https://erjm.journals.ekb.eg
ISSN: 1110-1180

DOI: ---------

ERJ
Engineering Research Journal
Faculty of Engineering
Menoufia University

An Integrated Modified Anaerobic/Slow Sand Filter Tertiary Treatment System for Domestic Wastewater Treatment at a Single Family Level

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ABSTRACT
A tertiary wastewater treatment pilot plant using a simplified UASB reactor followed by a SSF was operated on effluent wastewater from a house in an unsewered village in Egypt. The UASB reactor followed by a final sedimentation tank was operated at a constant hydraulic retention time of 12 hours while the SSF was operated at the different ROF 3, 4, and 5 m^3/m^2/day. A woven cotton textile media was placed above the sand layer to increase the filter efficiency and ease filter cleaning after the formation of the dirty skin. The overall system efficiency for the parameters tested was high and the values recorded for run 1 with a ROF of 3 m^3/m^2/day compared with the other rates were slightly higher. The main noticeable drawback was in the SSF operation period before clogging which varied drastically from 52 to 38 to 29 days for each run respectively. The highest removal efficiencies recorded were 99.67±0.04%, 98.51±0.44% and 98.06±0.43% for TSS, BOD_5 and COD respectively. While the removal rates of the nutrients monitored were 90.19±6.18%, 87.25±5.73% and 86.32±10.15% for NH_4-N, TN and TP respectively. Two bacteriological parameters were also monitored and their removal efficiencies were significantly high due to the biological dirty skin layer formed on the SSF and the removal values were 99.86±0.04% and 98.20±0.82% for Escherichia coli and fecal coliform respectively. Overall system evaluation can be rated as very low O&M requirements for both skilled manpower and energy requirements.

Keywords: *Wastewater; Anaerobic Treatment; Tertiary Treatment.*

1. Introduction

The consequences of urbanization, population growth, and climate change are making sustainable water use more difficult. Encouraging robustness in water management is a major development goal for many nations since it is closely linked to public health, food security, human rights, ecological services, and education [1].

Egypt's population increased at an average 2.1% yearly rate between 1989 and 2018, which is comparable to the global population growth trajectory. Due to the rising demand for food and other goods as well as direct consumption, this growing population puts strain on the limited supply of water [2]. According to the Falkenmark Index, in 2017 the total renewable water resource per capita was 628 m^3/yr, which was already below the threshold for water scarcity [3]. To overcome this escalating scarcity of natural water resources facing Egypt, many research work and ideas have been and are being currently postulated to solve or minimize the gap between the supply and demand. About 11 billion cubic meters per year are used for potable water and about 7 to 8 billion cubic meters per year are discharged as domestic wastewater. Treatment of domestic wastewater and its reuse for irrigation will help in many ways as it will decrease the pollution caused by the disposal of raw untreated domestic wastewater and its use in agricultural irrigation will decrease the high irrigation water currently used from the water resources (80-85)%.

On-site domestic wastewater treatment for further reuse using biological followed by physical treatment systems is thoroughly documented in literature [4 – 10]. Anaerobic treatment of domestic wastewater using different techniques using variable operating conditions is also documented in many research work [11-20]. Using a sand filter with grain size of 0.10 mm, secondary treated wastewater was tertiary treated and the parameters monitored were biochemical oxygen demand (BOD), chemical oxygen demand (COD) and total suspended solids (TSS). The average BOD value in the final secondary effluent was 82.67 mg/L compared with 33.33 mg/L obtained in the final filtrate, while average COD in the final secondary effluent was 169 mg/L higher than that recorded in the filtrate of 74.33 mg/L, while in the same manner TSS was 90 mg/L compared with 12.50 mg/L in the filtrate [21]. A simple anaerobic system followed by a rapid gravity sand filter obtained final effluent removal efficiencies of 93%, 87% and 93% for TSS, COD and fecal coliform respectively [22,23]. Using anaerobic treatment followed by trickling filters for the treatment of domestic wastewater is thoroughly documented in [24].

