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Waste materials and composites as a trickling filter filling

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ABSTRACT

Two variants (preliminary stage and main stage) of the experiment aiming to verify the possibility of using waste materials and composites for septic tank effluent (STE) treatment were investigated. The hydraulic load of filters during main stage was about two times lower than during preliminary stage. The aim of this study was to examine the mechanical and biological treatment efficiencies of four waste materials: polyethylene Raschel mesh (PERM), wood-polymer composite (WPC), cut plastic straws (CPS) and polyethylene (PE). Considering that the used STE was hardly biodegradable, the removal efficiencies of the used materials were relatively high. During main stage for PERM the removal efficiencies of chemical oxygen demand (COD), ammonium nitrogen (N_{NH4}), total phosphorus (P_{tot}) and total suspended solids (TSS) were 84.6%, 92.8%, 24.5% and 83.6%, respectively. For CPS, efficiencies for COD, N_{NH4}, P_{tot} and TSS were 58.8%, 40.2%, 43.1% and 84.7%, respectively. For WPC, efficiencies for COD, N_{NH4}, P_{tot} and TSS were 60.2%, 51.8%, 44.1% and 85.2%, respectively. For PE, efficiencies for COD, N_{NH4}, P_{tot} and TSS were 46.9%, 30.0%, 43.7% and 85.3%, respectively. The technology used in this study was relatively simple. For maximum effectiveness in wastewater reuse (e.g., for irrigation), mechanical pre-treatment should be performed.

Keywords: Composite; Filter material; Trickling filter; Waste

1. Introduction

In recent years, there has been an increased interest in small individual wastewater treatment plants, due to the possibility of local use of treated wastewater and full control of users over treatment systems [1] and due to the high-efficiency waste water treatment technologies that allow for the achievement of extensive elimination of pollution and rapid modernization of existing treatment plants without increasing the volume of the reactors already in use [2,3]. Biofilm reactors are one of the most important technologies being widely researched. Similarly, to activated sludge systems, they can provide organic matter removal, nitrification, denitrification and phosphorus removal.

Among the properties superior to activated sludge technology, the following are most often mentioned [4]: greater resistance to changes in the quality and quantity of influent wastewater and longer age of biomass.

Conventional trickling filters often have problems related to, among other things, the difficulty of uniform distribution of wastewater on the surface of the filter. An additional layer of sorbent is sometimes introduced into

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the filter beds or trickling filters in the form of, for example, activated carbon, granular carbon arranged alternately with sand layers – the so-called sandwich method (GAC sandwich), clinoptilolite [5] or cotton sticks [6]. This is due to the fact that it is difficult to obtain highly effective or wide-ranging wastewater treatment efficiency by filter beds or trickling filters with conventional filter materials.

Bio-carriers are one of the key components used in wastewater treatment and can enrich microorganisms at the surface to improve the amount of biomass in the reactor. Currently, there are many types of available bio-carriers, having different shapes and sizes; they are made of polyethylene, polypropylene or high-density polyethylene with a typical density slightly less than water.

Many types of media have been evaluated and are being used for trickling filters, for example, commercial rings, plastic carriers (corrugated), geotextiles, calcitic gravel, coal, tire rubber, ceramsite and zeolite, oyster shell, cylindrical luffa [7], sawdust [4], expanded polystyrene [8], shredded recycled plastic [9,10] and pozzolan [11].

Among several technologies based on fixed biomass (e.g., moving bed, rotating biological contactors), the system of conventional trickling filters is indicated as a little sophisticated mechanics, which confirms the good statement and low energy demand [12]. Due to the simplicity of their design and operation, trickling filters are a suitable solution for developing countries. Some problems with these systems that have occurred in the past were related mainly with lack of technical knowledge or improper operation [12].

Nowadays, polypropylene or polyethylene supporting media are most often used [9]. These are materials with very good properties, dedicated especially for applications in trickling filters as a filter material (biofilm supporting media, carriers). On the other hand, other aspects of environmental impact of supporting media have been raised recently, such as: life cycle duration, water and carbon footprint, microplastic emissions during production, use and recycling. Therefore, the search for alternative materials (including recycled, biodegradable, composite, etc.) is justified and it seems that in the future it may have a significant impact on the widespread use of not only conventional trickling filters, but also other bioreactors using solid or fixed biomass (or movable carriers).

One of most interesting filling/carrier material is wood-polymer composite (WPC) [13]. The carriers' shape, density, protected areas, and void volume are important factors that affect the performance of biological processes. Carriers can be made of different shapes such as square, round, and spherical. The shape can affect the carrier's strength and shearing. The carriers' protected areas range from 300 to over 2,000 m^2/m^3 depending on the shapes and internal structure. Biofilm reactor configurations applied in wastewater treatment include trickling filters, high-rate plastic media filters, rotating biological contactors, fluidized bed biofilm reactors, airlift reactors, granular filters and membrane immobilized cell reactors, as can be seen in Fig. 1.

