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Efficiency of Private Household Sand Filters in Removing Nutrients and Microbes from Wastewater in Finland

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Abstract: Sand filters have been shown to be an economic and effective solution for wastewater treatment in private households, although the removal of phosphorus (P) may be insufficient. However, P removal can be improved by adding a P-adsorbing material, such as biotite, into the sand filters. The physico-chemical characteristics and the microbial quality of the effluents of family-scale sand filters without adsorbing media (SF), sand filters with a biotite layer (B), and sand filters with a modular filter (MB) were followed for one year. Sand filters with a biotite layer displayed the highest capacity to remove nitrogen (N) and biological oxygen demand BOD_7. The efficiency of these filters did not depend on the age of the filter or the season. The P load of the effluent did not differ between sand filters with and without a biotite layer, but the modular sand filter failed to adequately reduce P. The treatment efficiency of sand filters without biotite decreased with increasing age. These private household sand filters can be a good way to treat domestic wastewaters, since these generally comply with the minimum requirements of a Finnish Decree (157/2017). However, enteric viruses (noro- and adenoviruses) were commonly found in the effluents, and the numbers of *Escherichia coli* were often above 10^3 colony forming units (CFU) 100 mL^{-1} (limit for the the EU Bathing Water Directive 2006/7/EC) for good water quality), signifying a risk of microbial contamination of nearby drinking water wells, as well as bathing and irrigation waters.

Keywords: on-site wastewater treatment; wastewater; sand filter; nutrient removal; microbial removal

1. Introduction

Worldwide there are many rural or peri-urban households that are not connected to centralized sewer networks, and thus they must organize their wastewater treatment on-site. In Finland, about 1 million people out of the country's total population of 5.5 million are not connected to sewer networks. The on-site treatment systems and their purification efficiency for the removal of total phosphorus, total nitrogen, and BOD_7 must meet the requirements listed in the Finnish Government Decree on Treating Domestic Wastewaters in Areas Outside Sewer Networks (Government Decree 157/2017) [1]. Traditionally, these waters are first treated with settling in septic tanks and then passed through a soil absorption bed. The purification efficiency of these techniques does not always meet the required level (in terms of P, N, and BOD) [2,3] and therefore there is a need to improve on-site treatment systems.

There are many treatment techniques available for domestic use [4–6]. Sand filters with or without a phosphorus-adsorbing layer have proven to be the most cost-effective and environmentally-friendly approaches if long-term use and renovation needs are considered [7,8]. It has been revealed [8–10], however, that the treatment efficiency of sand filters can be highly variable. Studies of many different sand filters demonstrated that those filters with P-adsorbing media were better at reducing phosphorus and nitrogen than filters without any adsorbing media [8,10]. However, it has been reported that sand filters without adsorbing media were able to reduce the levels of phosphorus and nitrogen better than systems with P-adsorbing gypsum or different ferro sulfate media [9]. Furthermore, sand filters without P-adsorbent media were able to remove BOD better than filters with a P-adsorbent media [8], although others have reported contrasting results [9]. However, the removal of BOD was at the required level in most of the sand filters, irrespective of whether they had P-adsorbing media [8,9], as confirmed in a later study [10]. It was found that the effluent quality was the lowest when modular sand filters were used [8,9]. Many different P-adsorbing materials can be exploited for sand filtration of wastewaters and the location of the materials can also vary; materials can be mixed with sand, a P-adsorbing layer can be placed between the sand layers, or a P-adsorbing material can be added as a post-treatment unit after a sand filter. These differences in the structures of the sand filters may explain the fluctuation in the published results.

Wastewater contains a large range of pathogenic microorganisms (bacteria, parasites, and viruses) [11], which can be inactivated with different mechanisms, but it is known that bacteria and viruses can be transported in soil with the risk of contaminating drinking water wells, bathing waters, or other surface waters [12–14]. The removal of enteric microbes in on-site treatment systems is therefore important, but unfortunately this property has been less extensively studied than the removal of nutrients, since only the latter is regulated by wastewater legislation. Moreover, there are only a few studies that have evaluated the treatment efficiency of sand filtering during long-term domestic use, when the filters are operated by families. These kinds of studies would be important, since treatment efficiency may decline over the years or during times when there is an uneven wastewater load, leading to leaching of untreated wastewater into the soil [2,15].

The objective of this study was to evaluate the efficiency of different sand filters to remove phosphorus, nitrogen, and organic material from domestic wastewaters over one year (as compared to the Finnish requirements (basic-level) described in Government Decree 157/2017 [1]) in a cold climate with a long, snowy winter. In addition, we studied the leaching of hygienic indicator bacteria and selected enteric viruses from the sand filters. The specific aim was to determine if season or filter age would exert any effect on the load of nutrients, and the number of the microbes in the effluent.

2. Materials and Methods

2.1. Sand Filters

The performance of three different sand filter types installed after septic tanks was evaluated over a one-year period. The first type included three conventional buried sand filters without (additional) P-adsorbing media (SF1–3), the second type included three buried sand filters with a biotite layer (B1–3), and the third type included one buried sand filter with a commercial module and a biotite layer (MB) (Table 1). Six of the seven filters were over 9 years old; in total, their ages varied from 5 to 14 years. All sand filters were situated in the rural area of Central Finland and received only domestic wastewater from a single household. All of the filters were situated behind a two- or three-chamber septic system as a form of pretreatment, and their sand layer had a thickness of around 80 cm along with the underlying collection pipes. Unfortunately, the gravel sizes of the filters are unknown. Filters B1–3 had a phosphorus (P)-adsorbing biotite layer, whereas the MB filter had a plastic module above the P–adsorbing biotite–sand layer. In all of the filters, the wastewater passed vertically through the sand layer into the collection pipe and continued flowing into the collection well before being released to the environment.

Table 1. Types and characteristics of the studied sand filters.

Code	Sand Filter	Surface Area of Sand Filter (m^2)	Age (Years)	Persons, *n* (Adults + Children)	Total Daily Water Load (L)	Total Daily Water Load (L)/(Persons × 1000)
SF1	Three-chamber septic tank (3 m^3) + sand filter	N. k.	14	2 + 4	660*	0.11
SF2	Three-chamber septic tank (3 m^3) + sand filter	40	9	2 + 3	367	0.07
SF3	Three-chamber septic tank (2 m^3) + sand filter	30	14	3 + 1	500	0.13
B1	Two-chamber septic tank (3 m^3) + biotite sand filter	N. k.	9	2 + 1	267	0.09
B2	Two-chamber septic tank (2 m^3) + biotite sand filter	40	9	2	300	0.15
B3	Three-chamber septic tank (2 m^3) + biotite sand filter	40	11	2 + 9	560	0.05
MB	Three-chamber septic tank (3 m^3) + module and biotite sand filter	8	5	2	367	0.18

N. k. = not known. * Estimation based on Government Decree 157/2017 [1].

The mean air temperatures in the study area over the period May 2010–May 2011 were: −13.2 °C (minimum −36.5 °C, maximum 1.7 °C) in winter (December–February) lasting for 13 weeks, 5.4 °C (minimum −20.9 °C, maximum 27.7 °C) in spring (March–May) lasting for 14 weeks, 17.4 °C (minimum 2.8 °C, maximum 35.4 °C) in summer (June–August) lasting 14 weeks and 3.3 °C (minimum −19.5 °C, maximum 19.5 °C) in autumn (September–November) lasting 12 weeks. The total seasonal precipitation values were: winter (mainly as snow) 130 mm, spring 154 mm, summer 157 mm, and autumn 162 mm [16].

