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Greywater treatment in Lamella settler and combined filters

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ABSTRACT

The study was carried out to meet a certain level of water quality for reuse. It was undertaken to evaluate the removal efficiency of some pollutants from greywater (chemical oxygen demand (COD), biochemical oxygen demand (BOD_5), total nitrogen and total phosphorus) on a lab-scale. The experimental set-up has consisted of a preliminary Lamella settler combined with a filter reactor made of geotextile pocket filled with activated carbon and medium or fine sand. The lab-scale set-up has removed more than 70% of COD and BOD_5, 75% of total phosphorus, 45% of total nitrogen in the raw greywater. Treated greywater from the installation has met requirements for irrigation in water shortage areas.

Keywords: Greywater; Sand filter; Lamella settler; Removal efficiency; Activated carbon

1. Introduction

Water scarcity is expanding and threatening numerous areas and territories all over the world. Mekonnen and Hoekstra [1] found that two-thirds of the global population (4.0 billion people, mainly in India and China) live under conditions of severe water scarcity at least one month of the year, and half a billion people face severe water scarcity all year round. Moreover, Roson and Damania [2] reported that a quarter of the world population is facing severe water shortages and this number rises a double in the next decade. The freshwater resource quality and quantity are also decreasing due to human activity and global climate change. Furthermore, the risk of water scarcity is increasing by industrialization, population growth, a constant tendency toward urbanization. To alleviate the stress on water scarcity, saving freshwater and reusing wastewater is encouraged.

Greywater reuse can reduce the stress of water shortages because of decreasing pressure on using freshwater [3]. In recent years, greywater is emerging as an important resource because it can be reused for toilet flushing, irrigation, washing cars, etc., which can save up to 30%–60% household water consumption [3–5]. The greywater from washing basin, bath, shower and washing machine represents up to 43%–80% of total wastewater in a typical household [3–5]. The greywater contains various products from people's activities as soap, shampoo, shower gel, powders, skin, hair, pathogen. However, the concentration of contaminants in greywater is lower than in mixed household sewage including the kitchen sink and dishwasher outflow, as well as blackwater from toilets [5,6]. The greywater constituents in form of organic matter, surfactants, pathogens, and other contaminants have the potential to pollute air, soil, and plants [7]. Hence, greywater should be

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treated to reduce the concentration of contaminants before its reuse.

Sedimentation and filtration are one of the most popular and effective methods of water treatment [8]. Settlers equipped with inclined Lamella plates achieve higher efficiency than conventional ones due to lower turbulence at the same mean flow velocity [9]. The removal efficiency of biochemical oxygen demand (BOD_5) of the inclined surface clarifiers reaches 60% [10]. Moreover, to increase the water quality in effluent, filters are usually applied following sedimentation. The efficiency of a filter depends on the filter material. Nakhla and Farooq [11] suggested that slow sand filters provide satisfying removal efficiency of suspended solids, turbidity, organic matter in wastewater. In addition, slow sand filtration of the secondary clarifier and septic tank effluent is a potential solution for wastewater reuse in water scarcity areas [12,13]. Another way, non-woven textile filters was also applied to greywater treatment in the study of Spychala and Nguyen [14]. Their main advantages are low capital cost and simple service [15–17]. The quality of effluent is better when combined settlers and filters are applied for treatment. However, the biggest challenge is how to connect them in a limited space. A compact solution was designed to treat greywater for reuse in irrigation. The innovative lab-scale installation consisted of Lamella settler connected with combined geotextile filters, filled with activated carbon and sand was established.

The aim of the study was to evaluate the performance of this installation. Specific objectives were (1) to determine the removal efficiency of organic matter (chemical oxygen demand (COD) and BOD_5), and nutrients (nitrogen, phosphorus) of greywater on the lab scale, (2) to compare the treatment efficiency under different operating conditions, (3) to compare the processing efficiency at different combinations of the filter materials.

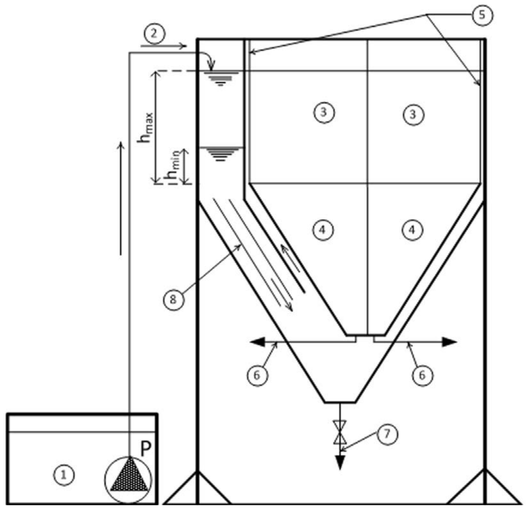
2. Materials and methods

2.1. Materials

The experiments were conducted on a lab-scale stand which was made of acrylic glass (Fig. 1). The total volume of the lab-scale installation was 20 dm^3. Lamella plates of the primary settler were inclined at angle 57°. Four combinations of filters (denoted as *R*) were installed inside the set-up. The structure of each reactor was shown in Fig. 2. The upper part (3) of each reactor was embraced with non-woven geotextile (TS 20) and filled with activated carbon whereas the lower part (4), made of acrylic glass, was filled with sand, as described in Table 1.

