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INFLUENCE OF FLOW VELOCITY ON PERFORMANCE OF A LOW LOADED DOWNFLOW BIOFILTER

Summary. Laboratory tests were carried out to assess the influence of flow velocity on the performance of a downflow biofilter treating a domestic wastewater with low concentration of organic carbon. Flow velocities ranged from 0.26 to 0.65 m h^{-1}, corresponding to hydraulic retention times from 19.5 to 48.6 minutes, and the incoming organic load ranged from 41.5 to 47.0 g C m^{-3} h^{-1}. The performance of the biofilter, filled with puzzolane grains, was analysed in terms of total organic carbon (TOC) removal and total suspended solids (TSS) removal. The effect of varying flow velocity on biofilter performance was analysed taking into account the hydrodynamic characteristics observed in two media sections (TM – P1 and TM – P2) and for the total media depth. The highest TOC removal efficiency was observed for the lower velocity reaching 40.2% of the total incoming organic load. For velocities between 0.39 and 0.65 m h^{-1} the total organic load removal rate (r_V C) was stable with values ranging from 26.3 to 33.6 g C m^{-3} h^{-1} corresponding to TOC removal efficiencies from 28.6 to 37.8%. In the upper filter section (TM – P1) a higher removal of organic carbon (ΔC) and TSS (ΔTSS) was observed, which seemed to be related to the occurrence of large dispersion conditions and the likely presence of completely mixed regime. The TSS removal was stable within the range of applied flow rates and seemed to not be influenced by the flow velocity. However, to maintain a good performance the biofilter should be washed every five days of the operating period. The results showed that this type of device would be very useful to reduce the residual organic and solid loads present in secondary treated domestic wastewaters minimizing environmental impacts on receiving waters. The final effluent characteristics indicated that it can be used for some reuse purposes. These last conclusions make admit that this type of biofilter may be used as a useful tool to help water resources authorities to fulfil some objectives defined by the European Water Directive (Directive 2000/60/EC).

WPŁYW PRĘDKOŚCI PRZEPŁYWU NA WYNIKI PRACY NISKO OBCIĄŻONEGO BIOFILTRU SPŁYWOWEGO

Streszczenie. Aby ocenić wpływ prędkości przepływu na wyniki pracy nisko obciążonego biofiltru spływowego, oczyszczającego ścieki domowe o niskim stężeniu węgla organicznego, przeprowadzono badania laboratoryjne. Prędkości przepływu były w przedziale od 0,26 do 0,65 mh^{-1}, co odpowiada hydraulicznym czasom zatrzymania od 19,5 do 48,6 minut, a ładunek organiczny był w przedziale od 41,5 do 47,0 $gCm^{-3}h^{-1}$. Wyniki pracy

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biofiltru, napełnionego ziarnami pucolanowymi, były analizowane pod względem usuwania całkowitego węgla organicznego (TOC) oraz pod względem usuwania całkowitej zawartości zawiesin stałych (TSS). Wpływ zmiennej prędkości przepływu na wyniki pracy biofiltru był analizowany, biorąc pod uwagę własności hydrodynamiczne obserwowane w dwóch sekcjach medium (TM – P1 i TM – P2) oraz dla całkowitej głębokości medium. Najwyższą sprawność usuwania TOC zaobserwowano dla niższych prędkości, osiągając 40,2% całkowitego wpływającego ładunku organicznego. Dla prędkości pomiędzy 0,39 a 0,65 mh^{-1} szybkość usuwania całkowitego ładunku organicznego (r_V C) była stabilna, z wartościami zmieniającymi się od 26,3 do 33,6 gCm^{-3}h^{-1}, odpowiadającymi sprawnościom usuwania TOC od 28,6 do 37,8%. W górnej sekcji filtru (TM – P1) zaobserwowano wyższe usuwanie węgla organicznego (ΔC) oraz TSS (ΔTSS), co wydawało się być związane z wystąpieniem warunków dużej dyspersji oraz przypuszczalnej obecności reżimu całkowicie mieszanego. Szybkość usuwania TSS była stabilna w przedziale zastosowanych prędkości przepływu i wydawała się nie podlegać wpływowi prędkości przepływu. Jednak aby utrzymać dobre wyniki pracy biofiltru w okresie eksploatacji, należy go przemywać co pięć dni. Wyniki wykazały, że ten rodzaj urządzeń byłby bardzo użyteczny dla zmniejszania ładunków pozostałości organicznych i stałych występujących w ściekach domowych czyszczonych biologicznie, minimalizując oddziaływanie na środowisko odbiornika ścieków. Końcowe własności ścieków wskazywały, że mogą one być ponownie używane w pewnych celach. Te ostatnie wnioski stwierdzają, że ten rodzaj biofiltru może być używany jako użyteczne narzędzie, aby pomóc władzom zarządzającym zasobami wodnymi w realizacji niektórych celów zdefiniowanych przez Europejską Dyrektywę Wodną (Dyrektywa 2000/60/WE).