Using a slow sand filter with biochar and woodchips media was used for the tertiary treatment of anaerobic treated wastewater. At a hydraulic loading rate of 0.05 m/hr COD removal rate of 90%, total organic carbon (TOC) removal efficiency of 80% and turbidity removal was below 35 NTU [25,26]. An anaerobic baffled reactor followed by a membrane filtration system was used for domestic wastewater treatment and the efficiency of the system was tested for turbidity and COD with removal efficiencies of 87.20% and 94.60% respectively [27,28]. COD and TSS removal of above 90% was obtained by using a combined integrated biofilm filter settler-based system [29]. Slow sand filtration gave better removal results due to the formation of the biological dirty skin layer. For sand effective size between 0.30 to 0.60 mm and a filtration rate of 3.5 to 7.0 m/day the BOD and COD removal rates were 95% and 88% respectively [7,8,30,31].

2. Aim and Research Significance

The objective of this research is to obtain a simple on-site treatment system that can be adopted on the single household level for the treatment of the collected domestic sewage and its reuse in irrigation. The selected system is cost-effective both for construction and operation and maintenance costs. The selected system was a simplified upflow anaerobic sludge blanket (UASB) reactor as given by [16,32] followed by a final clarifier. The tertiary slow sand filter used in the tertiary treatment stage was enhanced with a woven cotton layer to enhance the filter efficiency and ease the filter cleaning process.

3. Experimental Program

3.1 Study Site

The pilot system was constructed in a un-sewered area in Sharkia Governorate in Egypt. The building is for a local farmer with 9 occupants in Ezzbet Abu Sharaf, Elzawamil Village, Markaz Bilbes north east of Cairo at coordinates 30°22'07''N, 31°28'01''E. Prior to adding the treatment system, wastewater was collected in a septic tank which is drained periodically by trucks. The treatment system was operated for a period of 193 days.

3.2 Wastewater Flowrate & Characterization

The average wastewater from the building ranged from (1.0-1.25) m^3/day. A small submersible pump was added in the existing septic tank to lift the wastewater to the treatment system; this tank functioned as a holding tank in our research work. During the monitoring period, seven parameters were monitored and the analysis of the influent values are as shown in Table 1.

Table 1. Influent wastewater characteristics

Parameter	Minimum value	Maximum value	Average value
pH	5.80	7.50	6.65
Total Suspended Solids (TSS) (mg/L)	425	783	604
Biochemical Oxygen Demand (BOD_5) (mg/L)	480	825	680
Chemical Oxygen Demand (COD) (mg/L)	535	1150	815
Total Nitrogen (TN) (mg/L)	80	96	88
Ammonia Nitrogen (NH_4-N) (mg/L)	22	62	42
Total Phosphorus (TP) (mg/L)	24	52	38
Escherichia coli (E.coli) (CFU/100 mL)	2.22E+05	5.1E+05	3.66E+05
Fecal coliforms (FC) (CFU/100 mL)	6.84E+05	1.2E+06	9.42E+05

3.3 Pilot Treatment System Configuration

The pilot treatment system consists of a simplified UASB reactor followed by a final clarifier and a slow sand filter for tertiary treatment as shown in figure 1. The system was constructed from PVC pipes and was operated for three runs (varying the filtration rate) with following characteristics: -

Anaerobic UASB reactor: -

Average flow rate = 1.138 m^3/day
Diameter of tank = 0.50 m
Wastewater depth = 1.80 m
Volume of reactor = 0.56 m^3
Hydraulic retention time = 12.0 hours