2.2. Wastewater Sampling

The quality of wastewater in the first septic tank compartment (influent) was analyzed 1–2 times in each sand filter, i.e., a total of 11 samples. The effluent samples were taken 4–8 times per filter so that the samplings of SF, B, and MB covered all seasons. The effluents were sampled from the collection well or from the end of the collection pipe depending on the structure of the well. All samples were pooled from two individual sub-samples collected during the same day and mixed well. The effluent samples were collected in sterile plastic bottles, transported to the laboratory in a portable cooler and analyzed as two replicates within 24 h of sampling.

2.3. Physico-Chemical Analyses

Water samples were analyzed with Hach DR2010 spectrophotometer (Hach Co., Loveland, CO, USA) for total phosphorus (P_{tot}) (Potassium Peroxide Sulfate Digestion Method 8190), total nitrogen (N_{tot}) (Persulfate Method 10071), chemical oxygen demand (COD_{Cr}) (Digestion Method 8000), nitrate nitrogen NO_3-N (Cadmium Reduction Method 8039), nitrite nitrogen NO_2-N (Diazotization Method 8507), and ammonium nitrogen NH_4-N (Nessler Method 8038). Total suspended solids (SS) (SFS 3026) and biological oxygen demand (BOD_7, (using ATU)) (OxiTop Control OC110, WTW, Weilheim, Germany) were assessed according to the methods defined in Nordic and Finnish standards which correspond to the American standard methods (APHA 2005), except that the incubation time for BOD is seven days instead of five days. pH was measured with a Hach Hqd Portable meter (Hach Co., Loveland, CO, USA).

2.4. Bacteriological Analyses

All bacteriological analyses were conducted as two replicates from each water sample taken. *Escherichia coli* numbers were analyzed on CromoCult coliform agar (Merck, Darmstadt, Germany) by the spread-plate or membrane filtration method (Millipore membrane filter, pore size 0.45 µm, mixed cellulose ester, Molsheim, France). The plates were incubated for 24 ± 3 h at 37 °C and *E. coli* colonies were confirmed by Kovacs´s indole reagent. The detection limits were 1 or 10 CFU 100 mL^{-1} for the filtration method and 5 CFU 1 mL^{-1} for the spread plate method.

Intestinal enterococci were determined by filtration method on Slanetz–Bartley agar (Lab M, Lancashire, UK) according to the standard SFS-EN ISO 7899-2 [17]. The plates were incubated for 44 ± 4 h at 37 °C. The detection limit was 1 CFU 100 mL^{-1}, 10 CFU 100 mL^{-1} or 500 CFU 100 mL^{-1}, depending on the volume of filtered water.

Spores of sulfite-reducing clostridia were analyzed by membrane filtration method (pore size of the membrane 0.22 µm, Whatman Mixed cellulose ester, Dassel, Germany) according to the standard SFS-EN 26461-2 [18] after heating the sample water at 75 °C for 15 min. Plates (sulfite iron agar) were incubated for 44 ± 4 h at 37 °C in anaerobic jars. Detection limit was 1 CFU 100 mL^{-1}.

The presence of thermotolerant *Campylobacter* species (such as *Campylobacter jejuni*, *C. coli*, *C. lari* and *C. upsaliensies*) was tested following the techniques described in standard ISO 17995 [19]. After membrane filtration of 200–800 mL of the sample, the membrane was placed into an enrichment broth and incubated at 37 °C for 2 days in microaerophilic gas phase followed by plating on modified charcoal–cefoperazone–deoxycholate agar (mCCDA) for a further 2 days at 41.5 °C.

The heterotrophic plate count was analyzed by the spread-plate technique on Reasoner´s 2 agar medium R2A, (Lab M, Lacashire, UK) [20]. The plates were incubated for 3 days at 22 °C. The detection limit was 50 CFU 100 mL^{-1}.

2.5. Virus Analyses

F-specific coliphages (host *E. coli* ATCC 15597 (American Type Culture Collection, Manassas VA, USA)) and/or somatic coliphages (host *E. coli* ATCC 13706) were determined by using a single-layer agar technique from 100-mL samples [21]. The analysis was done with two replicates and the plates were incubated for 24 ± 3 h at 37 °C. The detection limit was 1 plaque forming units (PFU) 100 mL^{-1}.

Adenovirus and genogroups GI and GII of the norovirus were analyzed as described previously [22]. Samples (500 mL) were concentrated by a two-phase separation method and the viruses were analyzed with real-time (RT) qPCR methods. All samples were run with undiluted and 10-fold dilutions. The theoretical detection limit for adeno- and noroviruses was 0.5–2.3 genome copies (GC) 1 mL^{-1}.

2.6. Data Analyses

The loads of nutrients, BOD_7, and COD were calculated as g/cap·d (total-N, total-P, and BOD_7) according to Government Decree 157/2017 [1] by using Equation (1), which considers the water consumption and number of users varying between the sand filters (Table 1). The divisor 1000 in the equation is due to the conversion from milligrams to grams.

$$\text{Load }(\text{g}/(\text{cap}\cdot\text{d})) = \frac{(\text{mg/L } \times \text{ total water load}(\text{L/d}))}{(\text{persons }(n))/1000} \tag{1}$$

Statistical analyses were conducted by using IBM SPSS statistics 21. Bacteriological and coliphage data were $\log_{10}$-transformed for statistical analyses to obtain a normal distribution. Half of the detection limit was used in the statistical analyses if the result was below the detection limit. The statistical differences between three filter types or four seasons were analyzed by using the Kruskal–Wallis test with pair-wise comparison or by one-way ANOVA combined with Bonferroni post hoc test depending on the normality of the parameters. The statistical difference between different aged sand filters was analyzed by using the independent samples Mann–Whitney *U* test or the independent samples *T*-test. The association between the presence (yes or no) of enteric viruses with other analyzed microbes was tested with cross-tabulation combined with Chi-squared test or by the independent samples Mann–Whitney *U* test depending on the normality of the parameters. The difference was considered significant if the *p*-values were <0.05.

