The performance of peat-filled subsurface flow filters treating landfill leachate and municipal wastewater

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ARTICLE INFO

Article history:
Received 9 December 2007
Received in revised form 2 April 2008
Accepted 8 April 2008

Keywords:
BOD
COD
Hydrated oil-shale ash
Mineralized peat
Nitrogen
Phosphorus

ABSTRACT

The main objective of this study was to determine the treatment capacity of well-mineralized peat in vertical and horizontal flow filters designed to reduce phosphorus, nitrogen and organic matter in municipal wastewater from the town of Tapa and landfill leachate in Väätsa, Estonia. Two identically designed onsite experiments were conducted using the following filter systems: (a) a vertical flow (VF) peat filter, (b) a vertical flow peat/ash sediment filter (both materials in equal volumes) followed by a horizontal flow (HF) peat filter. Sphagnum peat and hydrated oil-shale ash (ash sediment) was used. In our experiments, one treated municipal wastewater over 6 months and another treated landfill leachate over 12 months. In both cases, effluent from a conventional treatment (aerated activated sludge treatment) plant was used. The median value of total phosphorus (TP) concentration in Väätsa landfill leachate was 3.4 mg P L$^{-1}$ and in municipal wastewater from Tapa 4.9 mg P L$^{-1}$. The reduction of TP in VF peat filters during the first 6 months was 58% and 63%, and in peat/ash sediment filters 94% and 67% for the Tapa experiment and the Väätsa experiment, respectively. Both experiments demonstrated that the P-removal efficiency in VF peat filters begins to decrease after 6 months of operation. The purification efficiency in HF filters fluctuated, and no significant removal of TP was found. In the removal of organic matter (BOD, COD values) and nitrogen, the best results were obtained in VF peat filters.

1. Introduction

Subsurface flow constructed wetlands (SSF CW) are used for the secondary treatment of wastewater and can effectively remove both organic material (expressed as biological oxygen demand, BOD) and total suspended solids (TSS) from wastewater, although nitrogen (N) and phosphorus (P) removal is known to be somewhat problematic (Cooper, 1999; Brix et al., 2001). The considerable advantage of CWs and SSF filters over conventional treatment methods is based on the favorable characteristics of the filter material—its large adsorbing surface area, typically long retention time, flexibility in alternating aerobic-anaerobic zones, and diverse microbiological populations (Mæhlum, 1999). Different contaminants are removed from water through various chemical, physical and biological processes, and particularly through
demonstrated that peat in CWs and SSF filters can effectively
chosen because several laboratory and field experiments have
waste components other than P, the ash filters were com-
(Väetsa location). Due to the limitations of ash-filter towards
municipal wastewater (Tapa location) and landfill leachate
ties of hydrated oil-shale ash sediment for P-removal from
iment. In 2006, pilot-scale experimental filter systems were
a laboratory batch experiment and in a small-scale field exper-
condition was studied because it is supposed to have a longer
time. Moreover, the peat filters are designed mostly as vertical
experiment on purification efficiency and peat filter life-
capacity of the peat and studied the effect of the duration of
forms, TSS and pH were monitored. We analyzed the removal
effect and overall improvement of water quality.

Recently, Vohla et al. (2005) and Kaasik et al. (2008) did show
the P-removal potential of hydrated oil-shale ash materials in
a laboratory batch experiment and in a small-scale field exper-
iment. In 2006, pilot-scale experimental filter systems were
installed at two sites in Estonia to explore the filter proper-
ties of hydrated oil-shale ash sediment for P-removal from
municipal wastewater (Tapa location) and landfill leachate
(Väetsa location). Due to the limitations of ash-filter towards
waste components other than P, the ash filters were com-
bined with peat filter elements. The peat filter material was
chosen because several laboratory and field experiments have
demonstrated that peat in CWs and SSF filters can effectively
reduce nitrogen concentration, remove suspended solids and
pathogenic bacteria (White et al., 1995), mineralize organic
material, and also retain phosphorus (James et al., 1992) and
heavy metals (Brown et al., 2000). Most peat filters are designed
for the treatment of domestic wastewater (Gunes and Ayaz,
1998), although several systems have also shown excellent
performance in the treatment of landfill leachate (Kadlec,
2003). Importantly, the peat filter would decrease the pH of
the leachate from the ash-filter system. Earlier small-scaled
studies with VF well-mineralized peat filters have shown
remarkable purification of landfill leachate—removal of BOD7
up to 95%, removal of NH4-N up to 93% and removal of P up to
81% (Köiv et al., 2006).

