Characterization of Textile Wastewater: Its Environmental Impact and Biotreatability

A. Žgajnar Gotvajn and J. Zagorc-Končan
University of Ljubljana, Faculty of Chemistry and Chemical Technology,
Chair of Chemical, Biochemical and Environmental Engineering,
Aškerčeva 5, SI-1000 Ljubljana, Slovenia, E-mail: andreja.zgajnar@ki.si

Original scientific paper
Received: October 3, 2003
Accepted: March 15, 2004

A reliable wastewater characterization is an integral part of treatment and management strategies for industrial effluents. A complex approach, based on stabilization studies was proposed, to determine biological treatability of textile wastewaters and possible persistent toxicity. Whole effluent toxicity was determined using three different toxicity tests. Next step was the determination of whole effluent ready biodegradability to assess its biodegradability in common environmental conditions. Determination of hazardous impact and treatability of the wastewater was accomplished with stabilization studies to characterize wastewater in terms of persistent and degradable toxicity. At the same time characteristics and treatment efficiency of activated sludge was also assessed in open respirometer, where we measured oxygen uptake rate ($mg_{O_2}\ g_{vss}^{-1}\ day^{-1}$). Textile wastewater expressed good biodegradability (more than 76 %), however some residual persistent toxicity has been reported. It was pointed out, that its environmental impact depends upon physico-chemical conditions in the receiving environment. On the other hand, toxicity measurements and respirometric analysis confirmed adaptation of activated sludge to selected wastewater. Presented complex approach confirmed biological treatment potential of the textile wastewater.

Keywords:
Biodegradability, biological treatment, stabilization study, textile wastewater, toxicity

Introduction

A reliable wastewater characterization is an integral part of treatment and management strategies for industrial effluents.[1,2] The use of biological treatment for removal of contaminants from effluents is preferred due to its economic acceptability when regulatory demands on effluent standards should be accomplished. In order to operate the wastewater treatment plant in efficient way information about the characteristic of influent is essential.[3] Any assessment of wastewater and/or determination of its biological treatability must beside determination of physico-chemical parameters include an evaluation of its degradability and toxicity, which could drastically reduce the performance of the treatment plant.[4] Monitoring of both parameters and their close link-up with wastewater composition can prevent costly upsets. Toxicity of the wastewater should be addressed with tests with mixed culture of microorganisms, which plays leading role in treatment processes. Usually it is determined with respirometric measurements of oxygen consumption[5] and/or of growth inhibition,[6] because the wastewater can react with the microorganisms for several generations. Therefore, the growth inhibition test additionally has the character of a chronic test.

For assessing biodegradation potential of pure chemicals and individual components of the wastewaters many standardized methods exist.[7] No such approach has yet been developed for biodegradability assessment of industrial effluents.[8] Biodegradability of the influent to the wastewater treatment plant could be determined using one of the existing testing methods as for the chemicals. The above-mentioned tests suffer from the fact, that biodegradability of minor wastewater constituents, including possible harmful components, cannot be detected and examined.[9] Therefore, testing of the whole influent is necessary and to this end a functional characterization in terms of toxicity reduction: stabilization study. It represents a link between toxicity and biodegradability of the wastewater.[4] Stabilization study has usually been accomplished in batch reactors, where wastewater is diluted with synthetic medium or natural surface waters, inoculated and than stirred and aerated for several weeks, until measured parameters have reached plateau. The type and number of physico-chemical analysis and toxicity determination as well as their schedule, should be selected according to the behaviour of the diluted effluent during stabilization study.

For optimal biological treatment of the industrial wastewater, besides the monitoring of the qual-

ity of the effluent, knowledge on the activated sludge behaviour is necessary. To investigate actual activated sludge characteristics and its response to the received wastewater, the biodegradability of the wastewater should also be assessed in open respirometer, where O_2 uptake rate ($mg_{O2}\ g^{-1}_{vss}\ day^{-1}$) for, both, endogenous and exogenous respiration should be measured to determine optimal load of the wastewater and retention time in the biological treatment plant. Kinetic parameters could than be calculated to predict the rate and efficiency of the removal processes in the treatment plant.[10,11]

The aim of our study was to link wastewater characterization in terms of its environmental impact and biotreatability to the respirometric determination of activated sludge performance. Physico-chemical analysis, toxicological and biodegradability assessment of textile wastewater were conducted, as well as degradation capacity of the activated sludge determined to complete evaluation of the wastewater.