1. Introduction

Discharges of wastewater to soils and receiving waters may cause adverse effects (*e.g.* groundwater pollution, dissolved oxygen depletion, nutrient enrichment and toxicity), reducing biodiversity and producing impacts on potential water and soils uses.

In the scope of international agreements and to stimulate more sustainable water management policy the European Union (EU) has been requiring from all Member States the implementation of the Water Directive (Directive 2000/60/EC of the European Parliament and Council of 23 October 2000). This Directive aims at establishment of a framework for the protection on inland surface waters, transitional waters, coastal waters and groundwater. The main objectives involve the prevention of degradation of water ecosystem, in regard to the water uses, the promotion of sustainable water uses based on long term protection of available water resources and the implementation of specific measures to reduce the effects of wastes discharges into water bodies. To achieve these objectives the Directive suggests the study and implementation of measures to promote an efficient and sustainable water use such as wastewater reuse. This type of measure may contribute to reduction of the use of natural water resources.

In Portugal, nearly 70.0% (INAG, 2000) of the domestic wastewater treatment systems use secondary treatment in order to reduce the inorganic and organic loads which may cause environmental impacts on water resources and soils. Biological wastewater treatment using fixed-film systems has been shown to have a high efficiency in removing the inorganic and the organic matter present in wastewater. However, there does still exist a residual part (mainly soluble microbial products and slowly biodegradable substrates), not removed by those infrastructures, which does not ensure compliance with the regulations and environmental policies, constituting concern in the domain of water quality, pollution control and environmental protection systems.

Biological filtration through submerged packed beds is a technology recently looked at as useful to be integrated in wastewater treatment systems for organic and inorganic residual removal. As referred by Crites and Tchobanoglous (1998) and Grady Jr. *et al.* (1999) they present numerous advantages such as high concentration of active biomass, good control of excess of biomass, good efficiency on carbonaceous removal, nitrification/denitrification and phosphorous removal associated with high filter capacity (avoiding setting facilities).

Scaled-up biological filters sometimes bring lower yields than expected. Several studies have been conducted in an attempt to identify factors affecting treatment efficiency of biological filters. One of the main causes of filters lower performance is related to poor liquid distribution which affects the distribution of both incoming substrates and reaction products. The results of laboratory tests carried out by Fdz-Polanco et al. (1996) and Albuquerque and Santana (2004) concluded that the main factors which may contribute to flow maldistribution are the presence of immobile areas, dead volumes, short-circuiting, internal recirculation and dispersion. Tay and Show (1998) examined the effect of media-related factors in the efficiency of biofilters treating a synthetic wastewater and concluded that the use of a support media with large pore size and porosity may reduce the extent of short-circuiting leading to a better wastewater performance. Tests carried out by Karamanev *et al.* (1994) for different flow velocities using a packed bed filled with porous solids aggregates showed that for velocities over 5.0 m h^{-1} the liquid flowed mainly between the solid material. As a consequence, less quantity of substrates were up taken inside the clusters of particles and biomass. Therefore, a study on the hydraulic characteristics of packed beds is an accurate procedure to get information concerning the presence of these flow disturbances.