3. Results

3.1. Influent Water Quality

The results of the physico-chemical parameters of influents and effluents are shown in Table 2. The physico-chemical quality (g/cap·d or mg/L) of influent water flowing into the buried sand filters did not vary significantly with any of the measured parameters between the filters without P-adsorbing media (SF), filters with a biotite layer (B), and a filter with a module and biotite layer (MB) (Table 2). The average P_{tot}, N_{tot}, and BOD_7 loads in influent were 1.8 ± 0.9, 13 ± 5 and 47 ± 26 g/cap·d, respectively. There were up to three $\log_{10}$ variations in the numbers of bacteria and viruses between different samples without any statistically significant differences between the sand filter types. Pathogenic viruses were frequently detected in the influent wastewater (Table 3). *Campylobacter* spp. was not detected in any of the samples.

Table 2. Averages ± standard deviations (minimum-maximum values) of physico-chemical (mg L^{-1}) parameters in influent and effluent of three buried sand filters without P-adsorbing media (SF), three buried sand filters with a biotite layer (B), and one buried sand filter with a module and biotite layer (MB).

Filter Types	Influents			Effluents		
	SF (*n* = 4)	B (*n* = 5)	MB (*n* = 2)	SF (*n* = 9–23)	B (*n* = 7–17)	MB (*n* = 3–8)
Total phosphorus (mg L^{-1})	13 ± 6.5 (7.4–22)	15 ± 3.3 (12–21)	17 ± 0.3 (16.6–17)	3.1 ± 2.2 (0.40–10)	3.7 ± 2.9 (0.40–12)	9.7 ± 3.0 (6.0–15)
Total nitrogen (mg L^{-1})	120 ± 31 (90–160)	110 ± 38 (86–180)	97 ± 5.7 (93–100)	71 ± 44 (11–170)	27 ± 16 (8–58)	72 ± 19 (50–100)
NH_4-N (mg L^{-1})	110 ± 20 (90–130)	97 ± 26 (76–140)	87 ± 4.6 (84–90)	26 ± 27 (4–77)	3.2 ± 3.5 (0.10–10)	11 ± 24 (1.2–31)
NO_3-N (mg L^{-1})	8.0 ± 5.3 (2.5–15)	17 ± 8.8 (9.5–13.5)	12 ± 1.8 (11–14)	30 ± 22 (1–130)	23 ± 26 (3.0–100)	34 ± 42 (15–61)
Biological oxygen demand$_7$ (mg L^{-1})	330 ± 103 (230–460)	420 ± 230 (240–820)	470 ± 96 (400–530)	72 ± 202 (2.4–900)	9.4 ± 8.9 (2.6–28)	28 ± 45 (5.6–130)
Chemical oxygen demand$_{Cr}$ (mg L^{-1})	690 ± 150 (470–810)	720 ± 320 (460–1200)	740 ± 130 (650–830)	53 ± 28 (19–130)	63 ± 130 (9–550)	130 ± 190 (26–560)
pH	7.6 ± 0.1 (7.5–7.7)	7.8 ± 0.5 (7.3–8.4)	7.6 ± 0.0 (7.62–7.63)	6.6 ± 0.7 (4.7–7.8)	7.3 ± 0.6 (6.5–8.5)	7.0 ± 0.3 (6.5–7.4)
Oxygen (mg L^{-1})	1.3 ± 0.8 (0.40–2.4)	0.40 ± 0.40 (0.20–0.90)	0.80 ± 0.30 (0.70–1.0)	6.0 ± 1.3 (3.3–7.9)	7.2 ± 0.8 (6.4–8.3)	5.7 ± 1.0 (2.4–7.5)

Table 3. Geometric means (minimum–maximum values) of microbial numbers (CFU 100 mL^{-1}, PFU 100 mL^{-1} or GC mL^{-1}) in influent water of three buried sand filters without P-adsorbing media (SF), three buried sand filters with a biotite layer (B), and one buried sand filter with a module and biotite layer (MB). If the value was under the detection limit (udl), half of the detection limit was used when calculating the geometric mean.

Influents	SF	B	MB
Heterotrophic bacteria (CFU 100 mL^{-1})	1.9×10^7 (1.4×10^6–4.8×10^8)	3.6×10^8 (6.1×10^6–2.2×10^9)	2.0×10^7 (5.4×10^5–7.3×10^8)

Table 3. *Cont.*

Influents	SF	B	MB
Escherichia coli (CFU 100 mL^{-1})	1.4×10^6 (8.5×10^5–1.8×10^6)	8.7×10^6 (4.5×10^5–9×10^7)	7.3×10^7 (3.6×10^7–1.5×10^8)
Intestinal enterococci (CFU 100 mL^{-1})	2.5×10^5 (5.9×10^4–8.7×10^5)	1.2×10^5 (5×10^3–2.1×10^6)	7.2×10^4 (5.4×10^4–9.6×10^4)
Somatic coliphages (PFU 100 mL^{-1})	200 (udl–6500)	2 (1–79)	udl
F-specific coliphages (PFU 100 mL^{-1})	udl	1 (udl–3)	udl
Spores of *Clostridium* (CFU 100 mL^{-1})	4 (0.5–40)	22 (0.5–290)	5 (2–11)
Adenoviruses (GC 1 mL^{-1})	udl	4 (0.3–200)	29 (12–68)
Noroviruses GI (GC 1 mL^{-1})	1.4 (udl–32)	1 (udl–15)	udl
Noroviruses GII (GC 1 mL^{-1})	45 (udl–3.0×10^3)	23 (udl–480)	11 (7–20)

3.2. Effluent Quality

3.2.1. Phosphorus

The P_{tot} load in effluent varied during the one-year study period from 0.03 to 2.7 g/cap·d depending on the sand filter type and the sampling time (Figure 1a). In total, 83%, 94%, and 0% of the SF, B, and MB effluents, respectively, achieved the demands set for P_{tot} loads (0.66 g/cap·d) by the Finnish Government Decree (517/2017) (Figure 1a). The P_{tot} load from the MB was significantly higher than that from the SF or B ($p < 0.001$), which did not differ significantly. There was no seasonal trend in the effluent P_{tot} load.

Within the SFs, the load was lower in the effluents of SF2 (0.12 $\pm$ 0.05 g/cap·d) than in SF1 (0.33$\pm$0.11 g/cap·d, $p < 0.05$) or SF3 (1.77 $\pm$ 0.54 g/cap·d, $p < 0.01$). The P_{tot} loads were 0.18 $\pm$ 0.22, 0.55 $\pm$ 0.21, and 0.32 $\pm$ 0.20 g/cap·d in B1, B2, and B3, respectively, without any statistical differences. An age effect was evident in the P_{tot} loads i.e., it was 0.47 $\pm$ 0.30 g/cap·d in 14-year-old SF1 and SF3, but 0.12 $\pm$ 0.05 g/cap·d in 9-year-old SF2 ($p < 0.001$), while the average P_{tot} load was 0.38 $\pm$ 0.28 g/cap·d in 9-year-old B1 and B2, and 0.32 $\pm$ 0.20 g/cap·d in 11-year-old B3.