Materials and methods

Wastewater

The same sample of the wastewater was used for all of the experiments. It was generated in the textile factory, where auxiliary medical supplies, products for hygiene and non-woven textiles are produced. The company runs out the processes of weawing and bleaching gauze and bandages, carding cotton batting and viscose wadding, produces fibrous and plaster bandages and process other semi-products. Wastewater was random grab sampled from the factory pipeline, entering the sewerage system, which ends in municipal wastewater treatment plant. Textile wastewater was the mixture of process wastewaters and other wastewaters, generated in the factory. Wastewater is mixed with municipal and several others industrial wastewaters prior to biological treatment (annual average load of textile wastewater is φ = 6.3 %) in municipal treatment plant (200 000 population equivalent). 58 % of the influent to the treatment plant represents municipal wastewaters, while 42 % of the hydraulic load goes to the industrial wastewaters.

Physico-chemical analysis of the wastewater

pH, BOD_5,[12] COD,[13] DOC,[14] IC[14] (Shimadzu TOC 5000A Analyser, 1998), nitrogen as Kljeldahl nitrogen,[15] ammonium nitrogen[15] (Kjeltec Auto Analyser FOSS Tecator, 1998), NO_2^-–N[16] and NO_3^-–N[16] and PO_4^{3-}–P[16] (DIONEX 120, 2000) were determined in fresh raw sample prior to toxicity and biodegradability testing. The same parameters were also determined at the beginning and at the end of a stabilization study.

Toxicity testing

Whole effluent toxicity was determined using three different toxicity tests. We determined the inhibition of oxygen consumption by activated sludge,[5] using low (γ_{vss} = 100 mg l^{-1}) and high (γ_{vss} = 1 g l^{-1}) mass concentration of the inoculum – activated sludge. Activated sludge consumes oxygen rapidly in the presence of easily biodegradable substrate (peptone), which is added in the closed system (300 ml BOD bottle) together with nutrients and distilled water. Addition of toxic volume fraction of the wastewater (as φ = 5, 10, 20 and 40 %) results in a decrease in the oxygen consumption rate. Oxygen concentration was followed up to 180 min at 20 ± 1 °C. The volume fraction inhibition of the oxygen consumption was estimated by comparison of oxygen consumption rate (mg l^{-1} min^{-1}) in the test mixture with a control containing no test material. Finally percentage of inhibition was plotted versus logarithm of wastewaters volume fraction (%) to determine EC values. The sensitivity of the test was checked with reference compound 3,5-dichlorophenol.

Chronic impact of the textile effluent was studied with the test for determination of the inhibitory effect of water constituents on the growth of activated sludge microorganisms.[6] Shake-flasks containing organic test medium and test material (φ = 1, 5, 10 and 20 %) were inoculated and incubated at 22 ± 2 °C. The biomass of these cultures and the blank controls were determined with measurement of turbidity at 530 nm. The growth inhibition (%) at the end of incubation period (during exponential growth phase which was lasting 4 to 6 h) was calculated by comparison with blank, and EC values were determined as for oxygen consumption method.

Both above mentioned toxicity tests with activated sludge were performed with non-adapted and adapted inoculum:

– The source of non-adapted inoculum was laboratory treatment plant with 8.3 l of aeration basin, sludge retention time was 9–11 d, and hydraulic retention time was 6–7 h. The plant was fed with synthetic municipal wastewater, constituted of 130 mg l^{-1} of peptone, 0.9 mg l^{-1} of P as KH_2PO_4, φ = 70 % of distilled water, and φ = 30 % of domestic sewage. The same activated sludge was also used in biodegradability assessment test and respirometric measurements in open respirometer, while in the stabilization study settled effluent from the same treatment plant was inoculated.

– Adapted sludge was collected at municipal wastewater treatment plant, where textile waste-

water was actually treated. Hydraulic retention time in aeration basin was 7 h; its volume was 6000 m^3.

We performed additional acute toxicity test with luminiscent bacteria *Vibrio fischeri*[17] (DR. LANGE LUMIStox, 2001), which was also used for monitoring changes in toxicity of the wastewater during stabilization study.