Biological filters flux direction is mainly of two types (Crites and Tchobanoglous, 1998; Grady Jr. *et al.*, 1999): upflow and downflow. The higher concentrations of substrate and biomass are normally located near the inlet as observed in the experiments of Tay and Show (1998) and Albuquerque (2003). This heterogenic colonization make difficult to study the relations between flow velocity and filter performances since the reaction rates at the inlet media are different from those at outlet media and they affect biomass growth. The inherent mixing conditions caused by flux and biogas also may distort the hydrodynamics conditions and may affect both substrate removal and biomass growth within the depth of the filter.

Although the role of media-related factors (Tay and Show, 1998), the influence of flow velocity using tracer tests (Karamanev *et al.*, 1994) and the evaluation of flow disturbances affecting the distribution of substrates (Fdz-Polanco *et al.*, 1996; Albuquerque and Santana, 2004; Albuquerque, 2003) have been studied, limited studies have been set up to evaluate the influence of flow velocities on the performance of laboratory biofilters treating domestic wastewater with low concentration of organic carbon.

Therefore, the main objective of this paper is to evaluate the influence of flow velocity on the performance of a biological packed bed used to remove wastewater residuals. A set of tests at different flow velocities using a secondary treated domestic wastewater was performed in order to evaluate the stability of the process in terms of TOC and TSS removal. An interpretation concerning the performance of the filter is done based on TOC and TSS removal in each test. The effluent characteristics and its potential reuse is analysed taking into account the objectives of the Water Directive.

2. Material and methods

2.1. Experimental setup

A laboratory acrylic glass column was used as the biofilter (Fig. 1). The device was 0.07 m in diameter and 1.25 m in height, 0.405 m filled with a homogeneous packed material (puzzolane) with 4.0 mm of effective diameter, providing an empty volume of 1.56 L. The characteristics of the solid packing media are presented in Table 1. Five sampling ports (from P1 to P5) along the depth of the filter were provided in order to allow the extraction of samples for analysis at various stages of treatment.

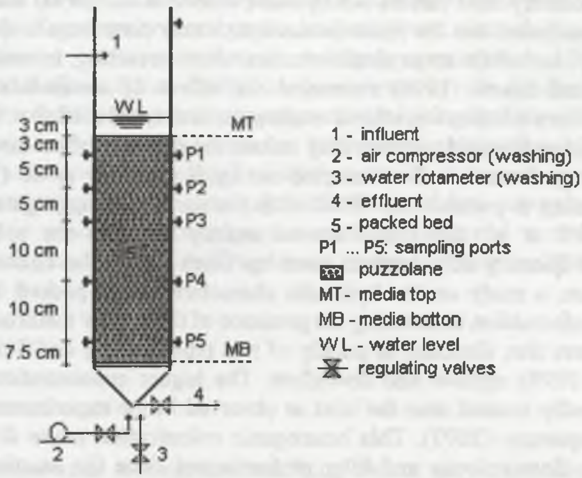

Fig. 1. Schematic representation of the laboratory biofilter
Rys. 1. Schematyczny widok biofiltru laboratoryjnego

Table 1

Characteristics of the support media

Media characteristic	Value
Material	puzzolane
Total packed height (m)	0.405
Granulometry (mm)	3.0 – 5.0
Volumetric mass (g cm^{-3})	2.18
Specific surface (m^2 m^{-3}) [1)]	1 744
Porosity (%)	52.0
Permeability (m s^{-1})	0.0014

2.2. Inoculation and feeding solution

The filter was inoculated with a biomass from an activated sludge system, previously acclimated to sodium acetate, and was operated in a closed system. Daily analysis on TOC and TSS were carried in order to evaluate the growth of biomass in the packed material. After fifteen days of operation the filter was considered colonised.

The feeding solution for the laboratory experiments came from the effluent of the wastewater treatment plant (WWTP) of Boidobra (Covilhã) which uses a packed fixed-film secondary treatment system. This solution was kept refrigerated at 4.0 ± 0.5 °C in a low temperature incubator ISCO FTD 220. The flow was regulated by an Ismatec MCP/BVP CA4 electronic peristaltic pump.