3.2.2. Total Nitrogen, Ammonium-N, Nitrate-N, and Nitrite-N

The N_{tot} load in the effluent varied during the one-year study period from 0.7 to 19 g/cap·d (Figure 1b). In summary, N_{tot} loads fulfilled the required Finnish purification efficiency (9.8 g/cap·d) [1] in 67%, 100%, and 37% in effluents of SF, B, and MB, respectively (Figure 1b). The N_{tot} of the B was significantly lower than that of the SF or the MB ($p < 0.05$), but the treatment efficiencies between SF and MB did not differ significantly. There was no seasonal trend in the effluent N_{tot} loads. When comparing the SFs, the load was lower in SF2 (3.9 $\pm$ 3.1 g/cap·d) than in SF1 (11 $\pm$ 5.3 g/cap·d, $p < 0.05$), but N_{tot} loads were not statistically different between SF2 and SF3 (7.3 $\pm$ 3.4 g/cap·d). Within B, all N_{tot} loads were low, without any statistical significance between these filters. Age of filter affected the efficiency of SF so that the N_{tot} load was higher (9.2 $\pm$ 4.7 g/cap·d) in the older (14-year-old) SF1 and SF3 than in the younger (9-year-old) SF2 (4.0 $\pm$ 3.1 g/cap·d) ($p < 0.01$). However, in biotite filters, age had no effect on the N_{tot} load being passed to the environment, with average values of 3.0 $\pm$ 2.5 g/cap·d in the 9-year-old B1 and B2, and 1.0 $\pm$ 0.8 g/cap·d in the 11-year-old B3.

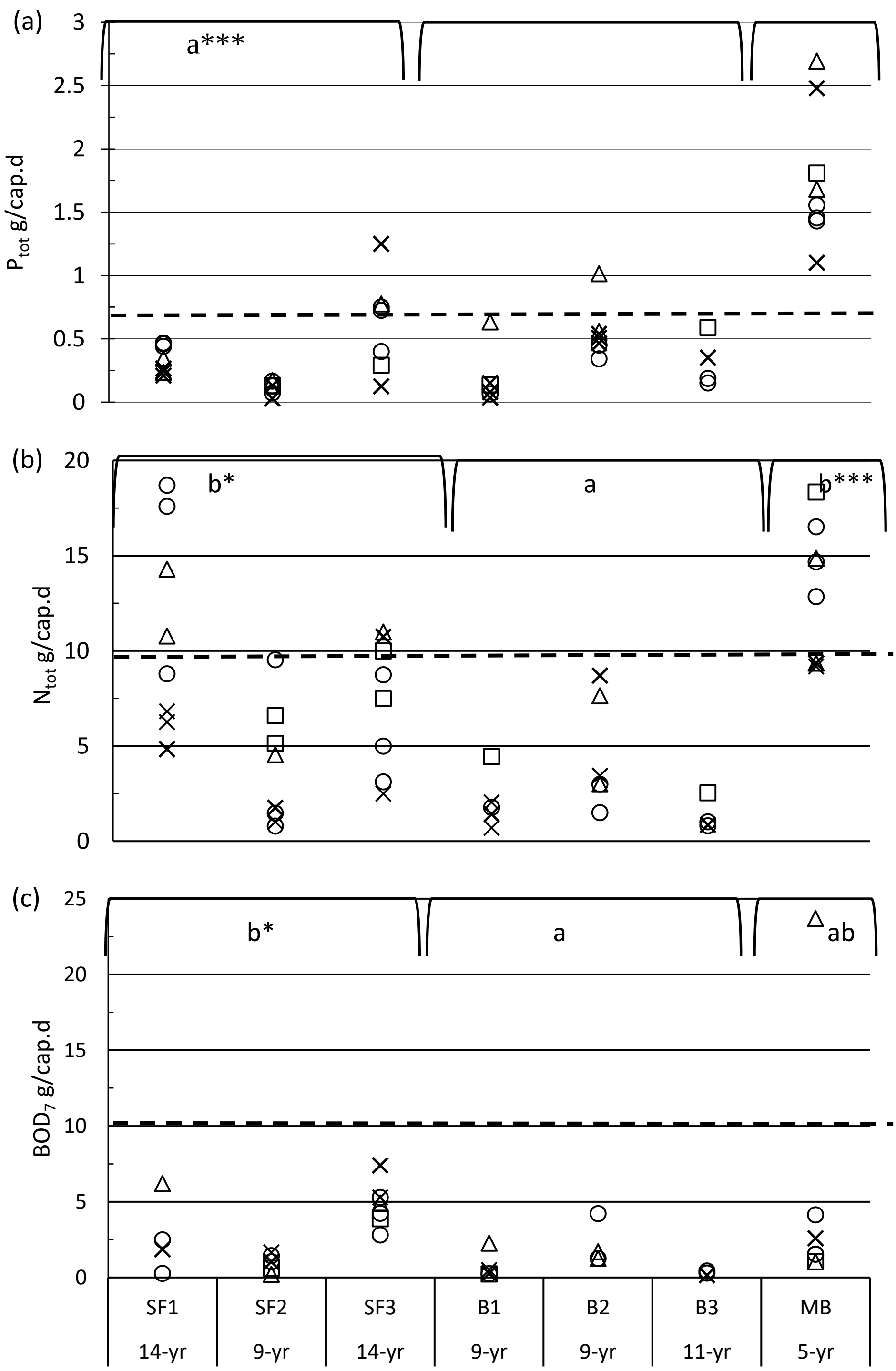

Figure 1. (**a**) Phosphorus (P_{tot}), (**b**) nitrogen (N_{tot}), and (**c**) biological oxygen demand (BOD_7) loads in effluents from buried sand filters without P-adsorbing media (SF1–SF3), buried sand filters with a biotite layer (B1–B3), and a buried sand filter with a module and biotite layer (MB). The dashed line represents the required (basic purification requirement) purification efficiency in Finland (Government Decree 157/2017 [1]). Different letters indicate statistically significant differences between the filter types (* $p < 0.05$, *** $p < 0.001$). x = spring, ○ = summer, □ = autumn and Δ = winter.