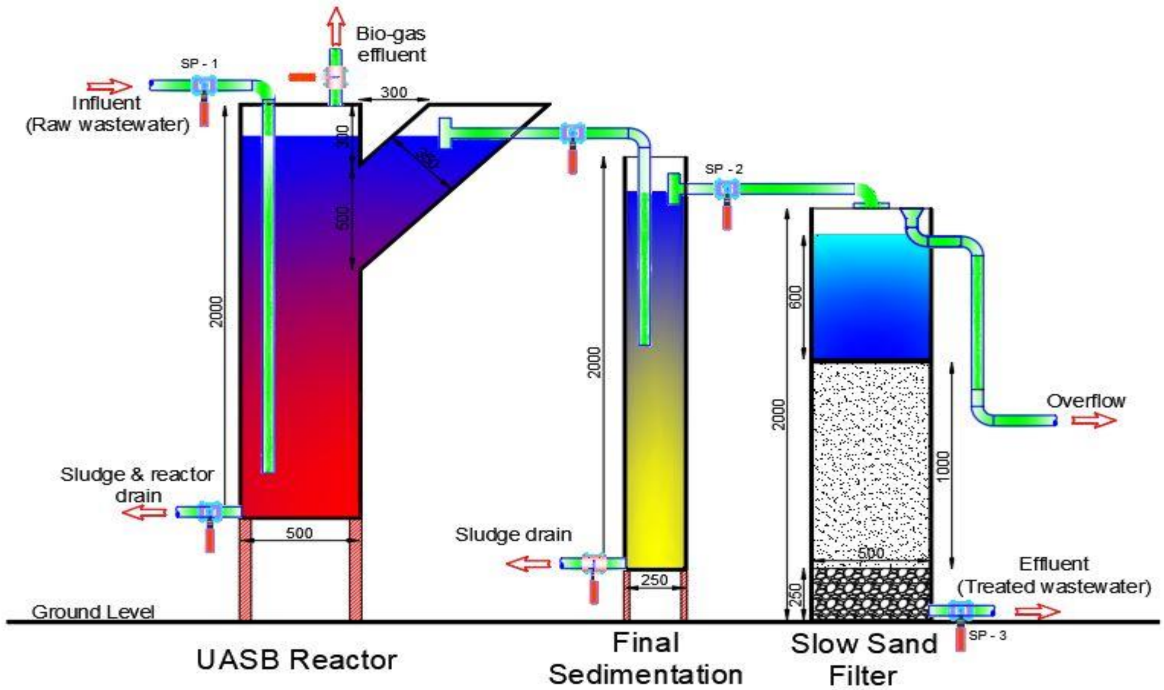

Figure 1 Schematic diagram of the pilot treatment system

Final clarifier (FC): -

Average flow rate = 1.138 m^3/day
Diameter of tank = 0.25 m
Wastewater depth = 1.90 m
Surface area of reactor = 0.0491 m^2
Volume of reactor = 0.0933 m^3
Surface loading rate = 23.18 m^3/m^2/day
Hydraulic retention time = 2.0 hours

Slow sand filter (SSF): -

Filtration rates = 3.0, 4.0, 5.0 m^3/m^2/day
Diameter of tank = 0.50 m
Sand depth = 1.0 m
Minimum overhead water depth = 0.60 m
Maximum overhead water depth = 0.75 m
One layer of woven cotton media.

3.4 Filtration Media

Two types of media were used in the slow sand filter; a woven textile cotton media placed on the surface of the sand media and their specifications are as follows:-

Sand media: -

Clean fine sand was used as filtration media with the following characteristics: -
Effective size of sand = (0.25-0.35) mm
Uniformity coefficient = below 3.0

Woven cotton media: -

A single layer of woven cotton media was used above the sand layer with the following characteristics: -
Fiber thickness = 27 * 27 Ne
Weft warp density = 25 *27 wire/cm
Pore size = 0.0018 mm

3.5 Analytical Experimental Measurements

Three sampling points were located in the pilot system; before and after the UASB reactor, after the slow sand filter. All the samples were analyzed in the laboratories of the Higher Institute of Engineering, El Shorouk Academy and Cairo Wastewater Company using Standard Methods (SM) [33] (APHA/AWWA/WEF 2017). Parameters monitored include total suspended solids (TSS), chemical oxygen demand (COD), biochemical oxygen demand (BOD_5), Escherichia coli (E.coli), Fecal coliforms (FC). pH values and temperature were recorded randomly using a multi-channel analyzer (Topac Consort C932). BOD values were measured using 300-mL incubation bottles and Hach HRI3P-2 (220V) incubator while COD values were measured using the closed reflux colorimetric method using a UV-VIS DR6000 benchtop, Hach spectrophotometer with wavelength range from 190 to 1100 nm and a resolution of 1 nm. E.coli and FC were measured using Quanti-Tray and Quanti-Tray 2000 (SM 9223 B). All the data were statistically analyzed using one-way analysis of variance (ANOVA) using JMP®, Version 13.2.1

(SAS® Institute Inc., Cary, NC) with application of the Tukey-Kramer test for post hoc comparison if needed.

3.6 Operational Schedule

The operation of the UASB reactor was started without inoculation and it was monitored for a period of about 60 days with the final clarifier before biomass build-up and reaching the steady state. After that the slow sand filter was connected to the pilot system operated for a period of 133 days (19 weeks) for the three runs and the following table shows the operational schedule and sampling frequency (Table 2).