Biodegradability testing

Biodegradability of the sample was determined by two standardized methods as for the pure chemicals, while additional data on toxicity changes during biodegradation were gathered in stabilization study. Standardised methods allowed us to determine ready biodegradability of the sample, while stabilization study enabled physico-chemical and toxicological monitoring of changes as a result of degradation processes.

First we have assessed whole effluent ready biodegradability. The combination of the two biodegradability assessment tests from the first level of tiered protocol for pure substances was employed.[8] Initial volume fraction of the wastewater (φ = 30 %) was chosen on the basis of toxicity test with measurement of inhibition of oxygen consumption,[5] because oxygen consumption[18] besides CO_2[19] was one of the mechanisms for following biodegradation. We have avoided any toxic impact of the sample to the degrading microorganisms and assured initial BOD high enough to follow biodegradation reliably. Both parameters were followed in a closed respirometer Micro Oxymax, Columbus Instruments, USA, 1996. Oxygen consumption indicates degradation of parent compounds, while CO_2 production confirms mineralization. Theoretically expected oxygen demand of the wastewater was 82.5 mg l^{-1}, calculated on the basis of experimentally determined COD.[13] The theoretically expected CO_2 production (240 mg l^{-1}) was evaluated on the basis of determined DOC. pH was controlled during the test (28 d) to avoid false CO_2 measurements, due to the HCO_3^- formation at higher pH[20].

As inoculum non-adapted activated sludge from a laboratory wastewater treatment plant was used. Its mass concentration in measuring chamber was 30 mg l^{-1} (corresponding to $4 \cdot 10^5$ cells $\cdot$ ml^{-1})[21]. Temperature was maintained at 20 ± 1 °C. All tests were run in 250 ml duplicates. Nitrification of the sample was prevented by addition of 4 ml $\cdot$ l^{-1} of alilthiourea.[12] Abiotic degradation of wastewater was evaluated under the same conditions simultaneously without inoculation. Biodegradation curves were plotted as % of degradation versus time.

Stabilization study

Wastewater was diluted (1 litre to 4 litres, φ = 25 %) with unpolluted river water on the basis of toxicity studies to avoid significant toxic impact. The unpolluted surface water was chosen to evaluate the environmental impact of the wastewater in the ecosystem where low selfpurification capacity is expected due to the low concentrations of microfauna and nutrients present. The initial volume fraction of the wastewater in the study was non-toxic to mixed culture of microorganisms according to measurements of inhibition of oxygen consumption[5] or growth inhibition.[6] Thus degrading performance of the microorganisms was not reduced. But at the same time diluted effluent was toxic to *Vibrio fischeri*, what enabled us to follow the changes in toxicity during biodegradation of the effluent.

Study was accomplished in 5 l reactor, the mixture was inoculated with 1 ml $\cdot$ l^{-1} (250–400 cells $\cdot$ ml^{-1})[21] of settled effluent from laboratory wastewater treatment plant. Opposite to the conventional biodegradability testing[18,19] no nutrients or buffer solutions were added. Some parameters like DOC,[14] IC,[14] pH, temperature, oxygen saturation and toxicity according to luminiscent bacteria[17], were monitored periodically during 28 d of the aerobic aging to allow comparison of measured values in terms of persistent and biodegradable toxicity. Blank test was run simultaneously.

Respirometric measurements of activated sludge

Treatment capacity of both, non-adapted and adapted activated sludge was determined in a discontinuous open flask respirometer. 1 litre of the activated sludge (γ_{VSS} = 3.44 g l^{-1}) was washed with tap water and put into the respirometer. First it was aerated well, to reach equilibrium oxygen concentration, γ_e (7.1 mg l^{-1} O_2 at 20 °C). Then the aeration was stopped and the O_2 concentration as a function of time was recorded. A decrease of O_2 concentration was observed due to endogenous respiration, which was regarded as practically constant for the time of the test. Than the suspension of activated sludge was aerated to the equilibrium concentration again to obtain data on oxygen transfer rate (k_{La}, min^{-1}) using equation 1, where γ_{O_2} (mg l^{-1}) is the concentration of O_2 and γ_{e,O_2} (mg l^{-1}) equilibrium mass concentration at the experimental conditions[10].