2.3. Experimental procedure

The biological filter was operated at 1.0 Lh^{-1} until steady-state conditions were observed. These conditions, characterized by a *quasi constant* removal rate of TOC, were observed after two days of operation. The average TOC at the inlet was 37.3 mg C L^{-1} which corresponded to an organic load of 46.1 g C m^{-3} h^{-1}. As observed in a more extensive study (Albuquerque, 2003) changing the organic loading conditions or washing the packed media may change the filter dynamics. In any case the return of steady-state conditions can be observed after eight hours of operation.

Four experiments were performed at flow rates from 1.0 to 2.5 L h^{-1} according to the initial conditions presented in Table 2. In order to allow steady-state conditions each run took approximately fifteen hours. After those periods samples were collected at the inlet, P1, P2 and outlet of the filter. For each sample the following parameters were measured: pH, temperature, dissolved oxygen (DO), TOC and TSS.

A multiparametric WTW Multiline P4 equipment was used to measure DO, pH and temperature. TOC was analysed using a TOC – 5000 A Shimadzu and TSS was evaluated by using a drying method presented in the Standard Methods for the Examination of Water and Wastewater (APHA, 1995).

Table 2

Operating and loading conditions

Experiment	Flow rate (L h^{-1})	U (m h^{-1})	HRT (min)	Characteristics of the influent at biofilter			
				pH	DO (mg O_2 L^{-1})	TOC (mg C L^{-1})	TSS (mg L^{-1})
E1	1.0	0.26	48.6	6.8	6.8	33.6	65.0
E2	1.5	0.39	32.4	7.0	6.3	37.6	85.0
E3	2.0	0.52	24.3	6.7	6.5	34.4	80.0
E4	2.5	0.65	19.5	6.8	6.1	38.1	70.0

HRT: hydraulic retention time

3. Results and discussion

3.1. Removal rates

The performance of the biofilter removing TOC and TSS also depends on the hydraulic behaviour induced by the support media and the growth of the fixed and suspended biomass. The study of the hydrodynamic characteristic of the biofilter illustrated in Figure 1 for the range of velocities used in this paper is presented in previous works (Albuquerque, 2003; Albuquerque and Santana, 2004). The results obtained will be used to help with the discussion of the filter performance.

The pH values ranged from 6.8 to 6.4 and the average DO values decreased from 6.4 to 1.1 mg O_2 L^{-1} trough the filter depth (from the inlet to the outlet point). The average DO value at the sampling point P2 was 1.8 mg O_2 L^{-1}.

The organic carbon removal (ΔC) observed in sections MT – P1, MT – P2 and MT – MB (the values calculated for this section correspond to the difference in TOC between the influent and the effluent) for each trial is presented in Table 3. It also included information concerning the main factors which contributed to flow maldistribution presented in the works referred to in the last paragraph.

The evolution of the organic carbon removal as a function of flow velocity for each filter section is presented in Fig. 2. It can be observed that the carbon removal decreases with the increase in the flow velocity (*i.e.* as the HRT decreases) especially for filter lengths above 3.0 cm (sections P1 – P2, TM – P2 and TM – BM). In the upper section (TM – P1) a slight decrease in organic carbon removal was observed indicating that the removal rate may not be influenced by the flow velocity for the range of flow rate used in this study.

Table 3

TOC removal and main mechanisms responsible for flow resistance for each sampling point

Experiment	ΔC (mg C L^{-1})		
	MT – P1	MT – P2	MT – MB
E1	6.5	11.4	13.5
E2	7.0	11.1	14.2
E3	6.3	8.6	11.3
E4	5.6	8.8	10.9
Main mechanisms	Dead volumes, short-circuiting	Dead volumes, short-circuiting	Stagnant volumes
Degree of dispersion	Large amount of dispersion	Intermediate amount of dispersion	Intermediate amount of dispersion

By local inspection a visible amount of biomass was observed within the TM – P1 section independently of the applied flow rate. This situation was also reported in the studies of Tay and Show (1998) and may be explained by the presence of higher amounts of oxygen and substrates since it is located near the feeding point.