The slow sand filter was given a period of 7 days for adjustment before each run and for the initial growth of the dirty skin layer on the woven cotton textile layer. Run 1 lasted for 52 days before clogging, while run 2 lasted for 38 days and run 3 duration was 29 days only; a 15 cms rise in the initial 60 cms water depth above the media marked the clogging of the filter. The filtration and flow rates from the SSF were maintained by adjusting the outlet filtrate valve and measuring the flow rate with a measuring cylinder and stop watch.

Table 2. Operational schedule and sampling frequency

	Run	R1	R2	R3	Sampling frequency
	Filtration rate (m^3/m^2/day)	3	4	5	
Monitored Parameters Samples	TSS	16	12	10	Twice/week
	BOD_5	11	8	6	Every 5 days
	COD	16	12	10	Twice/week
	TN	16	12	10	Twice/week
	NH^4-N	16	12	10	Twice/week
	TP	16	12	10	Twice/week
	E.Coli	8	6	5	Once/Week
	FC	8	6	5	Once/Week

4. Test Results and Discussion

The following sections demonstrate the results obtained by the operation of the pilot system both during the initial start-up of the UASB reactor and after the introduction of the SSF.

4.1 UASB Reactor Operation

As mentioned previously, the raw wastewater characteristics recorded high concentrations for all parameters and this was due to the local rural nature of experimental area with very low water consumption and possibility of the presence of animal wastes in the effluent.

The start-up period took about 60 days before reaching steady state and formation of the granulated sludge blanket. Consequently, the average removal ratios obtained for TSS, BOD_5 and COD, were 83±11.23%, 72±8.52% and 69±9.78% respectively. On the other hand, acceptable removal ratios were observed for total nitrogen (TN), ammonia nitrogen (NH_4-H) and total phosphorus (TP) and the average removal ratios were 48±5.60%, 51±12.48% and 42±14.88% respectively. However, in general, the removal rates didn't attain the permissible limits for secondary treatment for all parameters.

4.2 SSF Operation

The SSF was connected to the UASB effluent after reaching the steady state and was operated for three runs with variable filtration rates; 3, 4, and 5 m^3/m^2/day. Run 1 with the lowest rate of filtration gave the best removal results compared with the other two runs; but; however, the difference between the removal efficiencies between the three runs is negligible. The noticeable and observable feature is the SSF operation period as it varied drastically between the three runs and recording 52, 38 and 29 days for runs 1 to 3 respectively and each filter required an extra ten to fifteen days before effluent results reached the steady state. Removal in the SSF is attributed to the formation of the biological dirty skin layer on the top of the woven cotton textile layer with the fine sand media layer below. This gives a triple removal action; biological filtration in the dirty skin layer followed by physical filtration in the second two layers to trap any particles that might escape the dirty skin layer. The following sections demonstrate the removal efficiencies of the tertiary stage.

4.2.1 TSS Removal

Average effluent concentration of TSS from the UASB reactor was 102.68±5.12 mg/L while the average effluent after the SSF was 2.20±4.57 mg/L. Figure 2 shows the TSS removal percentages versus time for the three different SSF flux rates. The flux rate of 3.0 m/day exhibited high performance compared to the other loading rates in terms of TSS percentage removal, achieving an impressive average removal percentage of 97.86±1.15% after 52 days of operation before clogging. In case of flux rates of 4.0 m/day and 5.0 m/day the average removal percentage dropped slightly and was 90.57±4.43% and 86.81±3.51% after 38 and 29 days of operation respectively. Results obtained in run 1 are similar to those reported by [7] for a flux rate of 3.5 m/day and the run lasted for twenty days only.