$$\frac{d\gamma_{O_2}}{dt} = k_L a\,(\gamma_{e,O_2} - \gamma_{O_2}) \qquad (1)$$

We plotted logarithm of concentrations versus time to assess k_{La} using linear regression. Then 5, 30 and 100 ml of the raw wastewater was added to the suspension of activated sludge. Biodegradation of the wastewater caused oxygen depletion, which was measured until it was equal to equilibrium mass concentration (γ_{e,O_2}). The specific maximal exogenous O_2 uptake rate $r_{OUR_{ex,max}}$ ($g_{O_2}\ g_{vss}^{-1}\ day^{-1}$) was calculated for each addition of the textile wastewater using equations 2 and 3.[10,11]

$$\gamma_{max,O_2} = \gamma_{e,O_2} - \gamma_{min,O_2} \quad (2)$$

$$r_{OUR_{ex,max}} = \frac{k_L a \cdot \gamma_{max,O_2}}{\gamma_X} \quad (3)$$

γ_{min} (mg l^{-1}) represents the lowest mass concentration of the oxygen after addition of the certain amount of the wastewater, γ_X is the concentration of activated sludge in the open respirometer (g l^{-1}). $r_{OUR_{ex,max}}$ was calculated for both types of inoculum and plotted versus initial organic input, which expressed as mg of DOC per g of activated sludge. Actual $r_{OUR_{ex,max}}$ in the wastewater treatment plant was estimated on the basis of average annual load of the textile wastewater (6.3 %).

Results and discussion

Physico-chemical and toxicological analysis of the wastewater

Physico-chemical analysis of the textile wastewater is presented in Table 1. It was semi-transparent white coloured wastewater, containing some floating white fibres, which were removed prior to analysis with filtration (black ribbon).

Organic pollution appeared to be biodegradable, because BOD_5/COD ratio was high (0.76). Wastewater consisted mainly of carbon containing organics, while mass concentration of organic nitrogen components was low (12.58 mg l^{-1}).

Table 1 – *Physico-chemical analysis of the raw textile wastewater*

Quantities	Value
pH	9.25 (± 0.1)
γ_{COD}, mg l^{-1}	275 (± 15)
γ_{DOC}, mg l^{-1}	218.3 (± 4.4)
γ_{IC}, mg l^{-1}	68.23 (± 1.36)
γ_{BOD5}, mg l^{-1}	210 (± 20)
$\gamma_{Kjeldahl\ N}$, mg l^{-1}	15.72 (± 0.5)
γ_{NH4+-N}, mg l^{-1}	3.14 (± 0.12)
$\gamma_{NO2—N}$, mg l^{-1}	< 1.0 (± 0.1)
$\gamma_{NO3—N}$, mg l^{-1}	3.7 (± 0.3)
$\gamma_{PO43—P}$, mg l^{-1}	< 1.0 (± 0.1)

Wastewater slightly inhibited growth of non-adapted activated sludge microorganisms. EC_{20} values during four hours of incubation in the toxicity test are presented in Table 2.

Table 2 – *Toxicity of the wastewater according to growth inhibition of non-adapted microorganisms*

Time of incubation *t*/h	EC_{20}/%
2.0	84.5
2.5	83.8
3.0	50.6
3.5,	38.8
4.0	29.2

Toxicity of the wastewater increased during 2 h of incubation (from 84.5 to 29.2 %). The first measurement after 2 h period represented a beginning of growth exponential phase, while the last one was made at the end of exponential phase. Wastewater showed chronic impact on non-adapted microorganisms of the activated sludge. But on the other hand, it was not toxic to non-adapted activated sludge microorganisms, according to measurement of inhibition of oxygen consumption. We were only able to calculate 180 min EC_{10} which was 26.2 % with low concentration of microorganisms. The difference in results of both tests is probably due to different characters of the tests. With high concentration of non-adapted inoculum, addition of the wastewater had even increased oxygen consumption compared to the blank. That means, that added microorganisms were able to start immediately to degrade textile wastewater. No toxic effects on oxygen consumption were observed with adapted activated sludge. Wastewater was estimated as non-toxic to the activated sludge in the average concentrations in the existing treatment plant (6.3 %).

Toxicity testing using *Vibrio fischeri* was the most sensitive bioassay probably due to its specific character: single species testing and physico-chemical conditions. Its 30 min EC_{20} was 2.05 % and 30 min EC_{50} was 10.44 %.