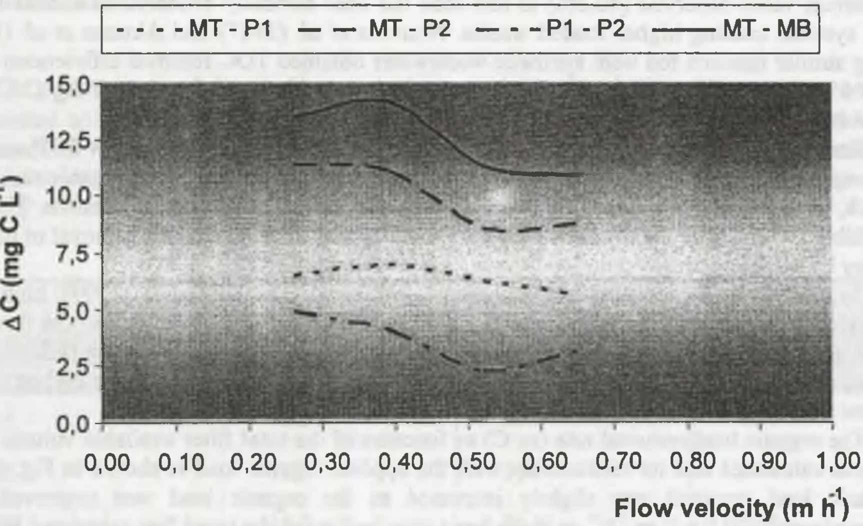

Fig. 2. Evolution of organic carbon removal as a function of the flow velocity
Rys. 2. Zmiany usuwania węgla organicznego jako funkcja prędkości przepływu

The presence of large dispersion conditions on that section (Table 3) probably made possible the occurrence of mixing even with the presence of dead volumes. The occurrence of closer values of ΔC may, therefore, be explained by the presence of a flow regime closer to completely mixed flow which allowed identical contact conditions between biomass and substrates.

The TOC removal efficiencies displayed in Fig. 3 also indicate that the filter seemed to exhibit somewhat equal performance in the section TM – P1. For the other sections the efficiency of organic carbon removal decreased as the flow velocities increased. The

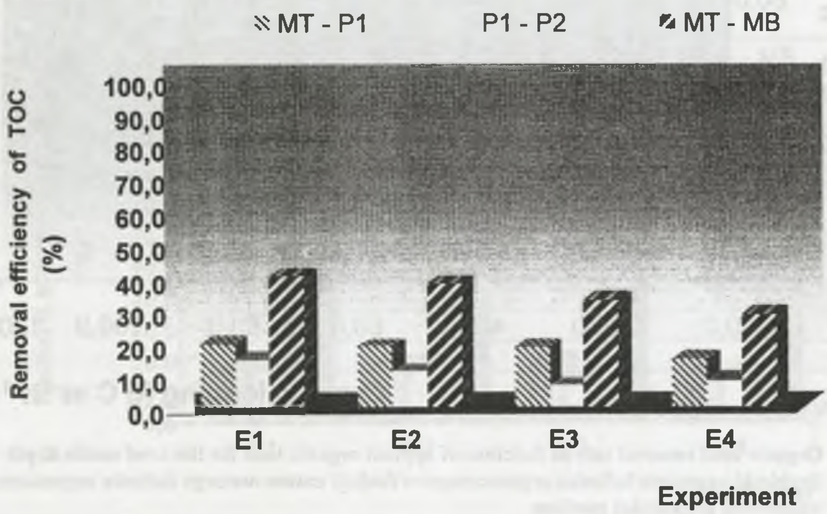

Fig. 3. TOC removal efficiencies observed in three filter sections for each experiment
Rys. 3. Sprawności usuwania TOC obserwowane w trzech sekcjach filtru dla każdego eksperymentu

maximum value observed (40.2%) is less than the ones normally observed in similar fixed-film systems treating higher loaded wastes. Nouvion *et al.* (1987) and Akunna *et al.* (1994) using similar reactors fed with synthetic wastewater obtained TOC removal efficiencies up to 50.0% and above 90.0% for inlet TOC concentrations between 70.0 and 80.0 mg C L^{-1} and between 154.0 and 352.0 mg C L^{-1} respectively.

Since the wastewater used in this study came from a secondary domestic WWTP some of the organic matter evaluated as TOC were sub-products of biodegradation (organic residuals) which, as mentioned by Grady Jr. *et al.* (1999), are normally difficult to remove. The less available DO for filter depths above 8.0 cm (port P2) may have limited the removal of organic matter by aerobic pathways.