A general division between fixed and moving bed processes based on the state of the support material is usually made. Fixed bed systems include all systems where the biofilm is formed on static media such as rocks, plastic profiles, sponges, granular carriers or membranes. The liquid flow through the static media supplies the microorganisms with nutrients and oxygen. Moving bed systems comprise all biofilm processes with continuously moving media maintained by high air or water velocity or mechanical stirring. By using a material with a large specific surface area (m^2/m^3), high biological activity can be maintained using a relatively small reactor volume. The biofilm thickness in the reactors is usually controlled by applying shear force, which is achieved by altering the stirring intensity, flow velocity or by backwashing.

This paper presents the results of research aimed at determining the possibility of using several kinds of materials to create elements of biological trickling filters. The conducted research included determination of the physical-chemical parameters of treated wastewater.

2. Materials and methods

2.1. Laboratory set-up and experiment conditions

The experiment was performed in the laboratory of the Department of Hydraulic and Sanitary Engineering, Poznań University of Life Sciences. The experiments were carried out at a temperature close to room temperature (17°C–27°C) from March to November 2019.

The tests were carried out using eight filter columns made of organic glass with a length of 100 cm and internal diameter of 4.4 cm. Each of the four materials was used to fill two columns. They were filled with filter material to a depth of 80 cm. The bottom part of the pipe was secured with a net to prevent the filter material from slipping

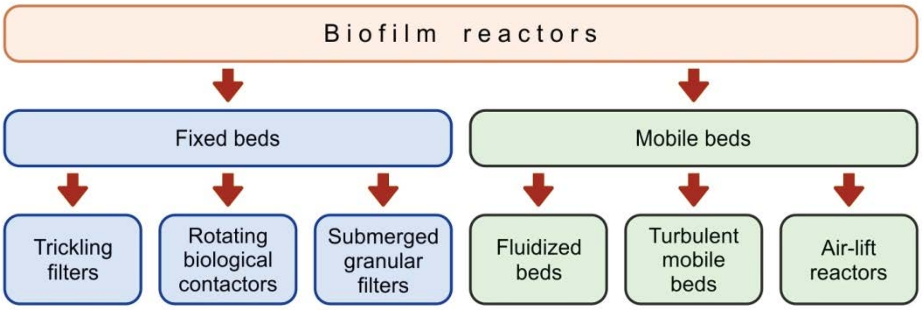

Fig. 1. Overview of common configurations for biofilm wastewater treatment [10].

out (Fig. 2). In the centre of the tubes the fountain pump sprinkler was located (5.0 cm sponge pieces were used to stabilize the central position). To supply the wastewater a tank with a capacity of 30 dm^3 with pumps was used. Treated wastewater was collected and measured using a vessel. Filter material was divided into four sections using inset transparent tubes made of very thin plastic material of 4.4 cm diameter. Each of these sections was closed with mosquito mesh at the bottom. Pumps were controlled by a programmable timer.

2.2. Material characteristics

In the experiment, four types of filter material were used, made with the intention of being used as biomass carriers. The first type of material from which cylindrical carriers were made was a WPC, where the matrix was made of polyethylene, the second was high-density polyethylene (PE), and the filling was a wood flour (Polyethylene: TIPELIN BA 550-13, wood flour: LIGNOCEL C 120 of particle size 70–150 µm, J. Rettenmaier & Söhne GmbH + Co KG, Holzmühle 1, 73494 Rosenberg, Germany), the third material was cut plastic straws (CPS) and the fourth was polyethylene Raschel mesh (PERM). The process of WPC carriers' manufacture is described in detail by Kruszelnicka et al. [14]. One and a half to two-millimetre diameter cables are shredded with a length of 1–2 mm for recycling. The variety of plastics contained in the sheath is wide and may include: silicone rubber, polychloroprene (PCP), polyethylene (PE), flexible polyvinyl chloride, crosslinking polyethylene (xPE), vulcanised rubber, ethylene propylene rubber (EPR), ethylene vinyl acetate (EVA), etc. [15]. The range of shredded cables' diameter was between 0.5 and 2 mm (Fig. 3). Raschel mesh is usually made of polyethylene or polypropylene [16,17]. The strength is adequate for its applications (e.g., as a packaging for vegetables and fruit). The most commonly used drinking straws (from which cut pieces were made) are made of a thermoplastic polypropylene polymer. This material is known for its durability, lightness and ability to withstand a relatively wide temperature range without deforming.

2.3. Effective surface area

The effective surface area of cut straws and WPC and PE fittings was estimated on the basis of the sum of the outer and inner surfaces of the shaped piece or straw piece multiplied by its number per unit area (Table 1). The effective surface of the PERM was estimated assuming that