Each reactor had a drainage gravel layer of height 1 cm at the bottom; the sand filter of depth h = 35 cm was laid between the drainage gravel layer and the activated carbon layer of depth h = 40 cm and volume 0.9 dm^3.

Reactors were installed inside the lab-scale stand. After flowing along with Lamella plates, the greywater was seeped through geotextile and activated carbon, and then through the sand layer. The outlets of reactors were connected by the collecting pipes to take the treated greywater out of the lab-scale stand.



1. Greywater tank; 2. Influent; 3. Activated carbon (AC); 4. Sand;
5. Embraced AC with a non-woven geotextile (TS 20) layer;
6. Effluent; 7. Discharge sludge; 8. Lamella.

Fig. 1. The scheme of the lab-scale stands for greywater treatment.

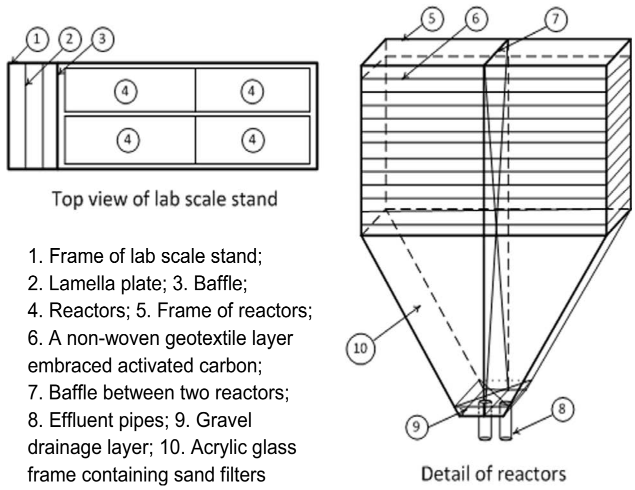


Fig. 2. The layout of reactors inside the lab-scale stand.

2.2. Greywater origin and composition

Experiments were conducted using real greywater which was collected in proportion 31%, 62%, and 7% of volume from the washing machine, bathroom and hand wash basin, respectively [14–18].

In every 39 dm^3 portions of greywater for the experiment, the following ingredients were present 12 dm^3 of laundry greywater discharged from the washing machine after washing 3–5 kg of clothes (20 g washing powder, Ariel, Procter & Gamble, Warsaw, Poland); 24 dm^3 of shower greywater containing 3.6 g of shampoo (Head & Shoulders, Procter & Gamble, Warsaw, Poland), 5.7 g of shower gel (Colgate-Palmolive, Warsaw, Poland); and 3 dm^3 of greywater collected from washing hand with 0.42 g of liquid soap (Serpol-Cosmetics Ltd., Poland).

Table 1
Description of the filter media

Reactor no.	Sand filter		Activated carbon
	Grain size, mm	Volume, dm^3	Type
R1	$0.5 \leq d < 1.5$	0.6	Particle size, <15 mm
R2	$0.125 \leq d < 0.5$	0.6	Pieces, 1–4 mm
R3	$0.125 \leq d < 0.5$	0.6	Particle size, <15 mm
R4	$0.5 \leq d < 1.5$	0.6	Pieces, 1–4 mm

2.3. Experimental set-up operation

Before adding to reactors, the filter materials were washed by using tap water. Prior to the start of experiments, all reactors of the lab-scale stand were filled with tap water to check their operability. The greywater was fed to the lab-scale stand by a metering pump at inflow rate 30 dm^3/h, during the first 5–8 min of each cycle. Four doses per day were applied – the treatment cycle for a dose therefore lasted 6 h. The experiment was carried out from November 08, 2016 to June 09, 2017. The temperature of greywater during the experimental process ranged from 17°C to 22°C. Removal of sludge (4 dm^3/week) was conducted from December 20, 2016. Greywater was treated in the filters under partly unsaturated conditions. The experimental process was divided into four periods:

- The first period lasted from 8 November to December 29, 2016. The lab-scale set-up was loaded at inflow rate 30 dm^3/h; the activated carbon column and geotextile were flooded 30 cm by the greywater (up to h_{max} in Fig. 1) at the time after 5–8 min after starting of a dose.
- The second period was accomplished from December 29 to February 02, 2017. All experimental conditions were the same as in the first period, and every week the effluent pipes were washed out inside every week.
- The third period lasted from February 02, 2017, to March 31, 2017. In this period, the treated greywater was recirculated in the middle of a cycle, with the volume of recirculation equal to the volume of the forward flow. The flow rate of recirculation flow was equal to 4 dm^3 min^{-1}. All reactors were back-washed once per week by treated greywater at a low flow rate (0.25 dm^3/min). Other conditions of this period were the same as in the first period.
- The fourth period (from March 31, 2017 to June 09, 2017) maintained the same conditions as the third period. However, the backwash was conducted every day with 0.4 dm^3 of treated greywater per each reactor.

