

# Phosphorus removal from greywater in an experimental hybrid compact filter system

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## Abstract

The aim of this paper is to analyse phosphorus (P) removal from greywater in an experimental hybrid compact filter system. The potential of a large number of substrates for the removal of phosphorus in greywater has been reviewed. These substrates mainly consist of natural materials, industrial by-products and man-made products. In this study we analyzed the potential effectiveness of P removal in different filter materials such as industrial by-products (hydrated calcareous oil-shale ash from Estonian thermal power plants) and man-made products (Filtralite<sup>®</sup> and Filtralite-P<sup>®</sup>). Household greywater consists of wastewater from kitchens, showers and laundry facilities. The reduction of total P in the ash filter system was up to 95%, achieving a median effluent concentration of 0.56 mg L<sup>-1</sup> (median concentration in inflow was 5.1 mg L<sup>-1</sup>), compared to the respective figures of 40–44% and 2.8–3.3 mg P L<sup>-1</sup> for Filtralite<sup>®</sup> systems.

*Keywords: constructed wetland, Filtralite, oil-shale ash, phosphorus sorption, subsurface flow filters.*

## 1 Introduction

Greywater is defined as water that is slightly contaminated by human activities and may possibly be reused after suitable treatment [1]. Greywater usually



includes water from baths, showers, hand basins, washing machines, dishwashers and kitchen sinks but exclude blackwater from toilets [2, 3]. Greywater constitutes 50–80% of the total household wastewater [2–4]. It is well known that greywater is less contaminated than blackwater, so purification is much faster, and purified greywater usually has several useful fields of application, such as toilet flushing, garden/crop watering, irrigation, groundwater volume enlargement etc [1, 5–7].

Constructed wetlands (CW), especially subsurface flow (SSF) filters, are well suited to greywater treatment [8, 9], although further research is required due to the great variation in greywater loading rates and characteristics [3] (Table 1). Greywater composition varies greatly with lifestyle: family size, the age of the residents, eating habits, washing habits, detergents used etc [10]. One option is to design a compact filter system that involves the separate treatment of greywater in a combined filter system, and high loading rates must also be applied.

Table 1: The characteristics of greywater by different categories [3].

	Bathroom	Laundry	Kitchen	Mixed
pH	6.4 – 8.1	7.1 – 10	5.9 – 7.4	6.3 – 8.1
TSS (mg L <sup>-1</sup> )	7 – 505	68 – 465	134 – 1300	25 – 183
COD (mg L <sup>-1</sup> )	100 – 633	231 – 2950	26 – 2050	100 – 700
BOD (mg L <sup>-1</sup> )	50 – 300	48 – 472	536 – 1460	47 – 466
TN (mg L <sup>-1</sup> )	3.6 – 19.4	1.1 – 40.3	11.4 – 74	1.7 – 34.3
TP (mg L <sup>-1</sup> )	0.11 - >48.8	0 - >171	2.9 – 74	0.11 – 22.8

## 1.1 Phosphorus

Phosphorus is an important nutrient, although even slightly elevated concentrations of P can trigger eutrophication [11]. Greywater normally contains a low level of nutrients (N, P) compared to toilet wastewater [9]. In countries where phosphorus-containing detergents have not been banned, dishwashing and laundry detergents are the main sources of phosphorus in greywater [9]. Average P concentrations are typically found within the range of 4–14 mg L<sup>-1</sup> [2]. In subsurface flow constructed wetlands, phosphorus is mainly adsorbed in filter material or precipitated [12, 13].

## 1.2 Phosphorus binding capacity

CWs have shown their ability to remove large amounts of P [14, 15] from wastewater using special filter materials with an enhanced P sorption capacity [16]. Phosphorus sorption efficiency is directly related to filter material grain size, distribution, pH, specific surface area and the content of Al, Fe, or Ca ions [17–20].



### 1.2.1 Filtralite<sup>®</sup> and Filtralite-P<sup>®</sup>

Filtralite<sup>®</sup> is a special filter material for wastewater treatment, particularly Filtralite-P<sup>®</sup>, which is specially modified for better P sorption [16]. Filtralite-P<sup>®</sup> has high pH (10) and high Ca and Mg content [21], which makes it good for P sorption. Ádám et al. [17] described the P-sorption efficiency in different scales: small-, meso- and full-scale CW. The results were 3887 mg P kg<sup>-1</sup>, 4500 mg P kg<sup>-1</sup> and 52 mg P kg<sup>-1</sup> respectively. Heistad et al. [22] studied a wastewater treatment system for use in single houses for 3 years. The system performed excellent total P removal throughout the experiment. The average reduction in the filter system was 99.4% [13, 22].