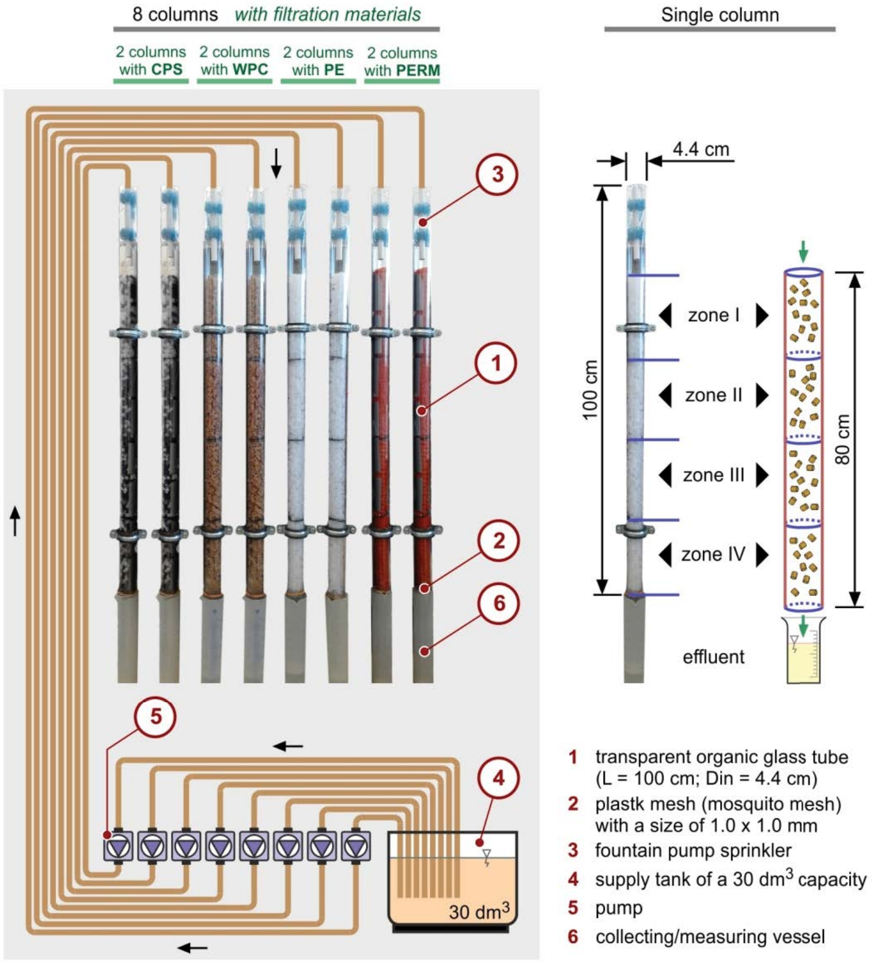

Fig. 2. Experimental set-up.

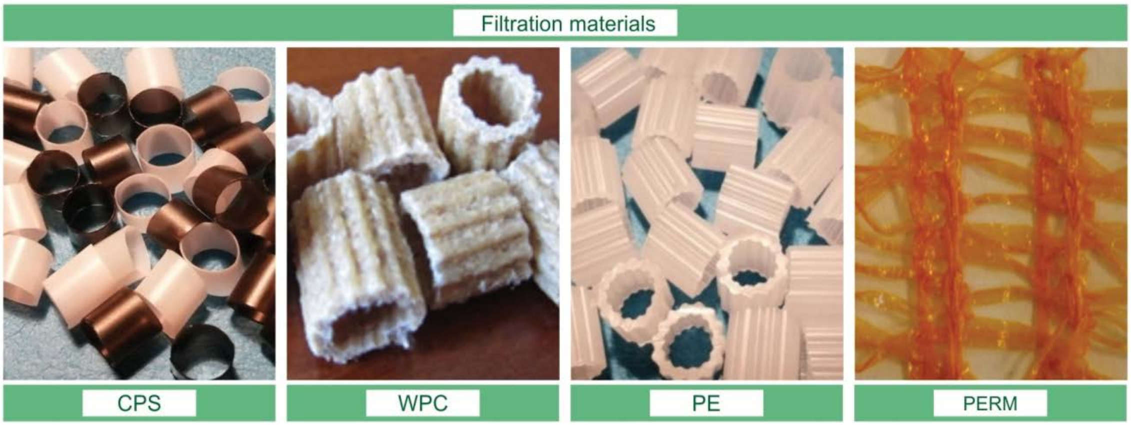

Fig. 3. Filter materials used in the study: cut plastic straws, wood-polymer composite, polyethylene and polyethylene Raschel mesh.

Table 1
Effective surface area of filter material used in the study

Filtration column material	Column depth	Number of carriers/coupons	Effective surface area (m^2/m^3)
WPC effective surface area of one peace: 7.54 cm^2	Zone 1	214	532.6 (511.0–550.7)
	Zone II	206	
	Zone III	222	
	Zone IV	217	
	Total	859	
PE effective surface area of one peace: 7.54 cm^2	Zone 1	195	488.1 (483.7–501.1)
	Zone II	195	
	Zone III	195	
	Zone IV	202	
	Total	787	
CPS effective surface area of one peace: 3.29 cm^2	Zone 1	470	559.3 (508.2–601.2)
	Zone II	538	
	Zone III	505	
	Zone IV	556	
	Total	2069	
PERM	Zone 1	1	442.5 (435.1–446.1)
	Zone II	1	
	Zone III	1	
	Zone IV	1	
	Total	4	

the mesh sheet is two-dimensional and has two regions different in terms of tape weave density (low and high-density region). The active surface was estimated on the basis of porosity (using the software ImageJ (open access) and Motic Images + 2.0 (Poznań University of Life Sciences license)), and then the estimated surface area was related to the unit volume occupied by it. The following values for the effective surface area have been estimated: for CPS: 559.3 (508.2–601.2) m^2/m^3, for WPC: 532.6 (511.0–550.7) m^2/m^3, for PE: 488.1 (483.7–501.1) m^2/m^3 and for PERM: 442.5 (435.1–446.1) m^2/m^3. The obtained values were quite high and, despite the different shapes and geometries, relatively similar. The obtained range of effective surface seems to be in the upper range of values used in structurally simple, low energy on-site wastewater treatment facilities. The higher values usually caused an increased risk of clogging and less effective oxygen availability.