2.4. Sampling and analyses

The samples of greywater influent and effluent from the lab-scale stand were collected and analyzed one or two times per week during the experiment. The numbers of samples collected to evaluate the treatment efficiency of the lab-scale stand in the four periods were 12, 5, 6, and 11, respectively. The following parameters were analyzed COD, BOD_5, total suspended solids (TSS), total phosphorus, total nitrogen. COD was measured by the dichromate method (spectrophotometer Merck 142, Germany) and a direct reading from the spectrophotometer at 420 nm (DR/2000, HACH). The BOD_5 of samples was measured using the OxiTop BOD system (WTW). The total phosphorus and total nitrogen concentrations were determined by kit (Merck, Germany) with Spectroquant kit (Nos.14752, 14773), respectively. TSS concentrations were determined by using the Standard Methods [19].

The treatment efficiency for the various contaminants was calculated as $E = (C_{in} - C_{out})/C_{in}$ 100 [%], where: C_{in} is the concentration of a given contaminant at the inflow, C_{out} is the concentration of the contaminant at the outflow.

2.5. Statistical analysis

The statistical analysis, conducted to compare treatment efficiency among reactors in the same period, and between the periods on a reactor at 95% confidence interval ($p \leq 0.05$) (ANOVA test and HSD Tukey test), using program *R*.

3. Results and discussion

3.1. Treated volume

All reactors run within water level range, h_{max} to h_{min} (Fig. 1). The maximum depth h_{max} was equal to 30 cm and the minimum h_{min} was variable, depending on the treated volume of effluent. In the first period (I), the treated volumes per one cycle have gradually decreased in all four reactors. The total treated volume, that is, effluent from all four reactors had fallen from 6.5 dm^3 down to 0.78 dm^3 at the end of the period (Fig. 3). At the beginning of the period, the treated volume among reactors was widely different. However, these differences were decreasing and at the end of the first period, they were statistically not significant (Fig. 3). The phenomenon which continuously diminished the treated effluent volume from all reactors was the clogging of filters [12]. After 30 d of this period, the treated effluent volumes from all reactors became stable, as follows: 0.21 ± 0.07 dm^3 (mean ± standard error of the mean), 0.20 ± 0.05 dm^3, 0.18 ± 0.05 dm^3, 0.33 ± 0.10 dm^3 per a cycle from R1, R2, R3, R4, respectively. Fig. 3 shows that the volumes treated by reactors R1 and R4 (medium sand) were always higher than by reactors R3 and R2 (fine sand), respectively.

In the second period (II), the effluent pipes of each reactor were rinsed inside once per week. The total amount of treated volume from all four reactors was higher, but it fluctuated wider than during the first period. This result showed that clogging occurred inside effluent pipes. The mucous and the translucent powder formed from fats, grease in the greywater were appointed as the cause of clogging [20,21]. The volumes treated in R1, R2, R3, and R4 during this period fluctuated and showed a decreasing trend decreasing treated volume from 4.0 to 0.97 dm^3, from 1.4 to 0.2 dm^3, from 2.2 to 0.85 dm^3, and from 2.5 to 0.1 dm^3, respectively. The treated volumes in this period were not correlated with the diameter of the sand filter grains as the first period. However, treated volume from all reactors correlated with the grain size of activated carbon. This result showed that in all reactors the clogging and biofilm formation in sand filter appeared.

In the third period (III), the difference in treated volume among 4 reactors were smaller than in the second period. The average treated volume per dose were equal to 1.03 ± 0.24 dm^3, 0.51 ± 0.18 dm^3, 0.55 ± 0.10 dm^3 and 0.86 ± 0.15 dm^3 from reactor R1, R2, R3 and R4, respectively.

The treated volumes from all reactors in the fourth period (IV) became more stable and higher than in the third period. The fluctuation of the treated volume on each reactor was smaller than in the other periods. The treated volume of R1, R2, R3, and R4 fluctuated from 2.3 to 0.5 dm^3, from 1.9 to 0.6 dm^3, from 1.8 to 0.8 dm^3, and from 1.3 to 0.6 dm^3, respectively. These results showed that the efficiency of the backwash treated a part of the clogging problems on the material of reactors.

The treated volumes by the reactors were disparate in the different operating conditions. The results showed that the treated volume was depended not only on the size of filter material but also on other factors. Moreover, they showed that the clogging phenomenon occurred in all reactors. This result was in line with the study of Zipf et al. [22] in which the filtration cycles of filters were longer when the diameter and permeability of filter material were higher [22,23].