In this contribution we report the performance of peat
filter systems in an experimental combined ash–peat filter
setup. The P-removal capacity and dynamics of ash sedi-
ment filters will be discussed elsewhere. The main objective
of this study was to determine the treatment capacity of
vertical and horizontal flow well-mineralized peat filters in
order to reduce phosphorus concentrations in leachate and
in municipal wastewater. In addition to P, other parameters
such as organic material (COD, BOD5), nitrogen in different
forms, TSS and pH were monitored. We analyzed the removal
capacity of the peat and studied the effect of the duration of
the experiment on purification efficiency and peat filter life-
time. Moreover, the peat filters are designed mostly as vertical
flow systems, and no data is available about horizontal flow
peat-filled systems. In addition, the HF filter with saturated
conditions was studied because it is supposed to have a longer
retention time and therefore better purification efficiency. In
HF filters the anaerobic conditions dominate, which replicates
peat conditions in natural wetlands (Kadlec and Knight, 1996).

2. Materials and methods

Identical pilot-scale experiments were conducted in parallel
at two sites: at the municipal wastewater treatment plant in
the small town of Tapa and at Väetsa landfill in Estonia. Small,
insulated houses were built for both experiments in order to
avoid the freezing of filters during the winter period. The Tapa
experiment lasted from September 2006 to March 2007, with
an average indoor air temperature of 9 °C. The Väetsa experi-
ment took place from September 2006 to September 2007,
with average indoor temperature of 7.6 °C in the period from
September to March and 14.7 °C from April to September.

2.1. Site description

The Väetsa landfill has been in operation since 2000. Approx-
mately 10–20 m3 of leachate is produced per day and treated in
a conventional biological treatment system, consisting of an
activated sludge treatment plant and an aerobic–anoxic pond.
The purification efficiency of the system is quite high; how-
ever, the treatment efficiency does not meet the limit values
(RT 1 2003.83.565) for COD, TN and TP, with median outflow
values of 825, 180 and 3.4 mg L−1, respectively.

Tapa wastewater treatment plant was established in 1996
for the treatment of the municipal wastewater from Tapa town
and the nearby food industry enterprises. The Tapa treatment
method is also a conventional biological treatment, and the
system has an activated sludge plant. The purification effi-
ciency of the Tapa system has been quite sufficient for all of
the required parameters, except for phosphorus, which had a
median outflow value of 4.9 mg L−1.

2.2. Filter materials

Well-mineralized Sphagnum peat (saprist peat, H7–H8 accord-
ing to the von Post scale; Puustjarvi and Robertson, 1975) was
used in both experiments. Peat was obtained from the lower
deposits of depleted industrial peat land, as described by Käär
et al. (2006). The average composition of peat is: 53–59% C,
5.2–6.4% H, 29.0–34.5% O2, 1.2–2.8% N, and smaller amounts
of other elements (e.g. S 0.1–0.3%). Compared to mineral soils,
peat has a high organic matter content and large surface area
(more then 200 m2/g) and is highly porous (80–90%; Brown
et al., 2000).

The peat was used in combination with Estonian oil-shale
ash sediment, which was brought from an industrial ash dis-
posal area at the Baltic Thermal Power Plant in North-East
Estonia. Oil-shale ash sediment is highly calcareous material
left after the burning of kerogenous oil-shale at Estonian ther-
mal power plants. The oil-shale is a solid fuel of low energetic
value with average calcite and dolomite content of 40–60% of
the mineral matter. The ash remaining after burning has a
high content of various secondary Ca-phases (Kaasik et al.,
2008). In our experiments, the hydrated ash was prepared by
crushing and coarse sieving into fractions of 5–20 mm. The
chemical composition of oil-shale ash sediment is dominated by Ca, whose content in CaO form is on average 29.22%, Al₂O₃ content is 6.25%, SiO₂ 25.96%, Fe₂O₃, MgO and K₂O content is 3.56, 3.42 and 2.97%, respectively.