Ranges and mean values are derived from two columns filled with the same material in the same amount.

2.4. Properties of septic tank effluent

The wastewater used for the tests came from an on-site wastewater treatment plant (produced by Pozplast) (Located in Rybojedzko, Wielkopolska Province, Poznań County, Stęszew Commune) consisting of a septic tank and a soil infiltration system, and was produced by a household of four.

Despite the fact that the wastewater flowing from the septic tank was collected from the same source (both in the preliminary stage and in main stage),), different values (even on average) of the quality indicators of the septic tank were obtained. The differences in septic tank effluent (STE) content could be the result of increased volume of sediments in the STE with time. After collection, the STE was transported to the laboratory and stored in a 30 dm^3 chamber at room temperature up to 7 d. The aim of such a procedure was to gain an extended retention time at increased temperature to simulate users' absence (vacation), usually at high-temperature conditions – summer season.

2.5. Research plan

The research was conducted in two stages (after the start-up period):

- The start-up period lasted six weeks; to determine the end of this stage, the following pollution indicators were measured: total suspended solids (TSS), chemical oxygen demand (COD) and five-day biochemical oxygen demand (BOD_5).
- Preliminary stage (stage 1) – for this stage a relatively high hydraulic load of 25–31 cm/d (380–470 cm^3/d per 15.2 cm^2 of inner filtering column surface area) was assumed (taking into account the literature data). The wastewater indicators TSS, COD and BOD_5 were measured; the period lasted nine weeks. Inlet wastewater samples were collected from one common reservoir at the same time. During this stage, the filtration columns were fed with a volume of about 20–25 cm^3 of wastewater every hour. The main goal of the preliminary stage was to check the removal efficiency at relatively high hydraulic load.
- After preliminary stage four columns (one column for each filter material) were dismantled with the aim of biomass investigation [13].
- The conditions for main stage (stage 2) were determined on the basis of the results obtained in the first stage – the hydraulic load was reduced by half, to the value 13.2–16.4 cm/d (approx. 200–250 cm^3/d per 15.2 cm^2 of inner filtering column surface area); the period lasted four weeks. The wastewater indicators TSS, COD, total phosphorus (P_{tot}) and ammonium nitrogen (N_{NH4}) were measured. Inlet wastewater samples for each column were collected separately. During this stage, the filtration columns were fed every 2 h (with a volume of about 20–25 cm^3).

During the preliminary stage the inlet wastewater samples for all columns were taken from supply tank. This procedure was used, because it was assumed that thanks to stirring of wastewater in supply tank, the concentrations of pollutants should be uniformed. During the main stage the columns' inlet wastewater samples were taken not from supply tank (as during preliminary stage), but from dosing tubes. It was done, because during preliminary stage several tests were made in order to check the inlet concentrations and they showed some small differences between pollutants concentration in individual outflows from dosing tubes.

2.6. Measurements of pollutant indicators

The samples of inlet and outlet wastewater (STE and treated STE) were collected and analysed usually once a week (with a few deviations, such as holidays, a holiday break). The following parameters were analysed:

- TSS – determined using the dry matter method using filtration through filter paper (4–7 µm); TSS concentrations were determined in accordance with the standard PN-EN 872 [18];
- COD – determined by the method consisting in the oxidation of organic compounds using potassium dichromate with the addition of sulfuric acid (H_2SO_4) (spectrophotometer Merck 142, Germany) and a direct reading from the spectrophotometer at 420 nm (DR/2000, Hach Lange, Wroclaw, Poland);
- BOD_5 – determined by the respirometric method using the OxiTop BOD system (WTW);
- P_{tot} and N_{NH4} – determined by spectrophotometric method. The P_{tot} and N_{NH4} concentrations were determined by a kit from Merck (Germany) and a Spectroquant kit (No. 14752), respectively.

Determination of indicators of dissolved organic and nutrient compounds (COD, BOD_5, N_{NH4}, P_{tot}) was performed using samples filtered through filter paper of 4–7 µm pore size. Analyses were carried out in accordance with the standards: COD: PN-ISO 6060 [19], P_{tot}: PN-EN ISO 6878 [20].

Outflows were measured twice or three times a week.

2.7. Statistical analysis

Student's *t*-test was used for statistical analysis to evaluate the study hypotheses. In the case of the student's *t*-test analysis, the method described by Łomnicki [21] was used; it examines whether the critical value for the significance level is higher or lower than the calculated statistics for the related pairs.