3.2. Treatment efficiency of Lamella settler

The raw greywater was mechanically treated in the Lamella clarifier of parallel-flow type flow pattern when the influent, effluent and sludge were flowing in the same downstream direction [24]. Organic contaminant concentrations (COD and BOD_5) were analyzed 13 times during the whole experiment. Their values are depicted in Fig. 4a.

The removal efficiencies of COD and BOD_5 reached their highest levels at 64% and 58%, on average 37% and 29% (Fig. 4b), respectively.

The results of the study showed that the removal efficiency of COD and BOD_5 varied within the range 15%–64% and 20%–58%, respectively. This result is comparable to the removal efficiency of inclined surface clarifiers reported by WEF [9] and Qasim and Zhu [11] that reached 60% and 35%–40% BOD removal from raw municipal wastewater, respectively.

3.3. Total removal efficiency

3.3.1. COD removal efficiency

The average COD in the influent was 522 ± 134 mgO_2/dm^3 which fluctuated in the range from 285–885 mgO_2/dm^3 during the experimental process. The experimental result (Fig. 5) showed that the COD in the effluent was not significantly different among reactors in the same period, excepting R2 in the second period when it was the lowest; and R1 in the first and third period when it was higher than the other ones.

The average removal efficiency of COD shown in Fig. 6 has reached the following values: 64% ± 4% in R4, 61% ± 7%

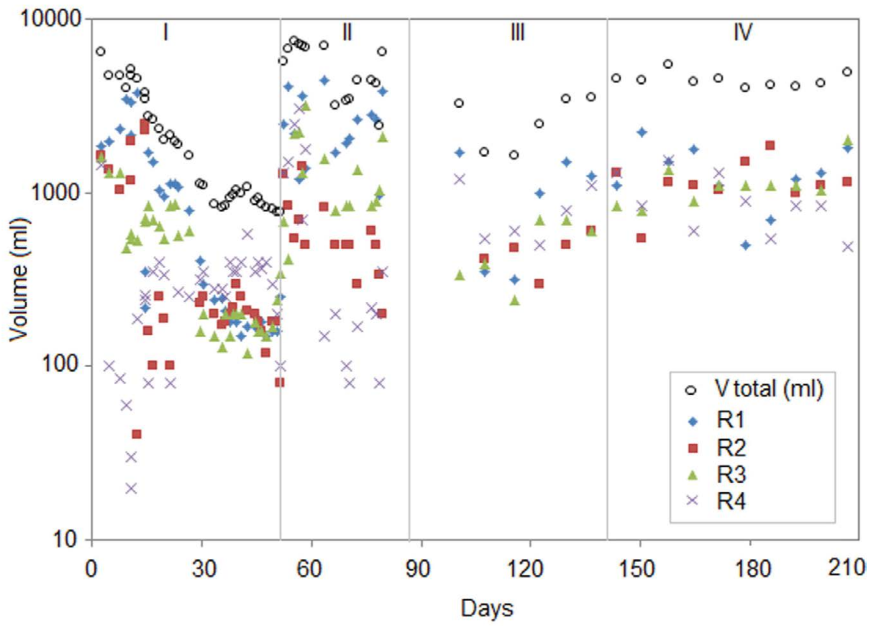


Fig. 3. Effluent volumes of greywater during four (I–IV) periods.