Biodegradability of the wastewater

Biodegradation curves of textile wastewater with added alilthiourea are presented in Figure 1. Abiotic elimination did not occur. pH remained constant (7.4 ± 0.4) during 28 d of the test.

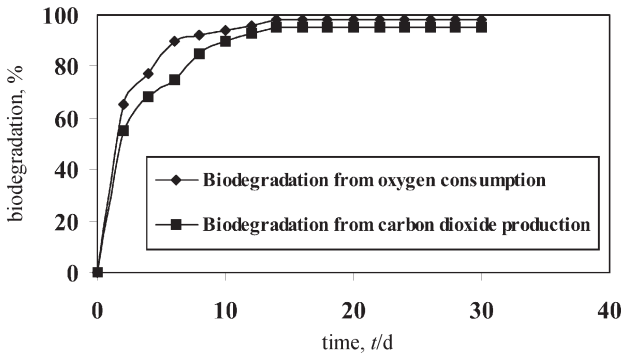

Fig. 1 – *Biodegradability of the raw textile wastewater (φ = 30 %) in the closed respirometer*

Wastewater degraded rapidly. Level of biodegradation reached 98 % according to oxygen consumption and 95 % according to carbon dioxide production. Both degradation curves were comparable, indicating complete mineralization of the wastewater without significant formation of the metabolites. Good biodegradability as BOD_5/COD ratio (76 %) was confirmed with biodegradability test. Regarding conditions of the applied tests, we could predict, that textile wastewater will degrade in common environmental conditions (surface waters, Etc.) rapidly without any side effects.[8] We wanted to verify this assumption in stabilization study.

Stabilization study

DOC in the blank test varied from 5 to 2 mg l^{-1}, IC increased from 45 to 48 mg l^{-1}. Other parameters remained constant: γ_{COD} and γ_{BOD5} were less than 5 mg l^{-1}, there was no Kjeldahl nitrogen and initially present ammonium nitrogen (4 mg l^{-1}) was converted to nitrate N. The river water, which was used in the stabilization study, has low phosphorous content (< 0.01 mg l^{-1}) and there was also negligible amount of PO_4^{3-}–P in the wastewater. Phosphorous seems to be limiting nutrient in the system. The same situation could also appear in natural river waters and thus data on the impact of the textile wastewater under investigated circumstances are important.

Blank test confirmed that there were no ambient impacts on the test system. Temperature was constant (20 ± 2 °C), as well as pH (7.8) oxygen saturation was above 95 % in the blank and in the diluted sample. γ_{DOC} and γ_{IC} mass concentrations during 28 d of stabilization study with textile wastewater are presented in Figure 2. Degradation of textile wastewater in stabilization study caused 76 % reduction of γ_{DOC} and increase in γ_{IC} of 33%. Increase of γ_{IC} concentration was caused by mineralization of organic pollution but it was lower than expected on the basis of DOC decrease. Minority of the formed IC was probably stripped off the system as $CO_{2(g)}$, while significant amount was used as a source of inorganic carbon for intensive nitrification. At the same time this could indicate formation of some stable metabolites.[20]

DOC decrease was lower than in biodegradation test as a consequence of lower inoculum concentration and probably due to the lack of nutrients. In stabilization study we have simulated biodegradation of the wastewater in clean surface waters, while in standardized biodegradability assessment test nutrient were added in excess. In stabilization study concentration of PO_4^{3-}–P was negligible all the time. Even if it was formed during biodegradation, it was immediately used. Concentration of nutrients (nitrogen as ammonia) was significantly reduced during first 10 days of the experiment due to the nitrification resulting in slower and non-complete mineralization of the sample afterwards.