As referred by Crites and Tchobanoglous (1998) and Grady Jr. *et al.* (1999), high HRT provides longer contact between substrates (organic carbon) and the biomass. On the other hand, mixing conditions allow less resistance to substrate diffusion into biofilm (Fdz-Polanco *et al.*, 1996). The combination of those factors may explain the higher organic carbon uptake at low flow velocities and the removal stability observed in section TM – P1.

The organic load removal rate (r_V C) as function of the total filter available volume (0.81 L) was calculated and its relationship with the applied organic load is shown in Fig. 4. The organic load removal rate slightly increased as the organic load was improved over approximately 70.0 g C m^{-3} h^{-1} as it can been seen looking at the trend line calculated by point interpolation (Fig. 4). This trend is different than the ones observed in the studies of Tay and Show (1998), which obtained higher values of r_V C for higher organic loads, but similar to the ones obtained by Silva *et al.* (2003) working with a secondary domestic effluent with an average TOC of 60.0 mg C L^{-1}.

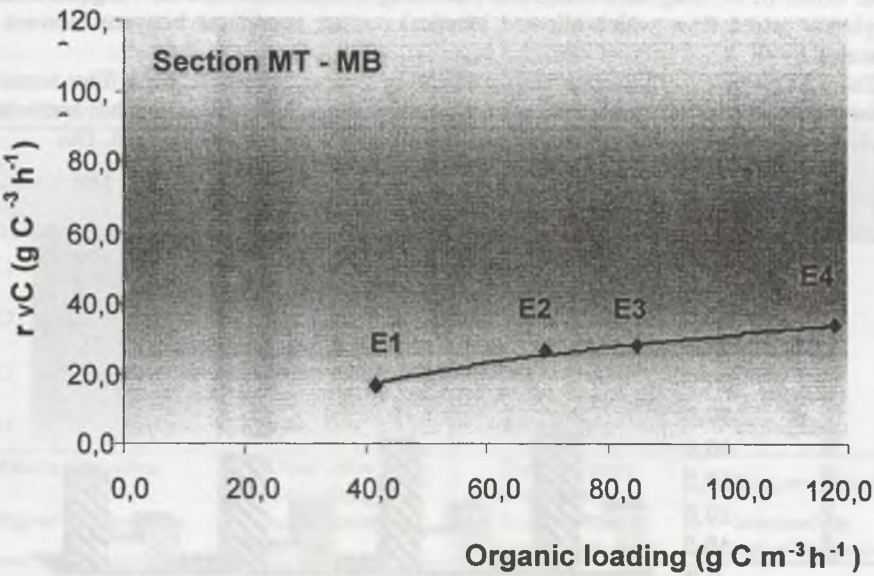

Fig. 4. Organic load removal rate as function of applied organic load for the total media depth
Rys. 4. Szybkość usuwania ładunku organicznego w funkcji zastosowanego ładunku organicznego dla całkowitej głębokości medium

3.2. Solids retention

The performance of the biofilter strongly depends on the ability of the reactor to retain suspended solids. Table 4 shows the results of the TSS removal (ΔTSS) observed in the sections MT – P1, MT – P2 and MT – MB for each trial. The solids retention in each filter section seemed to be similar for the range of applied velocities which indicates a good stability of the filtration process.

Table 4

TSS removal for each sampling point

Experiment	ΔTSS (mg TSS L^{-1})		
	MT – P1	MT – P2	MT – MB
E1	10.0	20.0	40.0
E2	15.0	30.0	55.0
E3	15.0	25.0	55.0
E4	10.0	20.0	45.0

The TSS removal efficiencies seemed to be independent of the flow velocity and stable in the sections TM – P1 and P1 – P2 as it can be seen in Fig. 5. Therefore, the media pore size and porosity seemed to be more favourable factors for TSS retention than the flow velocity or the HRT. The total removal efficiencies ranged from 61.5 to 68.8% and are consistent with those observed in the work of Tay and Show (1998). These results also showed a good filter capacity in retaining suspended solids, contradicting that observed in some examples presented in Crites and Tchobanoglous (1998) and in the work of Silva *et al.* (2003), which conclude that a final settlement tank is not necessary.