The percentages of ammonium-N from the total-N concentration in effluent were 36% (SF), 12% (B), and 36% (MB) (Table 2). The ammonium-N load in effluent varied during the one-year study period from 0.01 to 9.6 g/cap·d depending on the sand filter type and the sampling time. The ammonium-N load in effluent of B (0.24 ± 0.28 g/cap·d) was significantly lower than that of the SFs (2.90 ± 3.1 g/cap·d) ($p < 0.001$) or the MB (2.1 ± 1.9 g/cap·d) ($p < 0.01$), which did not differ significantly. There was no seasonal variation in the effluent ammonium-N load. As above, the age of filter influenced the SF so that ammonium-N load was higher (3.9 ± 3.3 g/cap·d) in the two older (14-year-old) SF 1 and 3 as compared to the younger (9-year-old) SF2 (0.90 ± 0.50 g/cap·d) ($p < 0.05$). Similarly, in B, the effluent ammonium-N load was higher (0.40 ± 0.10 g/cap·d) in the older (11-year-old) B3 than in its two younger counterparts, the (9-year-old) B1 and B2 (0.20 ± 0.30 g/cap·d) ($p < 0.01$).

Ammonium-N was partly nitrified, and thus the total-N of effluents was present as the nitrate form in 42% (SF), 85% (B), and 47% (MB) (Table 2). All nitrate-N loads in effluent were less than 14 g/cap·d. The nitrate-N loads of B (2.6 ± 2.9 g/cap·d) and SF (2.9 ± 3.3 g/cap·d) were significantly lower than those of MB (6.3 ± 3.0 g/cap·d) ($p < 0.05$). An age effect was found in B, i.e., the nitrate-N load was higher (3.2 ± 3.1 g/cap·d) in younger (9-year-old) B1 and B2 as compared to the older (11-year-old) B3 (0.5 ± 0.3 g/cap·d) ($p < 0.05$). In contrast, for the SF, the age did not exert any effect on nitrate-N load values, which all were less than 3.4 ± 4.0. The nitrite-N load in the effluent was always low, varying in the entire data from 0.001 to 1.7 g/cap·d during the one-year study period without significant differences between filters.

3.2.3. BOD_7 and COD_{Cr}

The BOD_7 load in the effluents varied during the one-year study period from 0.14 to 23.7 g/cap·d (Figure 1c). In total, 100% of the SFs and Bs and 86% of MBs succeeded in meeting the required Finnish purification efficiency (10 g/cap·d) (Government Decree 157/2017) (Figure 1c). The BOD_7 load of B (1.1 ± 1.2 g/cap·d) was significantly lower than that of the SF (2.9 ± 2.2 g/cap·d) ($p < 0.05$), but it did not differ significantly from that of the MB (5.1 ± 8.3 g/cap·d). Within the SFs, the load was higher in SF3 (4.8 ± 1.4 g/cap·d) than in SF2 (1.0 ± 0.5 g/cap·d, $p < 0.01$), while the loads did not differ between the B filters. There was no seasonal trend in the effluent BOD_7 load.

An age effect was found in SF such that the effluent BOD_7 load was higher (4.1 ± 2.1 g/cap·d) in the older (14-year-old) SF 1 and 3 than in the younger (9-year-old) SF2 (1 ± 0.5 g/cap·d) ($p < 0.01$). However, with respect to the biotite filters, age did not have any effect on the BOD_7 load values, which were 1.3 ± 1.3 g/cap·d in the 9-year-old B1 and B2, and 0.3 ± 0.1 g/cap·d in the 11-year-old B3.

The means of COD_{Cr} load varied during the one-year study period from 0.8 to 103 g/cap·d depending on the sand filter type and the sampling time. The level and the variation in COD_{Cr} in the MB filter (24 ± 34 g/cap·d) were significantly higher than that of the B (7.8 ± 20) ($p < 0.01$). COD_{Cr} values did not differ significantly between the MB and SF (5.7 ± 3.8 g/cap·d) nor between the SF and B. Season had no effect on the effluent COD_{Cr} load. Within the SFs, the load was lower in SF2 (2.5 ± 0.8 g/cap·d) than in either SF1 (6.3 ± 2.8 g/cap·d, $p < 0.05$) or SF3 (8.3 ± 4.3 g/cap·d, $p < 0.01$).

An age effect was found in SFs i.e., the COD_{Cr} load of effluent was higher (7.3 ± 3.6 g/cap·d) in the older (14-year-old) SF 1 and SF3 than in the younger (9-year-old) SF2 (2.5 ± 0.8 g/cap·d) ($p < 0.001$). However, in B, age did not exert any effect on the COD_{Cr} load values, which were 9.7 ± 22 g/cap·d in 9-year-old B1 and B2, and 1.5 ± 0.6 g/cap·d in 11-year-old B3. There was a positive correlation between BOD_7 g/cap·d and COD g/cap·d ($r = 0.65$, $p < 0.001$, $n = 37$).

3.2.4. SS, O_2 and PH

The concentration of suspended solids (SS) in effluents varied during the one-year study period, from 1.6 to 1200 mg/L. There was some oxygen in all effluents; its concentration varied from 2.4 to 8.3 mg L^{-1} depending on the sand filter type, but there were no statistical differences between the sand filter types (Table 2).

Age or season did not have any effect on the effluent SS or oxygen concentrations. Effluent pH varied from 4.7 to 8.5 during the entire study period (Table 2.). The pH of B was significantly higher than that of the SF ($p < 0.01$) but not of the MB filters. There were no seasonal effects on pH SF or MB. The age of the filter had no effect on the pH values of the effluent.

3.2.5. Bacteria

The numbers of *Escherichia coli* in effluents varied from 50 to 5 × 10^6 CFU 100 mL^{-1} (Figure 2a.) but in this parameter, there were no statistically significant differences between SF, B, and MB. Some seasonal variation was only found in SF ($p < 0.05$), where the numbers (1.9 × 10^4 CFU 100 mL^{-1}) were statistically higher in summer than in spring (1.5 × 10^3 CFU 100 mL^{-1}) ($p < 0.05$). The age of the filter had no effect on numbers of *E. coli*.

The numbers of intestinal enterococci in effluent varied from 1 to 1.3 × 10^5 CFU 100 mL^{-1}, the number of spores of sulfite-reducing Clostridia ranged from <1 to 46 CFU 100 mL^{-1} (34 of 47 analyzed samples were below the detection limit) and the number of heterotrophic bacteria ranged from 2.7 × 103 to 8.6 × 10^7 CFU 100 mL^{-1} (Figure 2a–d) without any statistical differences between SF, B, and MB. The numbers did not differ either due to the different seasons or between different ages of the filters. *Campylobacter* spp. was not detected in any of the samples.