### 1.2.2 Hydrated oil-shale ash

Kerogenous oil shale used in Estonian thermal power plants is a solid fuel of low energetic value, which after combustion leaves large amounts of ash (45–48% of dry mass of shale), and Estonian oil-shale is also highly calcareous [12, 13]. Batch experiments by Kaasik et al. [23] indicated the good (up to 65mg P g<sup>-1</sup>) P binding capacity of the hydrated oil-shale ash sediment, with a removal effectiveness of 67–85% [13, 23]. Vohla et al. [12] found a retention capacity of 8.2 g P kg<sup>-1</sup>, which is a lower capacity value, probably due to different methodology and calculation techniques [12, 13]. Liira et al. [20] carried out a laboratory experiment to investigate phosphorus binding capacity at different retention times. The result showed good removal efficiency (up to 91% at loading of 1.66 g P m<sup>-2</sup> d<sup>-1</sup>) in the experiment with the longest retention time. However, chemical clogging by carbonate precipitates probably reduces the availability of Ca from the dissolution of mineral phases of unstable ash sediment, and phosphate removal decreases rapidly from 91% to 49% [20].

The main objective of this study is to determine the treatment capacity of hydrated oil shale ash (an industrial by-product), Filtralite<sup>®</sup>, and Filtralite-P<sup>®</sup> in compact highly loaded filter systems, in order to reduce phosphorus concentration in household greywater, which includes water from kitchen sinks and dishwashers.

## 2 Materials and methods

### 2.1 Case

An onsite indoor experiment for the treatment of household greywater has been in operation since October 2009. The study was carried out using samples from a single household's greywater. The household has five residents. The separated greywater piping system collects wastewater from showers, hand basins, a washing machine and the kitchen.



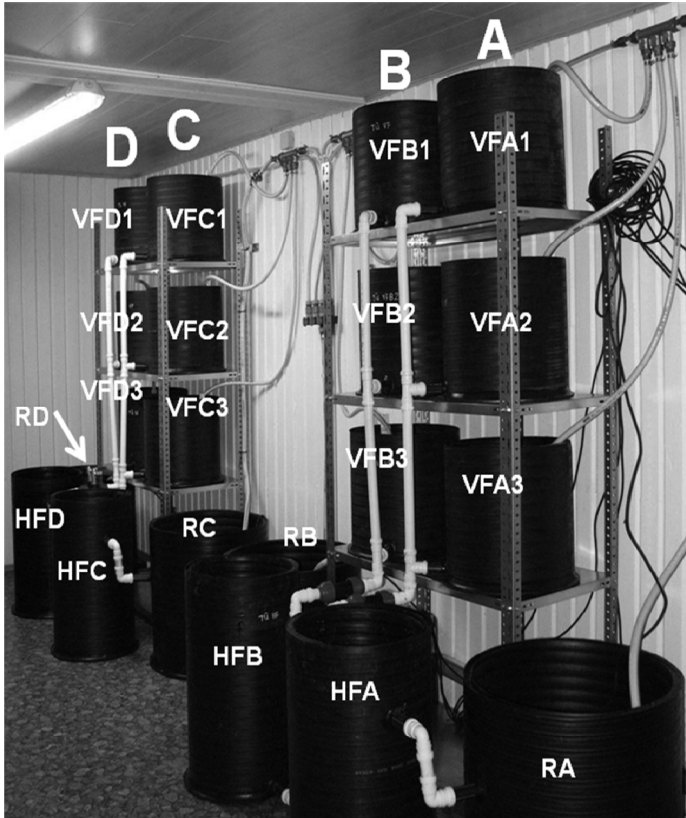


Figure 1: Pilot-scale layout: filter systems A, B, C and D consisting of three vertical flow filters (VF; on shelf) followed by horizontal flow filters (HF; on floor) and re-circulation wells (R; on floor).