2.3. Experimental design

In both experiments, the identical vertical flow (VF) peat filters (VV1 in Väätsa and TV1 in Tapa) and the sequential systems, which consisted of VF peat/ash sediment filters (VV3 and TV3) and horizontal flow (HF) peat filters (VH3 and TH3), were used (Fig. 1). The VF filters had a volume of 0.86 m³, and HF filters 1.24 m³. Both the VF filters (D = 1000 mm, h = 1.5 m) and the HF filters (D = 1200 mm, h = 1.5 m) were made of PVC pipe. Filters were filled with a 1.1 m thick layer of material. In combined VF filters, a 0.55 m thick layer of crushed oil-shale ash sediment was placed at the bottom of the filter, and was then covered by a 0.55 m thick peat layer above.

The filter systems were periodically loaded using timer adjusted pumping every 2 h, i.e. 12 times per day. The water amount in one dose was ~5 L. The loading rate was 76 mm d⁻¹ for VF filters, and 53 mm d⁻¹ for HF filters. The average flow rate for all filters was 60 L d⁻¹.

For the uniform distribution of inflow water over the whole surface of VF filters, water flow was distributed through percolated hosepipes and a washed granite glitter layer. In HF filters, the granite glitter layer was placed around the inflow and outflow zones. To provide maximal saturation and good contact between filter media and wastewater, the inflow water was pumped from the collecting well to the horizontal filter at the bottom, and an outflow pipe (percolated from the top) collected the water in the upper part of the filter (Fig. 1).

2.4. Sampling and analytical methods

The water samples from the inflow and outflow of the filters were taken once a week during the whole period of the operation, using standard procedures (ISO 5667–10:1992). In both experiments, BOD₇, COD, total nitrogen (TN), NH₄-N, NO₃-N, NO₂-N, total phosphorus (TP), PO₄³⁻ and pH were determined in a certified Tartu Environmental Research Ltd. laboratory using standard methods (APHA, 1989).

The normality of variables was checked using the Lilliefors and Shapiro–Wilk tests; for normally distributed variables the inflow and outflow values in different peat filters and efficiency of different filter materials were compared via the pairwise t-test. When the distributions were skewed, the non-parametric Wilcoxon pairwise test was used. The STATISTICA 7.0 software was used, and the level of significance of α = 0.05 was accepted in all cases. In following text, numeric values of wastewater parameters and purification efficiency are median values, unless otherwise specified.

3. Results

The composition of inflow water at both sites is shown in Table 1. It is evident that the composition of inflowing water at both sites, the landfill leachate and municipal wastewater, both treated in conventional systems, had significantly different composition. The wastewater treatment system of Tapa town generally has a good purification efficiency, and problems only occur in the removal of TP, which has a considerably higher variability (Fig. 2). In the Väätsa landfill, the inflow quality is quite stable (Fig. 2), but the treatment plant is unable to reduce the water quality to limit values (Table 1). The main problems in leachate at Väätsa are related to very high COD values and nutrient concentrations.

| Table 1 – Median inflow values of the variables (mg L⁻¹) in the Väätsa and Tapa treatment systems and limit values from the Estonian regulations (RT I 2003.83.565) |
|-----------------|--------|--------|--------|--------|--------|--------|
| Estonian regulations | Landfill leachate | 25 | 125 | 2.0 | 75 | 25 | 6–9 |
| Väätsa leachate | 1–6 months | 12.3 | 526 | 2.9 | 142.7 | 54 | 8.8 |
| 7–12 months | 25.4 | 1050 | 4.1 | 214.8 | 75 | 8.7 |
| Estonian regulations | Wastewater | 15 | 125 | 1.0 | 15 | 15 | 6–9 |
| Tapa wastewater | 1–6 months | 1.9 | <50 | 4.7 | 12.7 | 7.0 | 7.8 |
Fig. 2 – The removal of total phosphorus (TP) in the Väätsa (A) and Tapa (B) experiments. All outflow values are significantly different from inflows \((p < 0.001, \text{according to pairwise } t\text{-tests and the Wilcoxon pairwise test})\). The explanation of filters (VV1, VV3, VH3 and TV1, TV3, TH3) is described in Section 2.