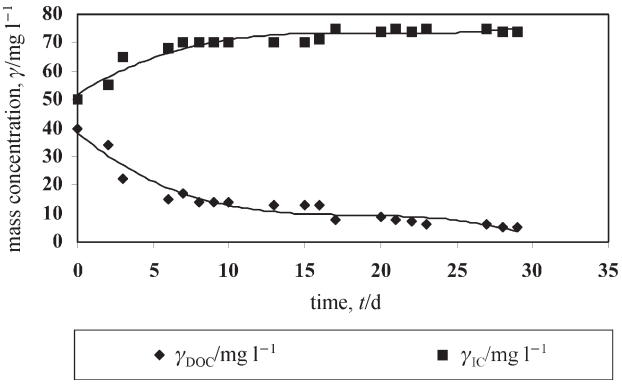

Fig. 2 – *DOC and IC mass concentration during stabilization study with the textile wastewater (φ = 25 %)*

Measured parameters at the beginning and at the end of the stabilization study indicated 71 % reduction of γ_{COD} (75/22 mg l^{-1}), 95 % elimination of γ_{BOD5} (55/less than 2 mg l^{-1}), more than 75 % decay in Kjeldahl nitrogen mass concentration (7/1.7 mg l^{-1}), and 69 % reduction of ammonia nitrogen (γ = 12.5/3.8 mg l^{-1}). Biodegradation of textile wastewater in stabilization study was also confirmed by increase in nitrate (134 %), chloride (104 %) and SO_4^{2-} mass fraction (364 %).

The extent of biodegradation was lower in stabilization study than in closed respirometer, probably due to the lower amount of microorganisms added and lack of the nutrients, particularly phosphorous. Stabilization study indicated, that standardized biodegradability assessment test is not enough for reliable prediction of a fate of a textile wastewater in the aquatic environment. Its biodegradation in surface waters could be drastically affected by physico-chemical conditions in receiving ecosystem, leading to less intensive biodegradation.

We determined toxicity of residuals and metabolites during biodegradation of the sample in the stabilization study by measurement of bioluminescence inhibition, which was the most sensitive indicator according to toxicity studies with raw textile wastewaters. 30 min EC_{20} values are presented in Figure 3.

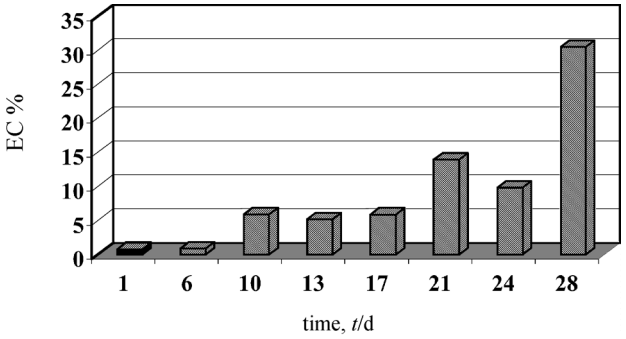

Fig. 3 – *Changes of toxicity during stabilization study with textile wastewater (φ = 25 %)*

At the beginning of the stabilization study diluted wastewater (25 %) was toxic to luminiscent bacteria, EC_{20} was less than 1 %. After 10 days of ageing EC_{20} increased indicating degradation of toxic components of the wastewater and/or transformation of produced metabolites. Toxicity was significantly reduced during last few days, when changes in DOC, IC and other measured parameters where not so intensive any more. But toxicity was still present, 30 min EC_{20} reached 30 %. Wastewater seemed to degrade to toxic metabolites or consisted of some minor harmful components, which could be toxic to aquatic organisms. That means that extent of biodegradation of textile wastewater is condition-dependent and it could be stopped at the point where toxic metabolites have been present. Performance of stabilization study assured additional data on the behaviour of the wastewater under certain environmental conditions, because formation of toxic metabolites during biodegradation was undetected in the common biodegradability assessment test.

Respirometric measurements of the activated sludge

Respirometric measurements were performed with both types of inoculum. k_{La} was 0.316 min^{-1} for non-adapted inoculum and 0.326 min^{-1} for adapted inoculum. Endogenous respiration was lower for non-adapted inoculum (0.12 $g_{O_2}\, g_{vss}^{-1}\, day^{-1}$) than for adapted inoculum (0.17 $g_{O_2}\, g_{vss}^{-1}\, day^{-1}$). In the Figure 4 relationship between maximal exogenous specific oxygen uptake rate ($g_{O_2}\, g_{vss}^{-1}\, day^{-1}$) and initial organic input of the textile wastewater