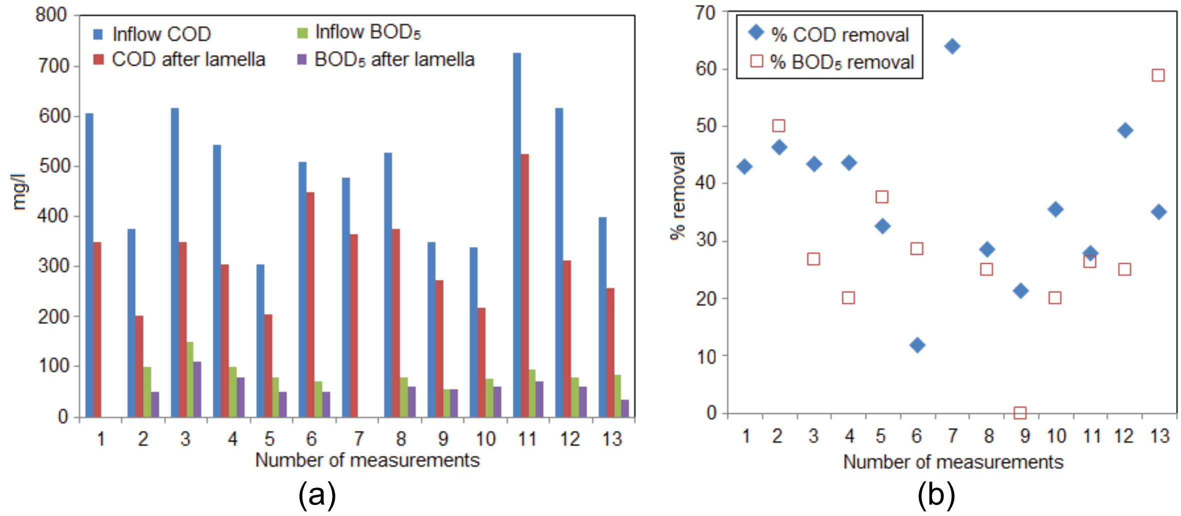


Fig. 4. Treatment performance of Lamella settler, (a) COD and BOD_5 before and after settler and (b) COD and BOD_5 removal by the settler.

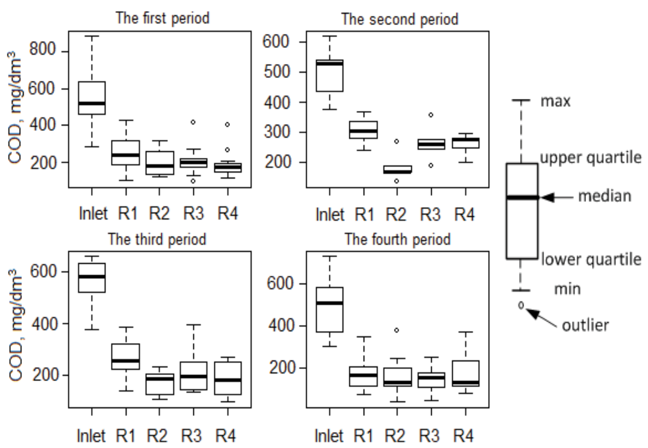


Fig. 5. COD in influent and effluent from particular reactors.

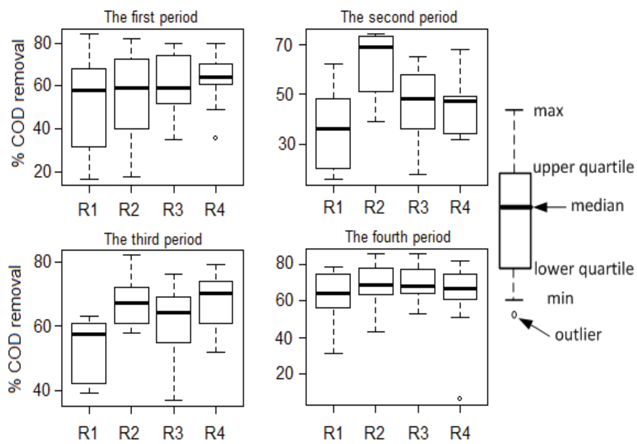


Fig. 6. The removal efficiency of COD in particular reactors.

in R2, 68% ± 5% in R2, and 70% ± 3% in R3 during the first, second, third, and fourth period, respectively. The removal efficiency between R3 and R4 in the first period was nearly the same, namely 61% ± 4% and 64% ± 4%, respectively. This result showed that the removal efficiency of COD in reactors with fine sand was always higher than those with medium sand. This result was similar to the conclusion from the study of Zipf et al. [22] and Abdel-Shafy et al. [25]. COD was reduced due to the biological degradation of proteins, fats, carbon hydrates and organic matter by biofilm on the filter material [26]. The COD removal efficiency of four reactors was less than 92.3% ± 2.1% and 99% for gravel, mulch applied earthworms with biochar filters [27] and biochar, sand filters [26]. However, this result was higher than 46% (filter 0.13mm) and lower than 72% (filter 0.025 mm) for sand filter [28]. In addition, the removal efficiency in the fourth period was the highest and stable among reactors. The result demonstrated that a microbial ecosystem was formed and developed on the filter materials [29].

3.3.2. BOD_5 removal efficiency

The BOD_5 of treated greywater highly fluctuated on reactors during the first and the second period. In these periods, the removal efficiency achieved on the low level which was lower than 40%. These fluctuations were affected by changing BOD_5 of raw greywater in the influent. Moreover, they occurred in the period in which biofilm was not yet formed stable on the media of the filter materials. In the third and fourth periods, it became more stabilized than in the previous period (Fig. 7). The values of BOD_5 in the effluent from all reactors in the fourth period fluctuated from 10 to 60 mgO_2/dm^3 and reached the lowest value at 10 mgO_2/dm^3 on R2 during this period, corresponding 82% BOD_5 removal (Fig. 8). ANOVA analysis (Table 2) has shown that the average removal efficiency of BOD_5 was significantly different among reactors in the same period and among the periods. The BOD_5 removal efficiency reached its highest performance during the fourth period.