If at the Väätsa landfill the leachate had relatively stable total phosphorus (TP) concentration varying between 2.5 and 5.2 mg L\(^{-1}\), at Tapa treatment plant the TP content in the inflow varied between 0.14 and 13.0 mg L\(^{-1}\) and had higher TP loading on filters (Fig. 2). Most of the inflow P in both sites was in the form of PO\(_4\)-P. Despite the significantly different phosphorus loadings and dynamics, we found that the reduction of TP in VF peat filters (VV1 and TV1) during the first 6 months was quite good. However, the Väätsa VV1 VF filter, with its lower and more stable inflow concentrations, did show a much higher reduction (median value 67%), whereas the TV1 VF peat filter at the Tapa site, which operated under variable phosphorus concentrations, resulted in 58% removal. However, the combined VF peat/ash sediment filters (VV3 and TV3) at both sites did show efficient TP removal, namely 67% and 94%, respectively, for the Väätsa and Tapa experiments (Fig. 2).

In HF peat filters VH3 and TH3 (respectively, the inflow from VV3 and TV3), the outflow TP concentration shows quite a great variation (Fig. 2), and the removal efficiency was very unstable. We must also note that in some cases the HF peat filters increased TP concentrations in the outflow—releasing the phosphorus back to water.

The dynamics of TP removal suggest that at given experimental conditions the TP removal capacity of peat in VF filters (VV1, TV1) gradually decreases over the first 6–7 months of operation. This is well demonstrated in the Väätsa experiment, where the decrease in removal efficiency shows a trend close to power law (Fig. 2). The same is evident in the Tapa experiment (Fig. 2), where the higher contamination rate and varying loading caused an even faster decrease in removal capacity, and the filter had lost its P-binding capacity in 5 months. Moreover, the data from the longer experiment (Väätsa landfill) show some P mobilization after saturation is achieved.

In contrast, the TP removal efficiency of combined VF peat/ash sediment filters is more stable over the experiment period (Fig. 2). In both sites the peat and peat/ash filters show similar efficiency at the beginning of the experiment. However,
whereas the peat filters exponentially exhaust their binding capacity after the initial phase, the combined filters show a rather gradual (linear) change.

Phosphorus removal in the HF peat filters that were installed after the combined peat/ash VF filters is more complex (Fig. 2). In both cases the phosphorus was not removed during the initial stages of operation at low TP concentrations in the inflow from the VF filters, and at least at the Tapa site, the mobilization of P was observed. However, the filters did show good binding capacity (up to 90%) after 5–6 months of operation, when the concentration of TP in inflow increased due to the failure of VF filters. In the Väätsa experiment, the removal efficiency of TP also increased during the 7–12 month period of operation, when the efficiency was 32% compared to the earlier period, when the efficiency was only 11%. The experimental results suggest that in saturated HF filters, phosphorus removal was initiated only if the TP in the inflow was above 1.5 mg L\(^{-1}\).

The removal of heavily decomposable organic matter (COD) is one of the greatest problems in leachate purification (Table 1 and Fig. 3) and in our experiments we also failed to observe any significant removal of COD. The reduction of COD was <10%, and only in the combined peat/ash VF filter at Väätsa (VV3) was the efficiency on the order of 17%. It should be noted that the COD in the inflow at Väätsa landfill reached 1200 mg L\(^{-1}\), which is an order of magnitude higher that that allowed by the regulations (Table 1). In the Tapa wastewater treatment plant, the COD was <50 mg L\(^{-1}\), which is well below the regulation limit (125 mg L\(^{-1}\)).

BOD removal, however, was quite efficient in the Väätsa experiment, where the inflow BOD value met the environmental requirements, but the VF filters nevertheless had good removal efficiency (75% in VV1 and 64% in VV3). In the Tapa experiment, the median BOD values of the inflow wastewater were also far below the limit value (Table 1), but no significant removal occurred in peat filters; only 17% removal of BOD was found in TV1 and 29% removal in TV3 (Fig. 3).