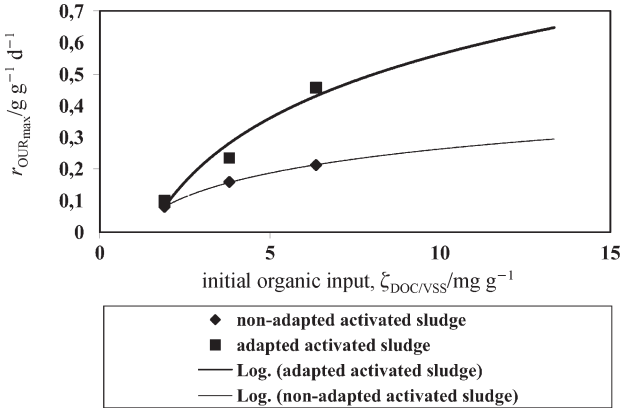

Fig. 4 – *Relationship between maximal exogenous specific O_2 uptake rate ($g_{O_2}\, g_{vss}^{-1}\, day^{-1}$) and initial organic input of the textile wastewater (mg g^{-1}) in the open respirometer*

(as mg DOC per g of VSS) in the open respirometer is presented.

The adapted inoculum expressed much higher specific maximal oxygen uptake rates than non-adapted inoculum. The higher was organic load, the more obvious was the difference between both types of inoculum, probably due to toxic effects of higher concentrations of wastewaters to non-adapted microorganisms of activated sludge. If actual average initial organic input in the wastewater treatment plant is considered (13.75 mg g^{-1}), calculated on the basis of average annual hydraulic load (6.3 %) and γ_{DOC} of the sample (218.3 mg l^{-1}, Table 1), the $r_{OURmax,ex}$ of the non-adapted inoculum in the wastewater treatment plant would be 0.29 $g_{O_2}\, g_{vss}^{-1}\, day^{-1}$ and 0.65 $g_{O_2}\, g_{vss}^{-1}\, day^{-1}$ for adapted inoculum respectively. 2.2-times higher $r_{OURmax,ex}$ confirmed adaptation of activated sludge from actual treatment plant to textile wastewater. Adaptation capacity of activated sludge has also been noticed in toxicity tests with non-adapted inoculum.

The textile wastewater was assessed as appropriate for biological treatment due to its low toxicity to mixed culture of activated sludge, high biodegradation potential at appropriate conditions and confirmed adaptation capability of the microorganisms. On the other hand, untreated wastewater poses significant environmental risk: its biodegradation in surface water may be slower and resulting in formation of toxic metabolites or presence of persistent toxicity.

Conclusion

In order to determine biological treatability of textile wastewater study on ready biodegradability, toxicity and aerobic stabilization, has been reported. Wastewater was very toxic to luminescent bacteria and much less to non-adapted activated sludge, while it was non-toxic to adapted sludge. Good bio-

degradability (> 95 %) has been shown by both measured non-specific summary parameters in closed respirometer. However, in the stabilization study with unpolluted river water residual toxicity has been detected. Textile wastewater contained persistent toxic compounds or they had been formatted during biodegradation. Dependency of biodegradation of wastewater in common environmental conditions on nutrient content of the ecosystem was indicated. On the other hand, respirometric measurements confirmed adaptation of activated sludge to selected wastewater. Textile wastewater was appointed as biologicaly treatable on the basis of presented approach. Treatment was confirmed as necessary due to its hazardous environmental impact.

ACKNOWLEDGEMENT

Ministry of Science and Education of Republic of Slovenia funded the study.

List of symbols

γ – mass concentration, mg l^{-1}

γ_{BOD_5} – biochemical oxygen demand, mg l^{-1}

γ_{O_2} – oxygen mass concentration, mg l^{-1}

γ_{e,O_2} – equilibrium oxygen mass concentration, mg l^{-1}

γ_{max,O_2} – highest oxygen mass concentration, mg l^{-1}

γ_{min,O_2} – lowest oxygen mass concentration, mg l^{-1}

γ_{COD} – chemical oxygen demand, mg l^{-1}

γ_{DOC} – dissolved organic carbon, mg l^{-1}

EC – effective volume fraction, %

φ – volume fraction, %

γ_{IC} – inorganic carbon mass concentration, mg l^{-1}

k_La – oxygen transfer rate, min^{-1}

$r_{OURex,max}$ – specific maximal exogenous oxygen uptake rate, $g_{O_2}\, g_{vss}^{-1}\, day^{-1}$

VSS – volatile suspended solids

γ_{VSS} – concentration of volatile suspended solids, g l^{-1}

t – time, h

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