 2, Figure 1). It can lead to the conclusion that only 20% of organic carbon compounds were recalcitrant to biodegradation.

The biodegradation of the high-loaded stream

In contrast to the low-loaded stream, the biodegradation tests in batch reactors showed poor biodegradability of the high-loaded stream. The parameter values in the effluents from both systems exceeded the levels of Polish legislation for the influents to surface water (Table 3, Figure 3). There was only one exception – BOD$_5$ values (Table 3). The biodegradable organic compounds were used almost completely – BOD$_5$ reductions were above 95%. Experiments were conducted with OLR between 0.21 and $0.67$ kgCOD·m$^{-3}$·d$^{-1}$. The high-loaded stream contained about 40% of recalcitrant organic carbon compounds – COD and TOC reductions oscillated around 60% (Table 3). There was no significant difference between the organic carbon removals in both systems (Figure 3). Lotito et al. (2012) observed COD removals between 54 and 78%. They also concluded that differences in the COD removal efficiencies were connected to the wastewater composition.

Similarly to the first stream, the TP values of the high-loaded stream were above the permissible level (Table 3) – there was no phosphorus removal. The values of VSS observed in the bioreactors were lower than during biodegradation of the first stream – varied between 0.6 and $2.3$ gVSS·dm$^{-3}$ in SBR, between 0.7 and $1.7$ gVSS·dm$^{-3}$ in anaerobic and aerobic reactors.

TN loads also exceeded permissible level (Table 3). There was significant difference between the SBR reactor and the anaerobic/aerobic system. In the SBR reactor more than 55% of TN was removed – 15.5 mgN·dm$^{-3}$ on average. Assuming that 1/20 of BOD$_5$ value might be embedded in

![Figure 1](https://iwaponline.com/wst/article-pdf/74/5/1079/459088/wst074051079.pdf) | TOC changes during the biodegradation of the low-loaded stream.

![Figure 2](https://iwaponline.com/wst/article-pdf/74/5/1079/459088/wst074051079.pdf) | Colour removal in different bioreactors – low-loaded stream biodegradation.
the biomass, about 9.3 mgN·dm$^{-3}$ might have been used for biomass growth (mean BOD$_5$ value – 186 mgO$_2$·dm$^{-3}$). It means that at least 6.2 mgN·dm$^{-3}$ was removed by the other processes. Most probably nitrification and denitrification processes occurred. It is possible that during the aeration phase ammonia nitrogen was oxidised to nitrites and/or nitrates, which were further reduced to gaseous nitrogen during the sedimentation phase as well as during the anoxic phase within the next cycle. This mechanism could not take place in the two-reactors system – there were no anoxic conditions after the aerobic ones.

As a result only 32% of nitrogen compounds were removed in the two-reactors system – about 9.0 mgN·dm$^{-3}$ on average (Table 3). Figure 4 shows variability of the TN values of the second stream over time. It also illustrates the differences in the outlet values for both systems. Lotito et al. (2012) obtained better results for total Kjeldahl nitrogen – up to 98% removal.

The two bioreactors system was more effective in the colour removal than the single reactor – observed by the wavelengths 525 nm (38.0 ± 9.8% two stage system, 28.9 ± 13.2% SBR reactor) and 620 nm (46.0 ± 9.2% two stage system, 23.3 ± 15.8% SBR reactor). By the 436 nm both systems reached a very similar level of colour removal – 27 ± 14.5% (Figure 5). Although decolourisation efficiency for the high-loaded stream was lower than for the low-loaded stream, again colour reductions obtained in this work were better in comparison to those acquired in investigations performed by Lotito et al. (2012).

### OUR tests

The OUR tests that were performed in this work allowed for the determination of the following kinetic parameters: maximum specific growth rate ($\mu_{Max}$), half-saturation constant ($K_S$), hydrolysis constant ($k_{hl}$) and decay coefficient for activated sludge biomass ($b_{hl}$). The mean values of these kinetic parameters are presented in Table 3. The results suggest an effective treatment of the textile wastewater in both systems.
parameters together with standard deviation are presented in Table 4.