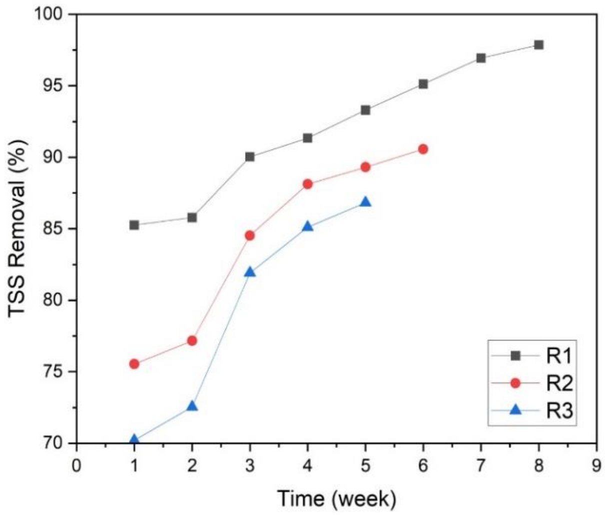

Figure 2. TSS removal percentages

4.2.2 BOD$_5$ & COD Removal

BOD$_5$ and COD removal percentages recorded high values as was experienced with TSS. Effluent concentrations after the UASB reactor were 190.4±14.58 mg/L and 252.65±18.14 mg/L respectively and the average removal rates for the first run with a flux rate of 3.0 m/day were 94.6±2.72% and 93.75±3.24% respectively. This run recorded effluent values as low as 10.12 mg/L and 15.80 mg/L for BOD$_5$ and COD respectively. For the other two runs R2 and R3 the removal efficiency dropped by about (5-10)% and the effluent values remained within the acceptable values for secondary treatment as per Egyptian requirements. Figures 3 and 4 show the removal efficiencies for the three runs for both BOD$_5$ and COD respectively. Results obtained are slightly higher than those documented by [7,8,30] under similar conditions and this is postulated due to the presence of the woven cotton media placed on the sand layer.

4.2.3 TN & NH$_4$-N Removal

TN and NH$_4$-N removal percentages were acceptable but slightly lower compared with other parameters discussed earlier. With regards total nitrogen, the UASB reactor removed about 48.12±6.23% and the SSF for run 1 removed about 75.48±4.43% giving a final effluent of 11.22±2.03 mg/L. The removal efficiencies in the other two runs dropped by about 5 to 10 %; figure 5. Ammonia nitrogen removal was similar to that of total nitrogen with about 51±3.45% removal in the UASB reactor giving an influent to the SSF of about 20.58±4.68 mg/L. The average removal efficiency was 79.98±6.19% giving and final effluent values of 4.12±1.27 mg/L. For the other two runs the removal efficiencies dropped by (5-10) %. Figures 5 and 6 show the removal efficiencies of TN and NH$_4$-N for the three runs.