## 2.2 Description of experimental system

Experimental pilot-scale hybrid filter systems (A, B, C, D; Fig. 1), each consisting of three parallel vertical flow filters (VF;  $0.02 \text{ m}^3$  each), are followed by a horizontal flow hydraulically saturated filter (HF;  $0.05 \text{ m}^3$ ), and those horizontal filters are followed by a recirculation well (R;  $0.07 \text{ m}^3$ ). The hydraulic loading rate of raw greywater is  $32\text{--}80 \text{ L d}^{-1}$  ( $100\text{--}250 \text{ mm d}^{-1}$ ), with an additional re-circulation rate of 300%, which is 60 cycles per day, equivalent to one dose every 24 minutes. The filter materials are different fractions of Filtralite<sup>®</sup> in the VF of systems A, B and C (2-4mm round, 4-10mm crushed and 4-10mm round respectively), Filtralite-P<sup>®</sup> in the HF of systems A, B and C in the fraction 0-4mm, and alkaline Ca-rich crushed/screened hydrated oil shale ash sediment ( $d=5\text{--}20 \text{ mm}$ ) in the VF and HF of system D. Raw greywater is first deputed in a settling tank ( $2 \text{ m}^3$ ) and then led to the collection well ( $0.4 \text{ m}^3$ ), which is

located in the test house. Then the pump in the collection well divides greywater to each system in equal parts.

### 2.3 Operational periods, sampling and water analysis

This experiment has been divided into 3 periods: the first period represents results from October 2009 to February 2010. In addition, results from 01.12.2009 – 22.12.2009 are not correct due to the inflow problem: blackwater and greywater were accidentally mixed. The second period started on February 2010, when system C was switched off due to poor purification effectiveness. Thereafter, the total hydraulic loading rate increased from  $32.5 \text{ L d}^{-1}$  to  $80 \text{ L d}^{-1}$  (Table 2). Finally, the third period began from June 2010, when the household started to use phosphorus-free detergents. Hydraulic loading rates in the third period were the same as in the second period. From April 2010 no further samples from system A were taken due to the non-satisfactory performance of the filter material, although the system is still running.

Water samples from 10 sampling points were taken regularly. The raw greywater samples were collected from the primary settling tank. Samples from the test plant were taken from the collection well, the outflow from vertical flow filters and the outflow from horizontal flow filters, which also make up the system's outflow. Five analyses were carried out on site: pH (also in the laboratory), temperature, oxygen concentration, dissolved oxygen and conductivity, which were all taken using a portable device (WTW Multi 350i). For the remaining parameters, samples were stored in a thermal box before being transported to the laboratory.

Table 2: System layout, flow regime, operational characteristics.

Parameter	Unit	Period 1 (Oct. 2009- Feb. 2010)	Period 2 (Feb.-June 2010)
Number of parallel systems	-	4	3
Total hydraulic loading rate	$\text{L d}^{-1}$	32.5	80
Hydraulic loading of VF filter	$\text{mm d}^{-1}$	104	256
Number of cycles	$\text{cyc d}^{-1}$	20	40
Length of cycle	sec	15	12
Re-circulation rate	%	300	300
Number of re-circulation cycles	$\text{cyc d}^{-1}$	60	120
Length of re-circulation cycle	sec	15	15

In the water samples,  $\text{BOD}_7$ , COD, total nitrogen (TN),  $\text{NH}_4\text{-N}$ ,  $\text{NO}_3\text{-N}$ ,  $\text{NO}_2\text{-N}$ , total phosphorus (TP),  $\text{PO}_4$  and pH were determined in a certified Tartu Environmental Research Ltd. Laboratory using standard methods [24]. In this paper only phosphorus has been taken into consideration.



### 3 Results and discussion

In the first period (October 2009–February 2010), the reduction of TP in the ash filter system was up to 95%, achieving a median effluent concentration of 0.56 mg L<sup>-1</sup> (median concentration in the inflow was 5.1 mg L<sup>-1</sup>) compared to the respective 40–44% and 2.8–3.3 mg P L<sup>-1</sup> for the Filtralite® systems (Fig. 2). In the second period (February 2010–June 2010) the reduction of TP in the ash filter system was up to 90%, achieving a median effluent concentration of 1.50 mg L<sup>-1</sup> (median concentration in inflow was 9.5 mg L<sup>-1</sup>) compared to the respective 39–46% and 6.3–7.0 mg P L<sup>-1</sup> for the Filtralite® systems (Fig. 2). In the third period (which began in June 2010), the household started to use P-free detergents, and then the inflow P concentration decreased remarkably. It is evident that purification efficiencies were slightly different in Filtralite® systems, but the performance of the oil-shale ash system was considerably better (Fig. 2). Regarding the oil-shale ash, the results indicate that under cold water temperature (median 8°C) and high pH (median outflow value 9.3) conditions, the filter system needs a longer starting period to develop a microbial community for biological processes. The high phosphorus sorption potential of hydrated oil shale ash is considered to be due to the high content of reactive Ca-minerals, of which ettringite Ca<sub>6</sub>(SO<sub>4</sub>)<sub>3</sub>(OH)<sub>12</sub>•26H<sub>2</sub>O and portlandite Ca(OH)<sub>2</sub> are the most important [23].