The values of Monod equation parameters, i.e. $\mu_{\text{Max}}$ and $K_S$ were generally higher than those found for domestic or municipal wastewater. However, the values of $K_S$ determined in this work for the low-loaded stream (low COD) were close to the ones determined for municipal wastewater or textile wastewater (Germirli-Babuna et al. 1998; Hauduc 2010). At the same time the mean saturation constant estimated in this work for the high-loaded stream (high COD) was about twice higher than for the first stream (Table 4). It was most probably associated with higher contribution of slowly biodegradable substrate in this type of wastewater, which made the carbon substrate less available for heterotrophic bacteria. It was in agreement with the observations made during the long-term experiments. High-loaded stream treatment demanded two times longer HRT than low-loaded stream. Despite the shorter HRT, the COD reductions were 20% higher for the low-loaded stream. Moreover, the biomass content in the reactors treating the low-loaded stream was up to

<table>
<thead>
<tr>
<th>Tested material</th>
<th>Mean $\mu_{\text{Max}}$ (d$^{-1}$)</th>
<th>Mean $K_S$ (mgO$_2$·dm$^{-3}$)</th>
<th>Mean $k_H$ (d$^{-1}$)</th>
<th>Mean $b_H$ (d$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low-loaded stream</td>
<td>$11.1 \pm 0.34$</td>
<td>$26.9 \pm 9.7$</td>
<td>$4.2 \pm 1.7$</td>
<td>–</td>
</tr>
<tr>
<td>High-loaded stream</td>
<td>$9.7 \pm 1$</td>
<td>$52.8 \pm 6$</td>
<td>$8.4 \pm 5.8$</td>
<td>–</td>
</tr>
<tr>
<td>Activated sludge biomass</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>$5.03 \pm 1.21$</td>
</tr>
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</table>

![Figure 4](https://iwaponline.com/wst/article-pdf/74/5/1079/459088/wst074051079.pdf)  
**Figure 4** | TN changes during the biodegradation of the high-loaded stream.

![Figure 5](https://iwaponline.com/wst/article-pdf/74/5/1079/459088/wst074051079.pdf)  
**Figure 5** | Colour removal in different bioreactors – high-loaded stream biodegradation.
The obtained results confirmed the usefulness of the stream division in the dyeing factory.

The susceptibility to biodegradation of the low-loaded stream was proved by the OUR tests as well as by the long-term batch tests. The biomass had higher affinity to this substrate (lower half-saturation constant value) in comparison to the high-loaded stream. During the long-term experiments the organic carbon compounds (estimated as COD and TOC) were removed by 80%. The BOD$_5$: TN ratio was within the optimal range for the biomass growth (according to Sherrard & Schroeder (1976)). As a result the effluents fulfilled the requirements of the Polish legislation for the influents to surface water with regard to carbon and nitrogen compounds loads. BOD$_5$: TP ratio remained below 100 – there was too much phosphorus for the biomass needs. The TP concentration after biotreatment exceeded the permissible level.

The high-loaded stream was not easily biodegradable. First of all, it contained more refractory organic compounds – the average removal of organic carbon compounds did not exceed 60% by BOD$_5$ reduction above 95%. Secondly, there were too high nitrogen loads for biomass needs – the BOD$_5$: TN ratio was significantly below 20. Thus, COD, TOC and TN values in the effluents from the batch reactors exceeded permissible levels. Thirdly, the biomass had lower affinity to this substrate – higher half-saturation constant value (OUR tests) and lower biomass content in the bioreactors (long-term tests) in comparison to the low-loaded stream.

The determined values of kinetic parameters, i.e. maximum specific growth rate, half-saturation constant, hydrolysis constant and decay coefficient for activated sludge biomass were higher than those known for biological treatment of municipal wastewater. However, they did not exceed the values determined for heterotrophic bacteria involved in the treatment of highly concentrated industrial wastewater. The kinetic parameter values are necessary for the optimisation of biological treatment of textile wastewater with the use of activated sludge models.

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REFERENCES


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