3. Results and discussion

3.1. Outflow rate

During the start-up period and stage 1 the filtration of wastewater was applied in two identical columns for each filter material, so the values obtained are the averages of several time periods for two repetitions.

The average outflow rates during the start-up period were as follows: 469 ± 27 cm^3/d ($n = 54$) for the column filled with CPS, 507 ± 29 cm^3/d ($n = 54$) for the column filled with carriers made of WPC, 510 ± 32 cm^3/d ($n = 54$) for the column filled with PERM and 549 ± 28 cm^3/d ($n = 54$) for the column filled with carriers made of PE.

The average outflow rates during preliminary stage were as follows: 393 ± 35 cm^3/d ($n = 30$) for the column filled with CPS, 419 ± 39 cm^3/d ($n = 30$) for the column filled with PE, 436 ± 36 cm^3/d ($n = 30$) for the column filled with PERM and 441 ± 38 cm^3/d ($n = 30$) for the column filled with PE.

The average outflow rates during main stage were: 209 ± 5 cm^3/d ($n = 9$) for the column filled with PERM, 254 ± 6 cm^3/d ($n = 9$) for the column filled with CPS, 258 ± 6 cm^3/d (*n* = 9) for the column filled with PE and 260 ± 5 cm^3/d (*n* = 9) for the column filled with WPC.

The effect of hydraulic load on wastewater quality indicators' removal efficiency was not analysed during the study; however, the hydraulic load was selected so that under technical conditions, it would be possible for four users (total outflow about 0.4 m^3/d) to use a trickling filter of a surface area not exceeding 2–3 m^2 in top view. It was assumed that the reactor should be as compact as possible to be installed in a room, for example, in a basement (in this case two filter sections of 1 m^2 would have to be placed under each other). The used hydraulic load of filters was relatively low (compared to conventional wastewater trickling filters), but quite substantial compared to sand or gravel filter beds.

3.2. Start-up period

TSS concentrations in STE supplied to test filters during start-up, apart from the last measurement (less than 200 mg/L), were not very diverse (from 422 to 538 mg/L; 440.6 mg/L on average) – as for the outflow from a septic tank serving a single household with a relatively small number of inhabitants (3–6). The efficiency of TSS removal increased at this stage from about 10% to over 50% (except for the WPC polymer, for which the efficiency for this indicator was about 20%–30%). In the case of plastic straws, there was a significant increase (from 20%–30% to 50%–70%) only at the last measurement.

COD values in the STE supplied to the test filters during the start-up period were highly diverse (from 359 to 591 mg·O_2/L). COD removal efficiency increased at this stage from less than 10% to about 30% (except for the Raschel mesh, for which the effectiveness for this indicator was over 40% – which was a consistent trend – the last five of all seven measurements).

BOD_5 in the STE supplied to the test filters during the start-up period was, similarly to COD, significantly variable (from almost 120 to 200 mg·O_2/L). BOD_5 removal efficiency increased at this stage from low and very unstable for the first two measurements to relatively high (57%–86%) for the last measurement in this stage. The Raschel mesh showed a significantly higher average BOD_5 removal efficiency at this stage.

3.3. Preliminary stage

TSS concentrations in STE supplied to test filters during this stage, apart from two measurement at the beginning (over 600 mg/L), were relatively uniform (from above 200 to above 300 mg/L). The efficiencies of TSS removal at this stage were highly heterogeneous – from negative values to about 60%–80%. It is worth to note that in general the TSS removal efficiencies decreased with run of the preliminary stage period.

At this stage, the Raschel mesh shows the highest efficiency in TSS removal (42.4%). In turn, the material through which most solid impurities (TSS) passed, turned out to be: polyethylene (–19.6% of removal efficiency on average) as well as cut straws (–0.8% of removal efficiency on average). WPC showed low and unsatisfactory removal efficiency (17%), however better than PE and CPS.

COD in the STE supplied to the test filters during preliminary stage was relatively uniform – from 430 to 1,580 mg·O_2/L (excepting measurement no. 7 – almost 1,600 mg·O_2/L). COD removal was in general between about 40% and about 70%, and on average from 50% to 70%. The most effective in COD removal was Raschel mesh (over 70% on average, only three of ten measurements were below 70%).

The BOD_5 values in the inflowing wastewater (STE) fluctuated between 120 and 980 mg·O_2/L, and their average value was 363 mg·O_2/L. Typically (except for series six and seven) the values were in the range of about 200–350 mg·O_2/L.

BOD_5 removal efficiency was relatively high (compared to COD) but not uniform (above 70% on average with the exception of Raschel mesh). The average BOD_5 removal efficiencies at this stage for straws, WPC, polyethylene and Raschel mesh were as follows: 72.3%, 77.8%, 78.7% and 60.8%, respectively.

3.4. Main stage

3.4.1. Results obtained during main stage

The results from main stage seem to be the most reliable, because for each of the filtration columns the inlet wastewater was collected separately (not mixed as during the previous stages).