The median reduction in the COD value was 85–88% for Filtralite® systems and 76% for oil shale ash systems, while the BOD<sub>7</sub> value was on average reduced by 86–93% and 78% respectively. The removal efficiency of TN was not remarkable, and the median efficiency of Filtralite® systems and the oil shale ash system was 55–65% and 52% respectively. Nevertheless, a median outflow concentration of 4.5–5.5 mg N L<sup>-1</sup> was achieved. Relatively low performance regarding the mineralization of organic material (relatively high BOD<sub>7</sub> and COD values) and N removal points to the slow development of microfilm on the filter material. Thus additional studies are needed to explain the possibilities for using compact hybrid filter systems with high hydraulic load.

### 4 Conclusion

The oil shale ash filter system performed at a high phosphorus removal capacity, achieving a median effluent concentration of 0.56 mg L<sup>-1</sup> and an up to 95% reduction of total P. In comparison, the Filtralite® filters demonstrated a TP removal efficiency of 40–44%, and effluent concentrations of 2.8–3.3 mg P L<sup>-1</sup>. Since nitrogen removal in the oil shale ash trial was less efficient than in the Filtralite® systems, the position of the P removal unit in the compact hybrid system's outline needs to be clarified in the course of further experiments.



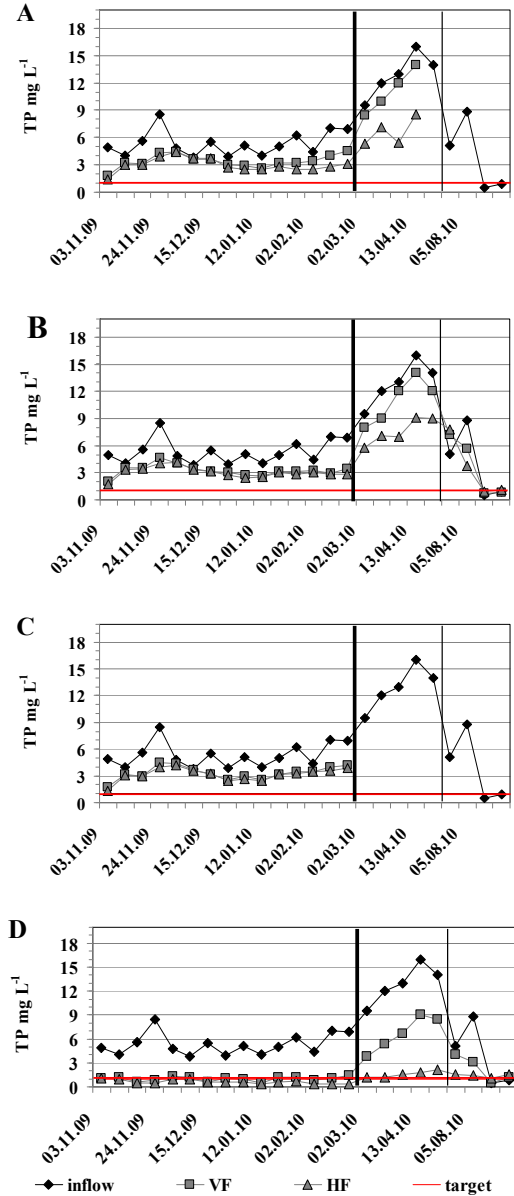


Figure 2: Dynamics of total phosphorus (TP) removal in filter systems. VF – vertical flow filter outflow, HF – horizontal flow filter outflow. The target line indicates the legislated standard outflow value ( $1 \text{ mg P L}^{-1}$ ) [25]. The thicker vertical line represents the end of the first period, and the thinner vertical line indicates the beginning of the third period.



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