At both sites, the conditions in HF peat filters (VH3 and TH3) were not suitable for the removal of organics, and probably due to the saturated and anaerobic conditions, we observed an increase in BOD and COD values in outflows (Fig. 3).

The pH variation at the outflow of each filter shows (Fig. 4) a clear dependence on filter material properties. If the pH of the inflow was quite constant at both sites, i.e. 8.7 and 7.7 for the Väätsa landfill leachate and Tapa wastewater, respectively, then in the VF peat filters the pH decreased to 7.5 in VV1 and 7.3 in TV1. The pH of water from combined peat/ash filters, on the contrary, increased to 8.6 in VV3 and 10.9 in TV3, due to the dissolution of Ca-phases (portlandite and ettringite) present in the ash material (the pH of water in contact with ash material is >12). However, both combined filters show a decrease in pH from an initial ~12–8.4 in Väätsa, which has a longer experiment length, and to 10.8 in Tapa, which has a shorter experiment period. The high pH from combined VF filters was significantly decreased, to a tolerable pH 7–9, by subsequent HF peat filters (Fig. 4).

Similar to the low BOD, the TSS concentration in the Tapa wastewater was also low (6 mg L\(^{-1}\); Fig. 3c) and meets environmental requirements. Nevertheless, the TV1 filter was able to further decrease this value by 33.3%. In peat/ash sediment filters (TV3), however, the hydrated ash caused an increase in the TSS concentration in outflow water during the first 4 months, probably because of the outwash of the small ash particles, which also caused higher pH values in the outflow from filter TV3 (Fig. 4). When the outwash decreased and finally
stopped, the TV3 also showed good removal of TSS (60%). In Väätsa leachate, the TSS concentration was considerably higher—61.5 mg L$^{-1}$. Both vertical flow filters VV1 and VV3 had good removal efficiency—60%—and the outflow values met the environmental requirements (25 mg L$^{-1}$, RT 1 2003.83.565). At the same time, HF filter TH3 had a negative effect on TSS concentration, and the outflow from TH3 was 19.0 mg L$^{-1}$. The outflow TSS concentration of the VH3 was 24.5 mg L$^{-1}$, but there were also peaks (max 76 mg L$^{-1}$).

Nitrogen forms and their removal efficiency in the studied filter systems show some seasonal dependency (Figs. 5 and 6). In the Väätsa experiment, most of the nitrogen in inflow leachate was in the form of nitrate-nitrogen (125 mg NO$_3$-N L$^{-1}$ and 9 mg N$_{org}$ L$^{-1}$) during the autumn–winter and summer period (Fig. 5). However, a rapid increase in organic nitrogen (N$_{org}$) occurred during the spring period, when nitrate decreased to 9 mg NO$_3$-N L$^{-1}$ and organic fraction increased to 176 mg N$_{org}$ L$^{-1}$. In the Tapa experiment, most of the nitrogen in inflow was in the form of NO$_3$-N (TN 12.0 mg L$^{-1}$ and NO$_3$-N 9.0 mg L$^{-1}$; Fig. 6). However, the last measurement on the 6th of March, before the Tapa experiment was finished, indicates that the share of organic nitrogen has considerably increased (27.2 mg N$_{org}$ L$^{-1}$) whereas nitrate decreased (2.8 mg L$^{-1}$), suggesting the same seasonal variability as in Väätsa (Fig. 5).

The median concentration of different forms of nitrogen of the inflow and outflow at both sites is shown in Table 2. The behavior of the Väätsa and Tapa filters in the area of nitrogen removal differs significantly. In VF filters at the Väätsa landfill, where the total nitrogen loading is more than 10 times higher than in Tapa (TN 180 and 12 mg L$^{-1}$, respectively), nitrogen removal is low (>10%). However, in Tapa the TN removal in peat filter TV1 is 78%, and in the combined filter TV3 is lower, but is still good, at 51%. Vertical flow filters VV1 and VV3 show good results in nitrification, when the rapid growth of the N$_{org}$
concentration in inflow leachate occurred (NO$_3$-N concentration in inflow decreased; Fig. 5). In the Tapa experiment, the inflow NO$_3$-N concentration was only 9 mg L$^{-1}$, but all filters showed a remarkable performance (reduction 72–92%; Table 2 and Fig. 6).