3.4.2. Total suspended solids

Despite the high variability of TSS concentrations in the incoming wastewater (120–527 mg/L), the efficiency of TSS removal was quite stable (excluding the last series – all results over 70%) in the second stage of the study (Fig. 4). All the tested materials' efficiencies were higher than 80% on average and almost equal (for straws, WPC, polyethylene and Raschel mesh they were as follows: 84.7%, 85.2%, 85.3% and 83.6%, respectively).

3.4.3. Chemical oxygen demand

COD values in inflowing wastewater varied between 276 and 386 mg·O_2/L, while the average value was 327 mg·O_2/L (Fig. 5).

The removal efficiencies were much more diverse compared to the inlet values. The Raschel mesh turned out to be the most effective (84.6%) compared to the other materials.

The average COD removal efficiencies at this stage for straws, WPC and polyethylene were as follows: 58.8%, 60.2% and 46.9%, respectively.

3.4.4. Total phosphorus

P_{tot} concentrations in inflowing wastewater were relatively stable – they varied between 20.3 and 28.5 mg·P_{tot}/L, while the average value was 24.7 mg·P_{tot}/L (Fig. 6).

The Raschel mesh turned out again to be the most effective (53.16%) material. The average P_{tot} removal efficiencies at this stage for straws, WPC and polyethylene were as follows: 43.1%, 44.1% and 43.7%, respectively.

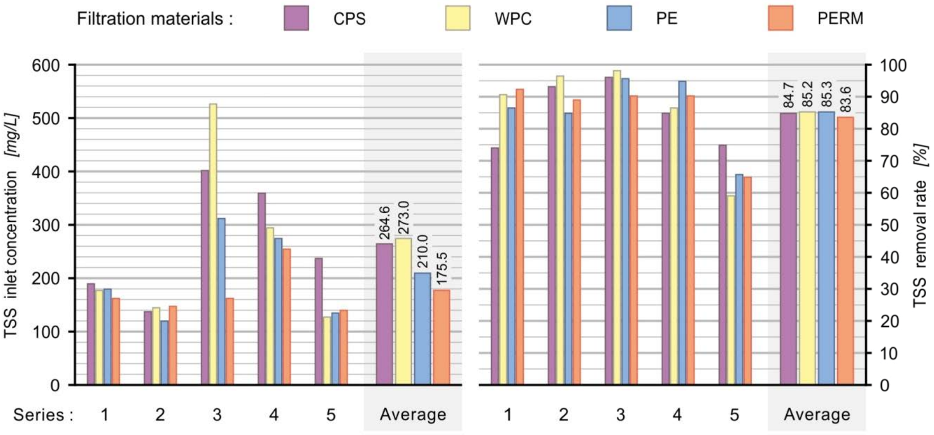

Fig. 4. Total suspended solids inlet concentration and removal rate during main stage.

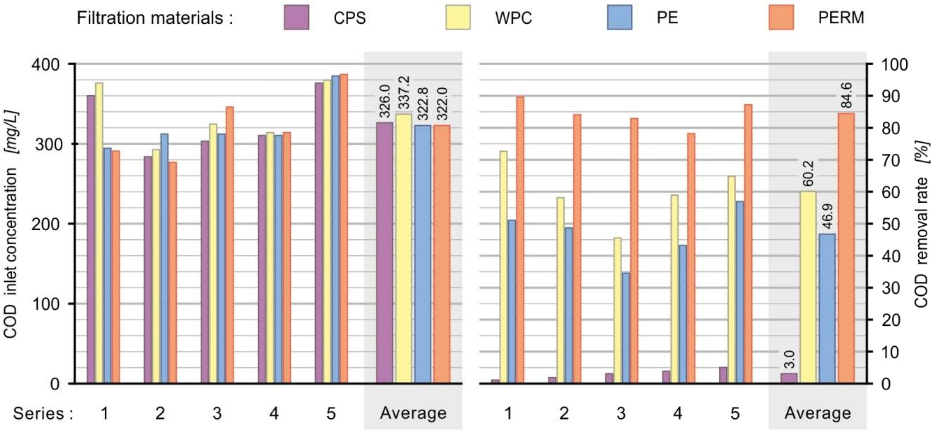

Fig. 5. Chemical oxygen demand inlet concentration and removal rate during main stage.

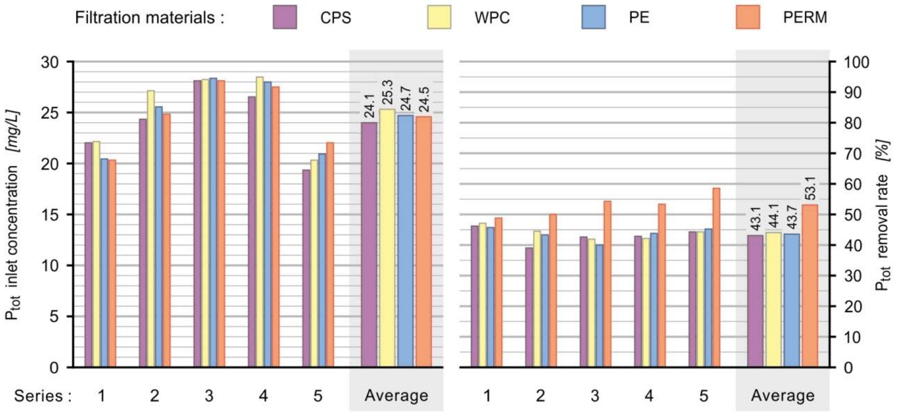

Fig. 6. P_{tot} inlet concentration and removal rate during main stage.