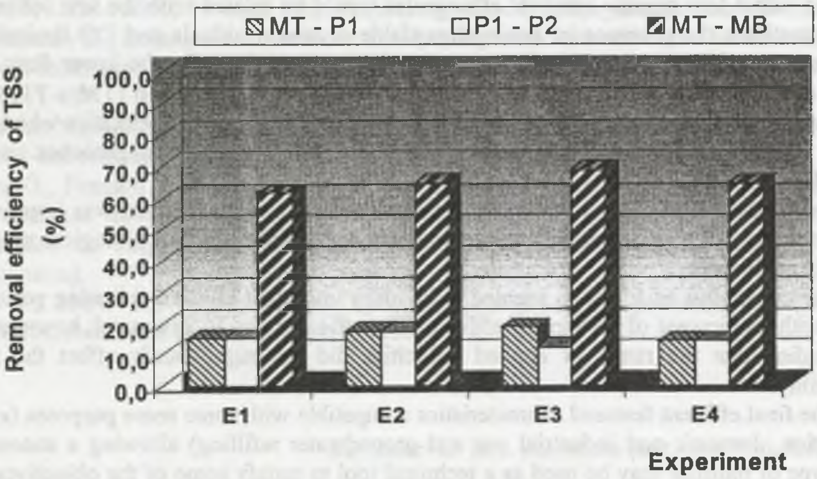

Fig. 5. TSS removal efficiencies observed in three filter sections for each experiment
Rys. 5. Sprawności usuwania TSS obserwowane w trzech sekcjach filtru dla każdego eksperymentu

During the experiments an increase was also observed in the effluent TSS after operating periods above 5.0 days. This occurrence suggested that after that operating period the filtration capacity was exceeded and the effluent quality started to decrease. To avoid reducing the treatment performance it was decided to wash the filter every 5.0 days during the operation.

3.3. Effluent characteristics

Looking at the values pointed out in Tables 3 and 4, the final characteristics of the treated effluent (20.1 to 27.2 mg C L^{-1} and 25.0 to 30.0 mg TSS L^{-1}) suggest, according to Crites and Tchobanoglous (1998) and Grady Jr. *et al.* (1999), that it can be reused in activities such as crops irrigation, domestic and industrial use not including human consumption (e.g. WC, car washing) and groundwater refilling.

The use of biological filters systems to remove organic residuals from secondary treated wastewaters seemed to be an advantageous solution in order to minimize environmental impacts on soil and water.

The results obtained in this study suggests that the use of this type of device can be useful to help the water management authorities to fulfil some of the objectives emphasised in the Water framework Directive (Directive 2000/60/EC) in terms of the prevention of degradation of water ecosystem and water conservation.

4. Conclusions

The use of a fixed-film treatment unit seemed to allow a quick start-up of the reactor with a high biomass concentration. Steady-state conditions were achieved in a few hours after changing the operating conditions (flow velocity) and after the washing period.

The rather low organic removal efficiencies would be related with the low influent TOC concentrations, the presence of nonbiodegradable organic residuals and DO limitation. The maximum total TOC removal efficiency (40.2%) was obtained for the lower flow velocity (0.26 m h^{-1}) and the higher HRT (48.6 min). In the upper filter section (TM – P1) the TOC removal rate was approximately constant within the range of applied velocities which seemed to be related with high dispersions conditions as the flow regime approaches completely mixed.

The organic load removal rate slightly increased as the organic load was improved over approximately 70.0 g C m^{-3} h^{-1} suggesting that the stability of the biological system was already achieved.

The constraints of filtration seemed to be more important after an operating period of 5.0 days with an increase of TSS in the effluent. The efficiency of TSS removal, however, allows concluding that the range of applied velocities did not significantly affect the filtration capability.

The final effluent featured characteristics compatible with some reuse purposes (*e.g.* crops irrigation, domestic and industrial use and groundwater refilling) allowing a statement that this type of biofilter may be used as a technical tool to satisfy some of the objectives pointed out in the Water Directive.

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