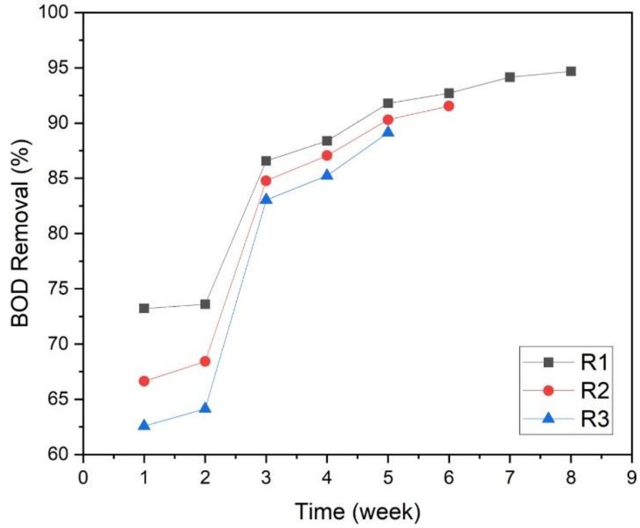

Figure 3. BOD$_5$ removal percentages

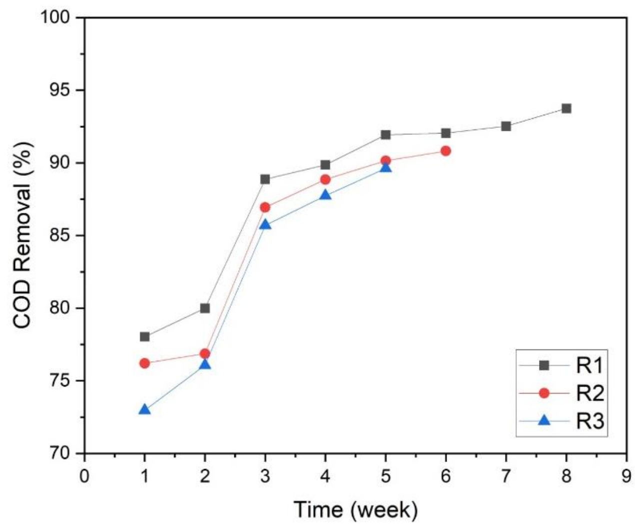

Figure 4. COD removal percentages

4.2.4 TP Removal

TP removal rates were similar to other nutrient removal tested in this research work. Effluent values in the raw wastewater was in the average of 38±4.55 mg/L and dropped after the UASB reactor to a values of 22.04±2.75 mg/L giving a percentage removal of about 42±4.55%. The average removal in the SSF for run 1 was 76.41±4.77% with an average effluent values of 5.20±1.05 mg/L. The removal efficiencies in the other runs dropped by a value of (5-8)%. Figure 7 shows the removal efficiencies of TP for the three runs.

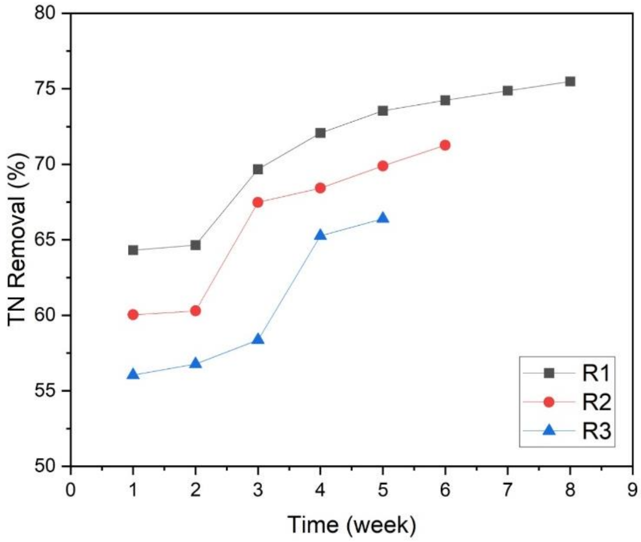

Figure 5. TN removal percentages

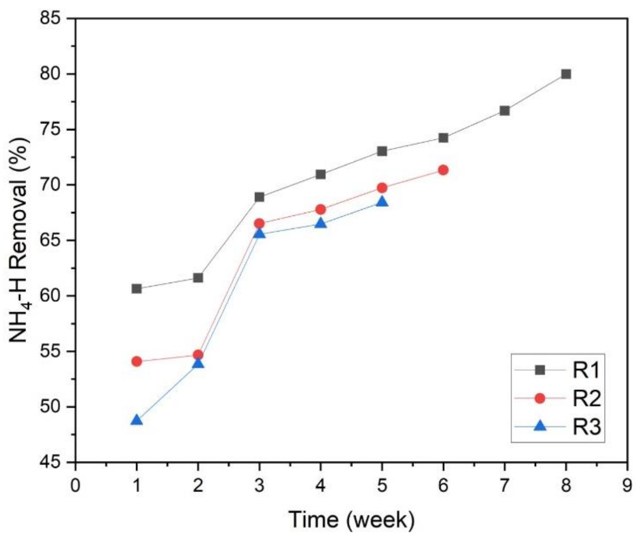

Figure 6. NH_4-N removal percentages

4.2.5 E.coli & FC Removal

Two bacteria types were monitored E.coli & FC and there removal rates in the UASB reactor were negligible. But on the contrary the SSF showed very high removal efficiencies which reached in some cases to 100 % and this is attributed to the presence of the biological dirty skin layer that is formed on the top of the SSF media layer. The average E.coli & FC removal efficiencies recorded for all runs were 99.86±0.04% and 98.20±0.82% respectively.