3.4.5. Ammonium nitrogen

N_{NH4} concentrations in inflowing wastewater varied between 69 and 126 mg·N_{NH4}/L, while the average value was 103 mg·N_{NH4}/L (Fig. 7). This range is rather common for domestic wastewater and septic tank effluent. The average values for all the filters were very similar – between 100 and 105 mg·N_{NH4}/L.

The removal efficiencies were highly variable. The Raschel mesh turned out to be the most effective – over 92%. The rest of the filter materials were much less effective (30%–52%).

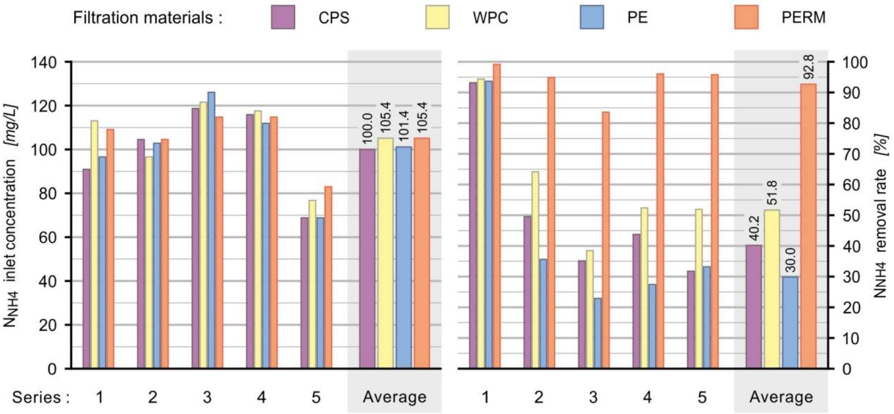

Fig. 7. N_{NH4} inlet concentration and removal rate during main stage.

3.5. Discussion of the results obtained during main stage

The study performed by Dąbrowski and Karolinczak [22] indicated that, the comparable to this study (for PERM only) COD removal efficiencies (80%) can be obtained for sewage from craft brewery at flow rate 30 cm/d. The removal efficiency of N_{NH4} (88%) was also similar to the results achieved during this study, however for PERM material only (92.8%) as well as in case of N_{NH4} – 34% removal in the Dąbrowski and Karolinczak [22] studies and 43.1%–53.1% in this experiment.

The inlet wastewater concentrations in Dąbrowski and Karolinczak [22] studies were quite different comparing to this study: COD – 1,891 mg/L on average (327 mg·O_2/L in this study), N_{NH4} – 2.8 mg/L (103 mg·N_{NH4}/L in this study) on average and P_{tot} – 17.2 mg/L on average (24.7 mg·P_{tot}/L in this study).

The studies were conducted by these authors at much higher hydraulic loads treated as averaged over a day (10.4 m^3/d), but considering the discharge over a single dose the loads in these authors' studies were comparable or even lower than their own. The uniformity of flow over time and space is so far not well recognized, requires further research, and was beyond the scope of this study. In the study by Kanwar et al. [7] operational time was 15 weeks.

The results obtained by Kanwar et al. [7] were comparable to the results of the studies presented in this article: for COD 87% and 79% (46.9%–84.6% in this study), for TSS 92 and 86% (83.6%–85.3% in this study), for N_{NH4} 38% and 32% (43.1%–53.1% in this study).

At the flow rate 30.6–76.4 m/d these authors achieved the removal efficiency comparable to this study and similar for both tested height of the filter media (40 and 80 cm): for TSS – from 82% to 90%, for BOD_5 – from 91% to 92%.

The COD inlet wastewater concentrations in Hamidi et al. [23] studies were comparable to this study – 289 mg·O_2/L on average (327 mg·O_2/L in this study).

The results obtained by Żyłka et al. [24] were comparable to the results of these studies: for COD 78.3% and 85.5% (46.9%–84.6% in this study), for N_{NH4} 78.4% and 88.8% (30.0%–92.8% in this study), for P_{tot} 28.0% and 42.0% (43.1%–53.1% in this study). The inlet wastewater concentrations in Żyłka et al. [24] studies were quite different comparing to this study: COD – 782 mg/L on average (327 mg·O_2/L in this study), N_{NH4} – 6.9 mg/L (103 mg·N_{NH4}/L in this study) on average and P_{tot} – 2.3 mg/L on average (24.7 mg·P_{tot}/L in this study).

Pearce [25] obtained lower (comparing to PERM – in this study) efficiencies of trickling filters used for upgrading low technology wastewater treatment plants (according to nitrogen removal) – total nitrogen removal efficiency was up to 50% (up to 63% – calculated for trickling filters followed primary treatment).