Although the NH$_4$-N concentration was low in both experiments (0.44 and 0.023 mg L$^{-1}$ at Väätä and Tapa, respectively), the VF filters were quite efficient in removing NH$_4$-N (56% in TV1, 63% in VV3 and 97% in VV1; Table 2), there was a slight increase in NH$_4$-N concentration only in filter TV3. However, HF filters at both sites did show a major (more than 1000%) increase in NH$_4$-N concentration in leachate and wastewater (Figs. 5 and 6).

4. Discussion

Earlier studies suggest that the reduction of P in mineralized peat may occur through the sorption, sedimentation and combination of complex compounds (Mann, 1990; Kadlec and Knight, 1996; Richardson et al., 1996). Alternatively, some P may be bound to the biofilm (Mann, 1990; Richardson et al., 1996), and the phosphorus can easily be transformed from organic to inorganic forms. Importantly, the phosphorus forms chemical complexes with organic and inorganic ligands, which can be adsorbed into the soil or be removed by precipitation (Mæhlum, 1998).

Phosphorus reduction in our experiments suggests that the main process that controls its removal from wastewater is related to sorption phenomena, which is evidently limited by suitable sorption sites on peat fibers, and removal efficiency falls while the sorption sites become saturated. The maximum phosphorus-binding capacity of used mineralized peat can be estimated through the integration of the removed P mass (i.e. the difference between inflow and outflow concentration at flow rate 60 L d$^{-1}$) over the period, within limits set at the beginning of the experiment (lower boundary) and the moment when the removal efficiency decreased to zero (upper boundary). For the VF peat filter at Väätä, we estimate the maximum P-binding capacity at given experimental conditions to be in the order of 81 mg kg$^{-1}$ of P for dry peat or $\sim$20 gm$^{-3}$ of P, assuming the dry density of peat to be 246 kg m$^{-3}$.

Interestingly, our results show that the phosphorus removal by HF peat filters does not occur if the P concentration is lower than $\sim$1.5 mg L$^{-1}$. The nature of this phenomenon is not clear, although this may suggest that the phosphate molecules need to be bound to complexes (the formation of larger molecular aggregates) to be adsorbed to peat surfaces. In aerobic wetland conditions, phosphorus appears in dissolved complexes together with Ca, and Mg ions in alkaline conditions, and with Fe or Al ions in soil with acidic to neutral pH (Nieminen and Jarva, 1996; Mæhlum, 1999), which can then be chemically adsorbed by peat particles.

The longer effective performance of combined peat/ash filters is directly related to an additional (or supporting) P-binding effect by ash sediment. Kaasik et al. (2008) shows that hydrated oil-shale ash is an effective filter material for P removal, and the main removal occurs through the precipitation of stable Ca-phosphate phases as a hydrated calcium phosphate Ca$_3$(PO$_4$)$_2$·nH$_2$O or as a $\beta$-form of calcium phosphate Ca$_3$(PO$_4$)$_2$. However, the ash filter is very sensitive regarding retention time, and its efficiency in VF regime with short contact time seems to be rather low compared

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<th>Table 2 – The median concentrations (mg L$^{-1}$) of different forms of nitrogen in the inflows and outflows of the filters</th>
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Significant differences between the inflow and outflow values of the contaminants in all of the filters studied (pairwise t-test and Wilcoxon pairwise test results): *$p<0.05$; **$p<0.01$; ***$p<0.001$.

$^a$ Organic N is calculated by subtracting the determined NH$_4$-N, NO$_3$-N and NO$_2$-N values from total N.
to peat material, which controlled the phosphorus removal in VF filters during the first few months of the experiment. Nevertheless, when the peat filter becomes saturated, the phosphorus precipitation in the ash material begins to dominate at lower efficiency, but for at least twice as long a period as the peat filter.

The total P removal from municipal wastewater in the Tapa experiment was more efficient than in the experiment with the Vääräsa landfill leachate, presumably because of the different water quality. The landfill leachate usually has a high concentration of recalcitrants (high COD value) and other pollutants than the municipal wastewater. Thus, the landfill leachate significantly decreases the purification efficiency of peat material. In addition, we can conclude from our experiments that efficiency is greater with higher inflow concentrations of phosphorus (Fig. 2).