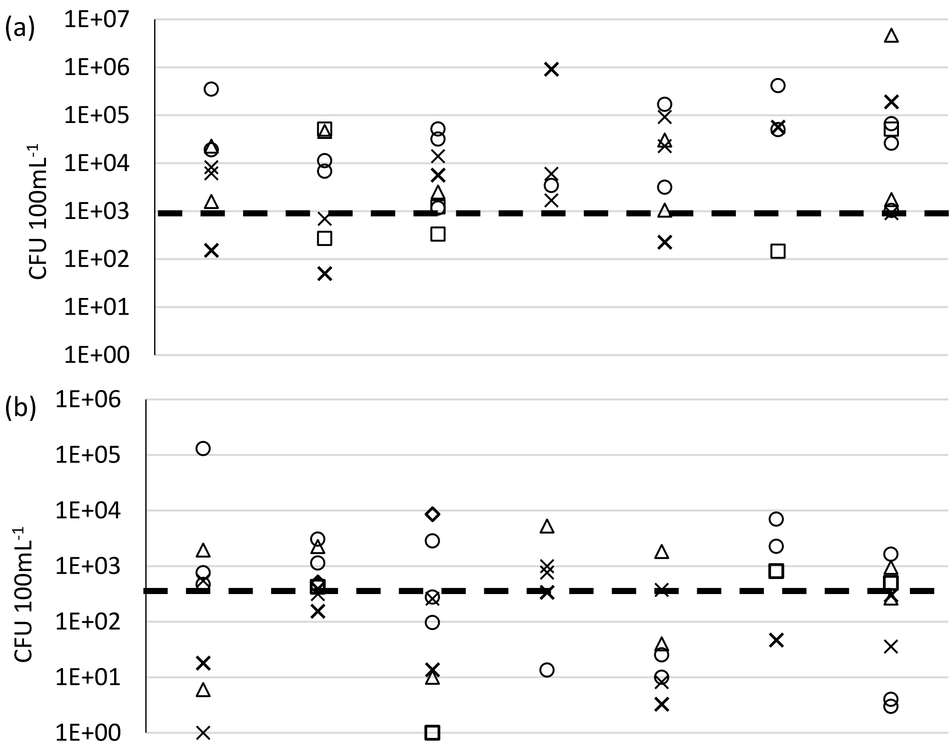

Figure 2. *Cont.*

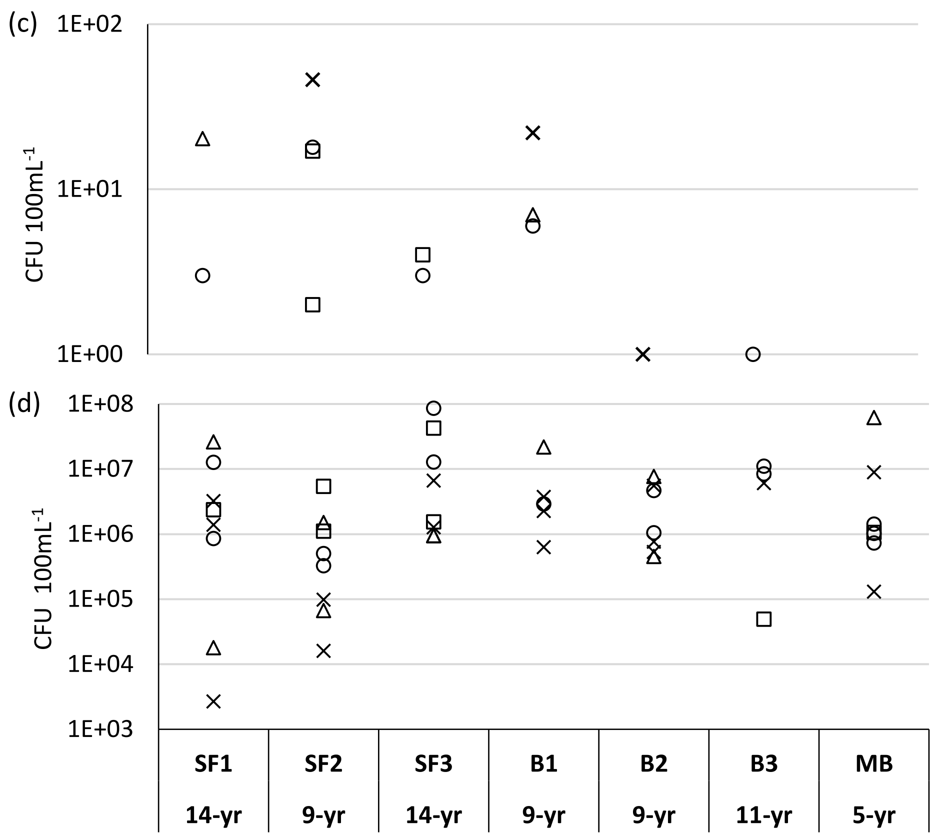

Figure 2. Numbers of different bacteria in effluents (CFU 100 mL^{-1}) during the one-year study period. (**a**) *Escherichia coli*, (**b**) intestinal enterococci, (**c**) spores of sulfite-reducing clostridia, and (**d**) heterotrophic bacteria from buried sand filters without P-adsorbing media (SF1–SF3), buried sand filters with a biotite layer (B1–B3) and a buried sand filter with a module and biotite layer (MB). The dashed line represents the levels assessed as sufficient quality for inland bathing water according to the EU Bathing Water Directive [23]. x = spring, ○ = summer, □ = autumn and Δ = winter.

3.2.6. Viruses

The number of F-specific coliphages in effluent was below the detection limit (1 PFU 100 mL^{-1}) in all other samples, except in two samples in which there were low numbers of coliphages (44 PFU 100 mL^{-1} in SF1 and 1 PFU 100 mL^{-1} in SF3).

The number of somatic coliphages in effluent varied in the entire data from below the detection limit to 10^6 PFU 100 mL^{-1} (16 of 25 analyzed samples were below the detection limit) (Figure 3a.) without any differences between SF, B, and MB filters. Within the SFs, the geometric mean value was higher in SF2 (18 PFU 100 mL^{-1}) than in SF1 (<1 PFU 100 mL^{-1}) and in SF3 (3 PFU 100 mL^{-1}) ($p < 0.01$). Age was found to decrease the numbers of somatic coliphages in SFs, such that the effluent contained 20 PFU 100 mL^{-1} in the younger (9-year-old) filters, while the effluent emerging from the older (14-year-old) SFs contained only 3 PFU 100 mL^{-1} ($p < 0.01$). Season had no effect on numbers of somatic coliphages.

Human adenoviruses were detected from the effluents of all filter types and human norovirus GI from three of seven of the soil filters and human norovirus GII from six of seven soil filters during the one-year study period (Figure 3b,c.). The number of adenoviruses in the effluent ranged from below the detection limit to 49 GC 1 mL^{-1} (39.6% positive samples), those of norovirus GI from below the detection limit to 83 GC 1 mL^{-1} (6.3% positive samples), and norovirus GII from below the detection limit to 898 GC 1 mL^{-1} (72.9% positive samples). There were no differences in the detection of adeno- and noroviruses which could be attributed to the different filters or differences between the members of the same filter types. Neither age of the filter nor season was associated with the adenovirus, nor norovirus GI or GII results. Nonetheless, the numbers of sulfite-reducing clostridia spores were higher in those samples where norovirus GII was also detected ($p < 0.05$).