Obtained P_{tot} removal efficiencies were rather typical for simple conventional trickling filters treating domestic wastewater. However, after a longer time (several years) the efficiency is expected to decrease due to the reduction of sorption effectiveness.

Disadvantages of the flow through the privileged routes inside the filter material are the decrease of pollutant concentrations on these paths and the decrease of the biomass content along with the depth. The key factor for the trickling filters seems to be the change in the position of the supporting carriers or the periodical changing of wastewater flow streams. Modelling simulations of BOD_5 removal efficiency [26] showed values comparable to real results (modelled – between 75% and 77%). The modelled values were almost the same as the real results of WPC and PE material treatment (78% and 79%, respectively), but slightly higher than the real efficiency of cut straws and Raschel mesh (72% and 61%, respectively). However, it should be noted that the simulation was done for an effective surface area of 300 m^2/m^3 (close to the upper limit value of the scope of applicability).

Comparable results to this study results (in case of COD and PO_4 for PERM only) were obtained by Rehman et al. [27] for trickling filter filled with plastic balls (surface area 4.5 cm^2) – after 48 h treatment: 93%, 86.25% and 57.8% for COD, TSS and PO_4, respectively. Rehman et al. [27] showed in modelling study average percentage reductions of 51%–73% and 74%–89% for COD and TSS, respectively. Aslam et al. [6] obtained comparable to this study (for PERM only) contaminants removal efficiencies (hydraulic load 9–24.2 cm/d) for trickling filter system supported by cotton sticks – 80% for COD removal efficiency (the system efficiency for COD was up to 70% after increasing the flow rate about 2.7 times,) and much lower (38%–56%) comparing to this study – removal efficiency for TSS.

Due to the removal of excess biomass from the filters the results of TSS removal efficiency are difficult to interpret.

The TSS removal efficiencies were significantly changeable during this stage, probably due to the potential excess biomass detachment. However, it is worth noting that during stage 2 they were much more unstable and much lower. Solid material in the filter effluent is often the result of biomass activity (growth and detachment). The biomass occupying filters consists not only of microorganisms but also of *Psychoda* fly larvae. These insects penetrate the biofilm by drilling holes, which can cause release of biomass particles from the filter [3]. In some technical scale conditions it would be necessary to use secondary settlers to remove excessive biomass from the effluent.

3.6. Statistical analysis for the results of main stage

Statistically confirmed differences were as follow:

- COD removal efficiency – comparison of a Raschel mesh: with cut straws (statistical value equal to 8.5, critical value equal to 2.8; df = 4), with WPC (statistical value equal to 6.7, critical value for df = 4 equal to 2.8), with PE (statistical value equal to 12.6, critical value for df = 4 equal to 2.8),
- N_{NH4} removal efficiency – comparison of a Raschel mesh: with straws (statistical value equal to 4.4, critical value: 2.8; df = 4), with WPC (statistical value equal to 4.4, critical value for df = 4 equal to 2.8), with PE (statistical value equal to 4.5, critical value for df = 4 equal to 2.8),
- N_{NH4} removal efficiency – comparison of WPC with PE (statistical value equal to 3.7, critical value: 2.8; df = 4),
- the difference for N_{NH4} removal efficiency was not confirmed statistically – comparison of WPC with straws (statistical value equal to 2.7, critical value for df = 4 equal to 2.8).

4. Conclusions and recommendations

Contrary to the apparently low values of the pollutant removal efficiency, they should be considered satisfactory and theoretically justified due to the relatively low filter height of 0.8 m [27].

The research showed that the expected efficiency of pollutants' removal by trickling filters may significantly differ from the actual (on a laboratory or technical scale) results. One reason (which is highly probable in the case of small, individual wastewater treatment systems) may be, as shown in this study, uneven wastewater load on the filter plan surface and inside the volume of the filter material. Thus a smaller part of the carriers' share in the treatment process and filter material coverage by the biomass is reduced (greater load of biomass with the load of pollutants).

High efficiency of TSS removal (over 80%) was observed in main stage for all tested materials. It is particularly important for the practical application of secondary treatment of STE. Relatively high and unstable concentrations of TSS in STE often cause clogging of infiltration systems or sand filters.

Relatively high effectiveness was demonstrated by the Raschel mesh. However, this material is characterised by a smaller active surface area than the other materials tested. It may indicate other important properties, such as the influence on the uniformity of the flow and relatively low number of "inactive" zones, for example, internal surfaces in the case of cylindrical carriers (WPC, PE, cut straws).

There is a need for further studies in terms of determinants and structures ensuring uniform loading of the filter surface and volume with wastewater, as well as regarding the search for new (or even better – waste) materials, not previously applied for this purpose. Such materials should show an effective inlet media (septic tank effluent or raw wastewater) distribution on the filter surface and consequently in the filter filling volume and optimal flow properties with effective oxygen access.

Due to the relatively low hydraulic load of the filter surface (view from the top), the required filter surface area for one family (four persons) is between 2.4 and 3.4 m^2. It is possible to locate the filters on two levels (one above the other); then the required surface area in the plan view will be reduced by half.

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