Surprisingly, the nitrogen removal capacity of peat filters was not as good as expected. Only the removal of NH₄-N in both experiments show that mineralized peat can nitrify the NH₄-N even at low inflow concentrations (efficiency in VV1 97.5% and in TV1 55.6%). Analogous results were achieved in Canadian studies, where the hybrid peat filter showed during 2 years of operation efficiency of 97% (Kinsley et al., 2004), and the pilot scale peat filter efficiency of 85.3% (Hu and Gagnon, 2006). However, the drawback was evident in the HF filters of both experiments, where the NH₄-N concentration in outflow increased significantly (Figs. 5 and 6). Such behavior suggests that the anaerobic conditions in saturated filters initiated the intensive decay of the organic matter in peat, which is also evident from increased BOD and COD values in the outflows from these filters, being supported by increased organic N values.

In the Vääräsa experiment, the poor removal of TN in VF filters was probably caused by the high concentrations of possible contaminants (e.g. high COD value and NO₂-N concentration) that may inhibit microbiological processes. Also, aerobic conditions that support the nitrification are not suitable for denitrification. On the contrary, in the Tapa experiment the contamination rate (inflow TN concentration not suitable for denitrification. On the contrary, in the Tapa experiment the contamination rate (inflow TN concentration not suitable for denitrification. On the contrary, in the Tapa experiment the contamination rate (inflow TN concentration 12 mg L⁻¹) was low and the overall removal of TN was satisfactory (78.5% in TV1).

Similar to Kinsley et al. (2004), most of the organic matter was removed from landfill leachate in VF peat filters, where reduction of BOD was the most efficient in the VF peat filter VV1 with 75% of reduction and in peat/ash sediment filter VV3 with 64% of reduction. This shows that the VF filters had a good O₂ supply and favorable temperatures for formation of necessary microbiological communities. The study by Talbot et al. (1996) demonstrated good results in removal of organic matter from municipal wastewater (BOD removal 96%), but in the Tapa experiment, however, the BOD value in the inflow to the pilot experimental filters was already very low and no significant changes were observed. On the other hand, the removal of suspended solids (TSS) in our filter systems was considerably less efficient (33% in TV1 and 60% in VV1, for an example) than reported in other studies of similar peat filters (91–98% according to Talbot et al., 1996). The observed discrepancy is most probably due to differences in (a) quality of inflowing water and (b) peat materials used in experiments—their botanical composition and most importantly the humification degree as far as well-humified peat beds (as used in this experiment) would release its fine partially decomposed particles and can reduce the overall purification efficiency.

The HF peat filters did not show significant removal of TP and different forms of nitrogen, and the peat even increased the content of COD, BOD₂, and the concentration of TSS. Therefore, the use of well-mineralized peat in saturated conditions is not recommended.

5. Conclusions
Our experiments show that well-mineralized peat is a suitable material for vertical flow filters, and has poor efficiency in saturated horizontal flow filters. Well-mineralized peat in vertical flow filters maintains a good P-removal efficiency for a 6-month period, and the estimated maximum P-binding capacity at given experimental conditions is 81 mg kg⁻¹ of P for dry peat. The main removal processes of phosphorus in peat are probably adsorption on the particles of the material and precipitation. The high and stable phosphorus-binding potential of hydrated oil-shale ash (up to 65 g P kg⁻¹) is considered to be due to the high ratio of reactive calcium minerals, whereas the main removal process in oil-shale ash sediment is Ca-phosphate precipitation.

The best results in the mineralization of organic matter (BOD, COD values) and nitrogen removal were obtained in VF peat filters.

The use of well-mineralized peat in HF filters with saturated conditions is not recommended, although further study with different types of peat is necessary.

Acknowledgements
Financial support was provided by Enterprise Estonia research and development project No. EU23687 and Target Funding Project No. SF180127s08 of the Ministry of Education and Science of Estonia. Ph.D. students and scientists from the University of Tartu and colleagues from the Estonian University of Life Sciences, as well as staff from Vääräsa landfill and Tapa Vesi Ltd., are acknowledged for their field assistance.

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