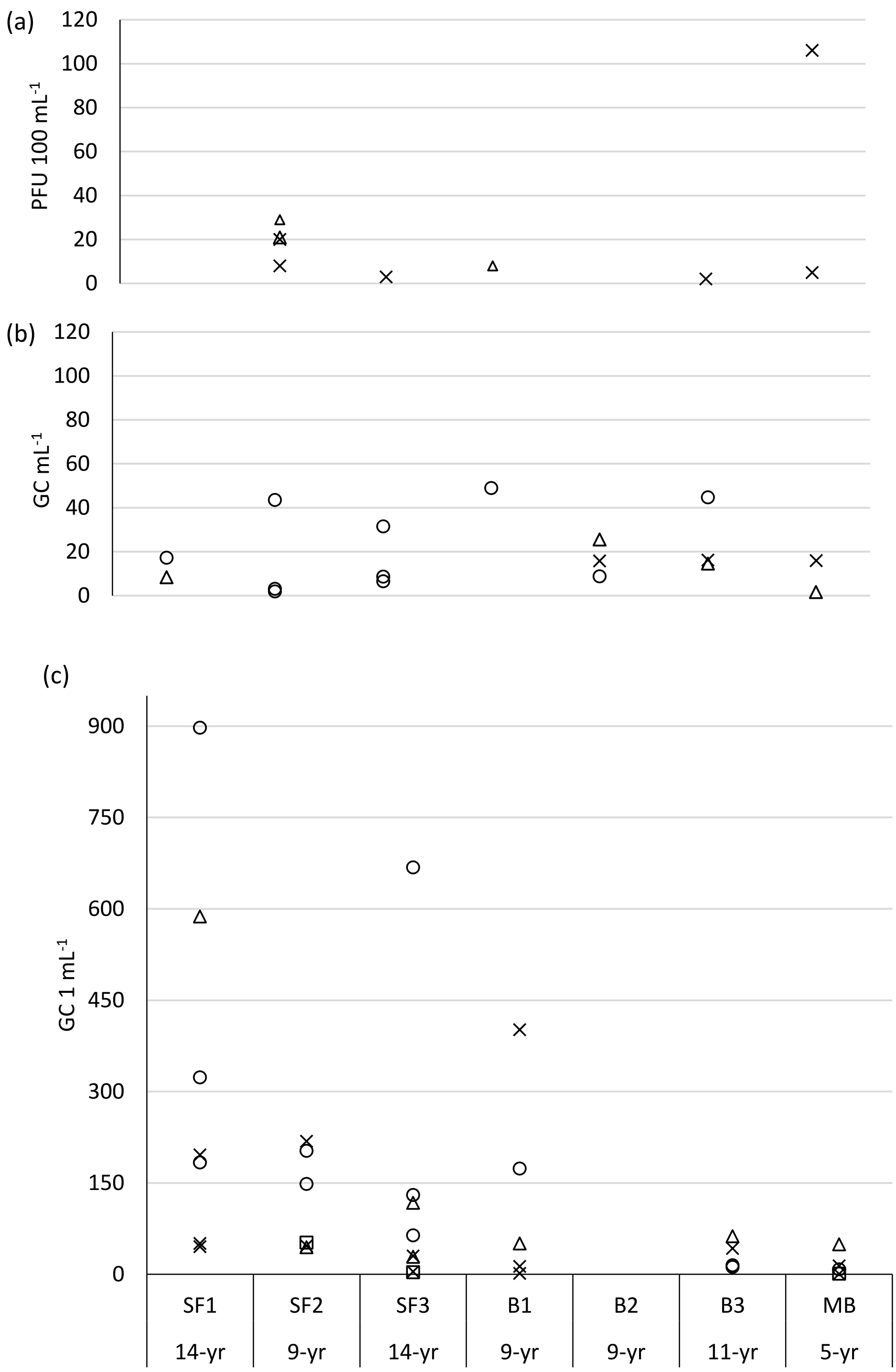

Figure 3. Numbers of viruses in effluent plaque forming units (PFU) 100 mL^{-1} or genome copies (GC) 1 mL^{-1} during the one-year study period. (**a**) Somatic coliphages, (**b**) adenovirus, (**c**) norovirus GII from buried sand filters without P-adsorbing media (SF1–SF3), buried sand filters with a biotite layer (B1–B3) and a buried sand filter with a module and biotite layer (MB). x = spring, ○ = summer, □ = autumn and Δ = winter. Only positive samples are presented in the figure.

4. Discussion

There were rather similar P_{tot} loads entering the environment from B filters with a biotite layer and SF filters without P-adsorbing media; their treatments were sufficiently effective to fulfill the Finish Government Decree 157/2017 [1] as presented in Figure 1a. Biotite has been found to enhance the adsorption of phosphorus [10,22,24]. However, in some cases, SF filters without P-adsorbing media have been able to reduce the levels of P more than sand filters with P-adsorbing media [9]. The differences between results may be due to different P-adsorbing capacity of sand and specific P-adsorbing materials including biotite, different ferro sulfate products etc., and different experimental designs, i.e., full scale vs. pilot scale study.

Unfortunately, those previous publications have not provided any details to determine if the age of the filters could have exerted any effect on the filters' purification capacities. In our study, P_{tot} load was lowest in B filters and only 1 of 17 samples (6%) compared to 4 of 23 samples in SF filters (17%) exceeded the basic level described in the Finnish requirement [1], Seven of 17 samples (41%) in B compared to 14 of 23 samples (61%) in SFs exceeded the more stringent level of the Finnish requirement [1]. The use of biotite is supported the idea to turn by-products of the mining industry to useful products in wastewater treatment. There was no apparent seasonal effect in P_{tot} loads, although a previous study has claimed that there would be higher P_{tot} in effluents in the summer months, possibly due to consumption by the household of a phosphate-rich diet during summer [8].

Due to nitrification and denitrification, the B filters of the present work seem to be more effective in reducing nitrogen and BOD than the other filters studied, in accordance with previous results [22]. The effluents from B sand filters with P-adsorbing media contained significantly less N_{tot} and BOD_7 than the effluents of SF filters without P-adsorbing media and significantly less P_{tot} and N_{tot} than the effluent of MB filter (Figure 1a–c). Thus, the P-adsorbing layer enhanced the removal of nitrogen, as also reported previously [8]. However, in other Finnish studies, SF filters without P-adsorbing media have been able to reduce more N_{tot} than the sand filters with P-adsorbing media containing different ferro sulfate products or gypsum but not biotite [9,25]. The high percentage of total nitrogen as nitrate and the removal of total nitrogen are evidence for both nitrification and denitrification in B filters. The presence of nitrate in effluent is more favorable than the other forms of nitrogen since it would not consume oxygen after its release into surface waters [26,27]. A seasonal variation was only found in B, in which the N concentration as nitrate was higher in winter (2.6–9.0 g/cap·d) than in summer (0.20–0.70 g/cap·d, $p < 0.05$) apparently due to more extensive denitrification in summer.