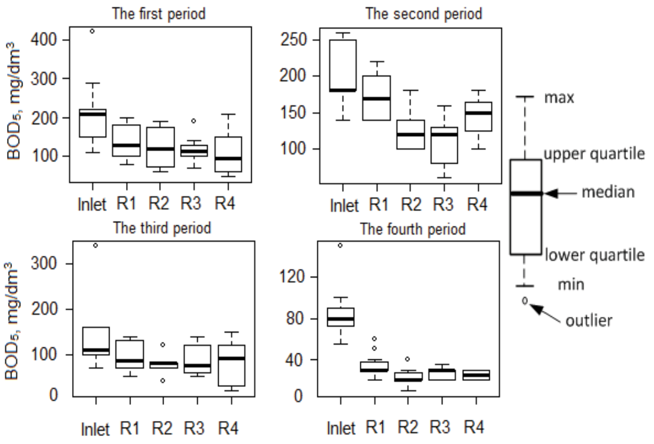


Fig. 7. BOD_5 in influent and effluent from particular reactors.

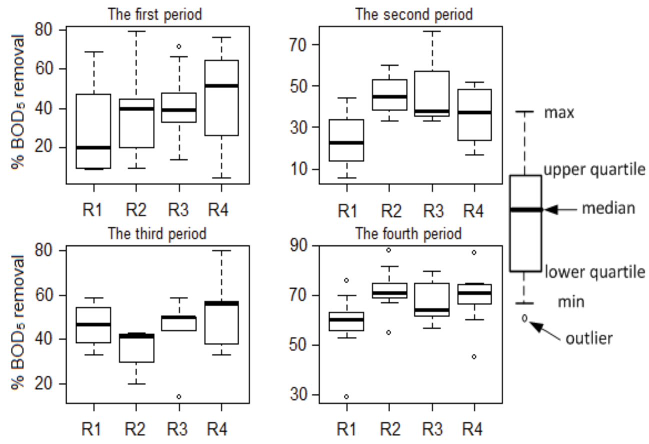


Fig. 8. The removal efficiency of BOD_5 in particular reactors.

Table 2
Treatment efficiencies of all reactors during the experimental time

Reactor no. and *p* for periods		Efficiency, %, in period				*p* for reactors
		I	II	III	IV	
COD	R1	51 ± 6	36 ± 9	54 ± 4	63 ± 4	0.062
	R2	55 ± 7	61 ± 7	68 ± 5	68 ± 4	0.287
	R3	61 ± 4	45 ± 9	61 ± 6	70 ± 3	0.022[a]
	R4	64 ± 4	46 ± 6	67 ± 4	63 ± 6	0.125
	p	0.329	0.183	0.108	0.634	
BOD_5	R1	30 ± 8	24 ± 8	46 ± 6	59 ± 4	0.0019[a]
	R2	37 ± 9	46 ± 6	39 ± 7	72 ± 2	0.0001[a]
	R3	41 ± 6	49 ± 13	43 ± 9	67 ± 2	0.0032[a]
	R4	46 ± 10	36 ± 8	53 ± 10	69 ± 3	0.0103[a]
	p	0.513	0.205	0.467	0.019[a]	
Total P	R1	51 ± 4	42 ± 13	64 ± 4	76 ± 5	0.182
	R2	57 ± 6	63 ± 19	75 ± 5	75 ± 2	0.400
	R3	63 ± 5	55 ± 8	63 ± 5	71 ± 4	0.480
	R4	65 ± 6	53 ± 5	71 ± 4	76 ± 2	0.152
	p	0.412	0.508	0.224	0.661	
Total N	R1	43 ± 10	–	10 ± 1	33 ± 9	0.236
	R2	52 ± 11	–	29 ± 1	33 ± 11	0.416
	R3	56 ± 11	–	29 ± 18	47 ± 8	0.432
	R4	42 ± 7	–	33 ± 0	44 ± 10	0.794
	p	0.715	–	0.384	0.645	

[a]95% confidence interval for statistically significant difference among all reactors in the same period and among all periods on a reactor.

The BOD_5 was treated by 59% ± 4%, 72% ± 2%, 67% ± 2%, and 69% ± 3% in R1, R2, R3, and R4, respectively (Fig. 8). The result in the fourth period for the removal efficiency of BOD_5 was not different from the study result of the sand filter column (72% ± 2% with the hydraulic loading rate was 0.032 m^3 m^{-2} d^{-1}) [8]. BOD_5 in the effluent of all reactors in the fourth period fluctuated from 20 to 40 mg/dm^3. The quality of this treated greywater meets the standard for agricultural irrigation in the scarcity areas [4–30].

Therefore, the lab-scale stand was effective in greywater treatment, especially during the last (IV) period. Moreover, the Lamella settler in the lab-scale stand has played an important role in removing a part of organic matter (as COD and BOD_5) in the raw greywater, similarly as in other research studies [9,10–25].