The effluents of B filters had the lowest values of BOD_7, which is in line with previous Nordic studies [8,9,25]. All B filters in our work fulfilled also the requirements of the tighter 90% reduction required in the Governmental Decree [1] or in Swedish regulations governing the reduction in the demands for BOD_7 [28]. The good removal of organic matter in B filters was seen also in COD_{Cr} results; in our study, these loads were significantly lower in the B filter effluents than in the effluents from the MB filter. BOD_7 and COD_{Cr} displayed a high statistically significant positive correlation, it can be assumed that COD_{Cr} would be sufficient when measuring the effluents' oxygen demands.

The efficiency of B filters to remove P_{tot}, N_{tot}, and BOD_7 as required in the Finnish Wastewater Decree (157/2017) [1] was not affected by the season or the age of the filter, whereas age reduced the ability of SF filters to remove P_{tot}, N_{tot}, and BOD_7. The results showed that old B filters perform more consistently than old SF filters, although the age range of B filters (9–11 years) was somewhat narrower than the age range of SF filters (9–14 years). The efficiency of SF filters to remove N, P, and BOD_7 (as stipulated in the Decree [1]) and also COD_{Cr} was reduced as the filter aged. However, SFs aged less than 10 years old seem to be suitable for treating wastewater with respect to these parameters. The lifetime of sand filters has been assumed to be at most around 30 years [29]. It has been reported that P removal with an SF filter declined to such an extent that it no longer met the required level already after 250 days of use [30], which is a rather short time compared to the expected lifetimes of sand filters. According to our results, the lifetime could perhaps be less than 30 years in some cases, since some P_{tot} and N_{tot} values in SF filters exceeded the required level in the 14-year-old filters. Thus, there is a need to determine the effect of ageing on the purification efficiency and to find methods to delay the decline in their efficiency.

The quality of effluent emerging from the MB filter was the poorest of all the studied samples, and 100% of P_{tot}, 63% of N_{tot}, and 14% of BOD_7 samples did not fulfill the required loads [1]. For example, the P_{tot} load of the MB filter was approximately three to five times higher than in the SF or B filters, supporting earlier reports from a commercial modular sand filter where, on average, the P_{tot} concentration of effluent was four times higher than in sand filters with or without a P-adsorbing material [8]. Previously, MB filters have been found to be less effective than their SF or B counterparts [22,31].

Less than half of all effluent samples would reach a quality regarded as sufficient for bathing [23] (Figure 2a) or the recommended irrigation water quality [32] with regards to the numbers of *E. coli* and intestinal enterococci, confirming the previous results obtained with sand filters [8,10]. There were no clear differences in microbial quality between B, SF, and MB filter effluents. In a pilot-scale study, the inclusion of a separate phosphorus removal unit enhanced the removal of microbes [22], but in our full-scale study, this effect of P-adsorbing media on the removal of microbes could not be confirmed. The only statistical difference in bacterial data was found between *E. coli* numbers emerging from the SF filters; these were higher in summer than in spring, but no clear reason for this difference could be discerned.

It was important to note that *Campylobacter* was not detected in any effluents. Adeno- and noroviruses were frequently found in effluents; norovirus GII was the most prevalent virus (Figure 3b,c). The numbers of adenoviruses and noroviruses GI and GII in effluents were similar to those presented in a pilot-scale study [20]. Similarly, the numbers of F-specific coliphages were lower than those of somatic coliphages as observed previously [22]. It is noteworthy that both human adeno- and noro-viruses were detected over several seasons within the same filter, highlighting their prolonged persistence in these systems. This result is in line with the previous reports which have demonstrated the long-term persistence of virus genomes in different water samples [33,34].

The viruses present in these systems may pose a risk to human health via contamination of drinking or recreational waters [33]. In Finland and northern countries, the threat of groundwater contamination by escaping pathogens is especially high due to the shallowness of the soil layers protecting groundwater [30,35]. Furthermore, recreational waters can be contaminated should the effluent be released close to the recreational areas. It is important to ensure the safety of these waters, since effluent can pose a risk via nutrients or microbes. One option in private households is to ensure that the sand filtered effluent is passed through a P-removal unit. It has been found that these treatment units also reduce the number of bacteria and viruses [22]. There can also be antimicrobial amended layer added to the sand filter system [36,37]. In larger treatment units, such as public buildings e.g., schools and hotels or where the systems are shared between several households, disinfection of effluent can be a good option; it has been recommended that peracetic acid is a good choice as a disinfectant [8]. It is commonly recognized that when effluents are passed into a lake, river etc. then any contaminants will be rapidly diluted. Also, retention time must be long enough, and it is important to ensure that all wastewater flows slowly through the filter and there are no bypass flows. There was no clear seasonal difference. This may be on the fact that temperature of influent is approximately 20 °C and the temperature of soil may be close the annual mean temperature 2–3 °C [16].

The poor quality of the effluent released from MB filters may be traced to either design or construction faults, for example, the filter may have been partly blocked due to low permeability of biotite under the module. This module had been manufactured to handle wastewater from five persons, but the size of this modular biotite filter was only some 20% of the size what it should have been [31]. There were only two persons living in the household using the MB filter, but both of them used 186 liters of water per day. It has been pointed out that appropriate sizing is essential for the quality of effluent [8]. Therefore, the sizing of the system must be selected properly based on the number of residents and the estimated water consumption of the property.

5. Conclusions

In conclusion, buried sand filters with or without a phosphorus-adsorbing biotite layer remove nutrients efficiently from rural wastewater. Even though they are able to reduce the numbers of microbes, these can still represent a risk of microbial contamination to nearby natural water resources. The filters with a biotite layer may perform better than an SF in long-term usage. It is important that SF and B filters are designed to treat wastewater in exceptional situations, including holiday periods when water consumption and quality can differ from the norm; at these times, biological phosphorus binding can be inhibited due to either a shortage or an excess of carbon sources, leading to anaerobic conditions [15]. Effluent should be released to a location where contamination and the resulting health risks will be minimized if no post-treatment is applied. The microbial quality of effluent should also be considered when determining the efficiency of wastewater treatment in order to minimize hygienic risks. Future studies to find ways to improve effluent microbial quality would be beneficial.

The results indicate that the present types of sand filters (SFs) and sand filters with biotite (B) could trap wastewater BOD as set by law and 94% of B and 83% of SF fulfilled the P-reduction claim. The module sand filter would perhaps have been effective with a filter surface area of 25 m^2 [31].

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