The performance of COD and BOD_5 removal was positive when compared to the efficiency of many other studies. The result of COD and BOD_5 removal of all reactors during four periods were significantly higher than those in other systems of the sand filter; sand filter + granular activated carbon; slate waste filter; or slate waste filter + granular activated carbon [25]; gravity sand filtration + chlorine disinfection [31]; sand filter (0.13 mm of diameter) + UV disinfection [28]. In addition, the removal efficiency of BOD_5 in the third and fourth periods was higher than in the system with 0.025 mm diameter of sand filter + UV disinfection but COD removal efficiency was lower than in it [31].

3.4. Phosphorus removal efficiency

The concentrations of total phosphorus in the raw influent and effluents during all four experimental periods are shown in Fig. 9. These results show that the total phosphorus concentration in the effluent from all reactors during all four periods was relatively low, especially during the third and the fourth period. The total phosphorus concentration in influent during four periods ranged from 5.3–19 mg/dm^3. The highest removal efficiencies in the successive periods were: 87% (R2), 80% (R2), 87% (R2), and 81% (R1), respectively (Fig. 10). These results indicate that the highest removal efficiency of total phosphorus was reached in reactor R2, consisted of activated carbon (pieces) and fine sand. It confirms the removal efficiency of total phosphorus in the study [15], which depended also on the grain size of filter material.

The total phosphorus of treated greywater was in not high ranged from 2–6 mg/dm^3. The removal efficiency of total phosphorus in this study was the similar result to Abdel-Shafy et al. [25] when greywater was treated with sedimentation + sand (1–2 mm) + gravel (2–4 mm) or gravel (2–4 mm) at hydraulic loading rate 86.5 dm^3/m^2/d. However, the removal efficiency of total phosphorus in this study was more depressed than in the study of greywater treatment on column filters with bark material (97% ± 2%), charcoal (91% ± 8%), or sand (78% ± 8%); but higher than with foam material (36% ± 34%) [8].

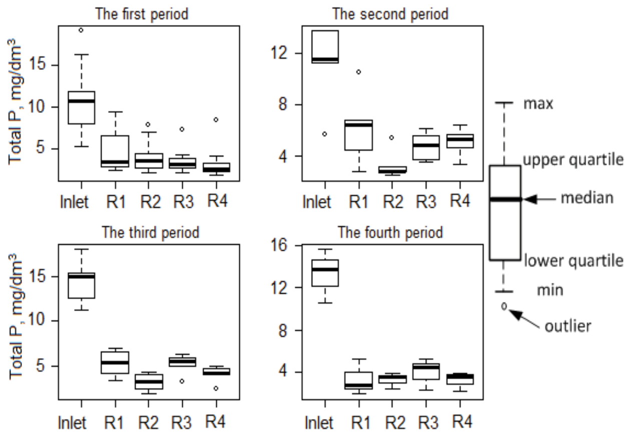


Fig. 9. Total phosphorus concentrations in influent and effluent from particular reactors.

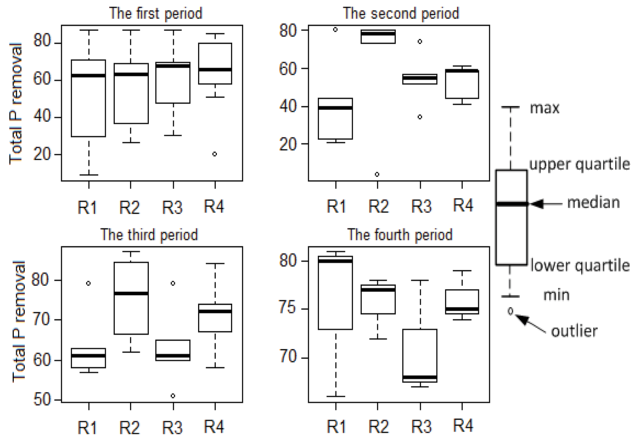


Fig. 10. The removal efficiency of total phosphorus in particular reactors.

3.5. Nitrogen removal efficiency

The total nitrogen concentration was measured to assess treatment efficiency in the first, the third, and the fourth period during the experiment (Fig. 11). The total nitrogen of the effluents from all reactors in the same period fluctuated from 5.0 ± 0.9 to 8.0 ± 2.6 mg/dm^3, from 20.0 ± 9.0 to 28.5 ± 13.5 mg/dm^3, from 15.3 ± 1.2 to 19.3 ± 2.0 mg/dm^3 in the first, the third, the fourth period, respectively. The average percentage removal of total nitrogen on R1, R2, R3, and R4 in the first period were 43% ± 10%, 52% ± 11%, 56% ± 11%, and 42% ± 7% while that were 10% ± 1%, 29% ± 1%, 29% ± 18%, 33% ± 0% in the third period and 33% ± 9%, 33% ± 11%, 47% ± 8%, 44% ± 10% in the fourth period, respectively (Fig. 12). Nakhla and Farooq [11] proved that the filtration rate and sand-size did an effect on the nitrification process. Nitrogen in greywater was treated by organic nitrogen degradation, and most probably due to nitrification and denitrification processes [27].

In the observed three periods, the efficiency of total nitrogen removal was not high. These results were lower than in studies [26,27] with biochar as the main filter medium. However, the result presented here is advantageous for irrigation purposes because of containing a little nitrogen useful for plants. Nitrogen in the study was treated by conversion and adsorption by activated carbon. This result agrees with Dalahmeh et al. [8] observation that a part of nitrogen was adsorbed by activated carbon and total nitrogen in the effluent was composed of N–NO_3 and N–NH_4.

3.6. Treatment efficiency among reactors

The efficiency of contaminant removal in all four reactors with the different grain sizes of filter materials during the four periods was analyzed by using the ANOVA test at a 95% confidence interval ($p < 0.05$). The analysis of results showed that there was no statistically significant difference in the efficiency of COD removal among four reactors in the same period. However, there was a statistically significant difference between the four periods in R3 ($p < 0.05$) (Table 2). Specifically, the HSD Tukey test has shown a difference between the second period (45% ± –9%) and the fourth period (70% ± 3%).

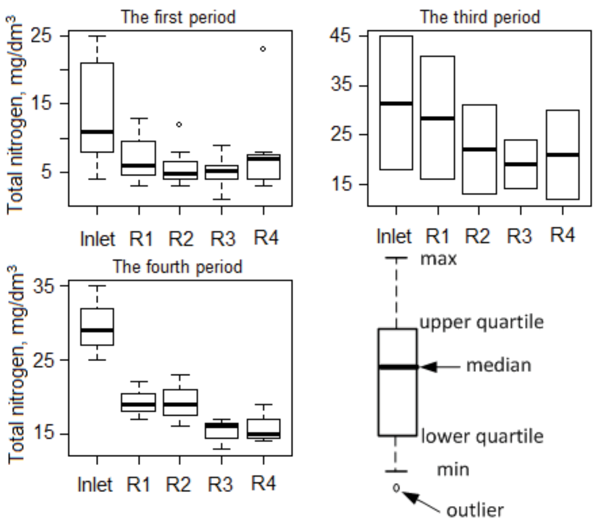


Fig. 11. Total nitrogen concentrations in influent and effluent from particular reactors.

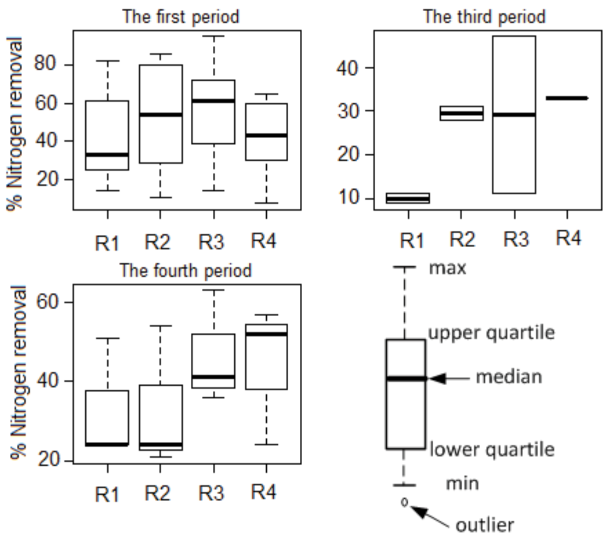


Fig. 12. The removal efficiency of total nitrogen in particular reactors.

However, the removal efficiency of BOD_5 had a statistically significant difference among the four periods in the same reactor and among the four reactors in the fourth period at a confidence interval of 95% (Table 2). The removal efficiency of BOD_5 by reactors in the fourth period was higher than by the other ones. The result suggests a hypothesis that the organisms have been inoculated on media and effect on BOD_5 removal efficiency. In the fourth period, the removal efficiency of BOD_5 on R2 was statistically significant difference comparing to R1 ($p < 0.05$). However, R2 was not significantly different from R3 and R4.

The efficiencies of total phosphorus and total nitrogen removal were not statistically significantly different between the four experimental periods (three periods for total nitrogen). Moreover, statistically significant differences among the four reactors in the same period were also not found at a confidence interval of 95%.

The result of statistical analysis showed that the fine sand (R2 and R3) is better than medium sand for BOD_5 removal from greywater.

4. Conclusions

- Greywater treatment in the Lamella settler and combined filters, using the innovative set-up, has fulfilled requirements for irrigation, therefore it has the potential to be applied for households in water shortage areas.
- The operating conditions of the experimental set-up have affected significantly both quality (COD and BOD_5) and quantity of the treated greywater effluent. The best results were obtained with recirculation equal to the forward daily flow at halfway through dosing and with the daily backwash of the filters.
- The combined filter materials in this study did not significantly influence the treatment performance, excepting the removal efficiency of BOD_5 in the fourth period, which was better using fine instead of medium sand.

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