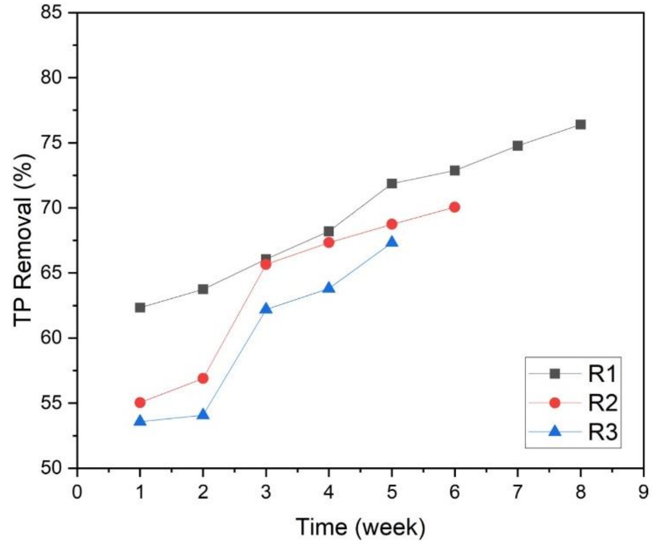

Figure 7. TP removal percentages

4.3 Overall System Removal Efficiencies

The overall system removal efficiency for all the three runs was very high and the variance in the removal rates is negligible and almost the same and the main difference between the runs was in the operation period before clogging. The duration of the three runs were 52, 38 and 29 days respectively and the total system removal percentages were higher than separate UASB and SSF removal efficiencies. The modified SSF with the woven cotton textile media was effective in many ways it helped in the improving the SSF removal efficiencies and it also simplified the filter cleaning process as the water level was lowered and the woven cotton textile layer was carefully removed. This textile cotton layer can be replaced or washed and returned back for operation when considered for low flow rates. Table 3 summarizes the average removal efficiencies for each run for all the parameters monitored in this study.

4.4 Gas Production

Gas produced by the UASB reactor was trapped at the top of the tank and measured using a Cole-Parmer RYTON flowmeter with a 3.5 digit LCD screen for direct gas flow rate recording. The total gas produced was measured using a Cole-Parmer flow rate monitor and totalizer. This totalizer was connected to the flowmeter and total gas production was read on the 6-digit LED display screen. The flowmeter had an accuracy of ±0.5% and a temperature operating range of (0 to 50)ºC while the totalizer had an accuracy of ±0.05%, temperature working range of (0 to 65)ºC and an update rate of one second. The gas measured was in the range of (0.30-0.45) m^3/day reflecting a COD removal range of (370-795) $gCOD_{removed}$/

m^3/day. However, the gas produced was not utilized by any means and it was left to diffuse in the atmosphere and occasional manual trails were done to determine its flammability and it demonstrated the presence of high methane content.

Table 3. Overall system removal efficiencies

Parameters	(%) Removal efficiency		
	Run 1	Run 2	Run 3
Total Suspended Solids (TSS)	0.04±99.67	0.52±98.40	0.66±97.76
Biochemical Oxygen Demand (BOD_5)	0.44±98.51	0.85±97.63	0.68±96.96
Chemical Oxygen Demand (COD)	0.43±98.06	0.71±97.15	0.89±96.78
Total Nitrogen (TN)	5.73±87.25	4.97±85.06	6.71±82.52
Ammonia Nitrogen (NH_4-N)	6.18±90.19	7.25±85.95	8.16±84.52
Total Phosphorus (TP)	10.1±86.32 5	11.2±82.63 5	10.7±81.05 8
Escherichia coli (E.coli)	0.04±99.86	0.04±99.86	0.04±99.86
Fecal coliforms (FC)	0.82±98.20	0.82±98.20	0.82±98.20

4.5 Overall System Operation

The overall system operation was smooth with no any drawbacks or malfunctions recorded during the monitoring period. Occasionally, the household owners were left to follow-up the system after some guidance and explanation was given to them. The system initial cost is very low and its operation and maintenance requirements are very low both with regards cost and required skilled manpower. A very low rate submersible pump was only required to lift the wastewater to the UASB from the existing septic (holding) tank.

4.6 Sludge Handling and Disposal

Although sludge collection facilities were made after the UASB and FC, sludge was not removed from the UASB reactor as it was reported to be counterproductive especially for reactors at a household level with low loading rates and this might affect the sludge blanket formed [12,16,17]. Sludge granules that might be washed out with the UASB effluent were trapped in the FC; the FC in turn was de-sludged daily with an amount of about 1 to 5 liters drained manually and disposed in nearby agricultural land. Sediments from the biological dirty skin layer were buried in the soil due to the potential risk of the presence of any pathogens.

5. Conclusions

Operation of the pilot system understudy on a household level proved to be very promising in many ways. The system is easy to construct and operate and helps to reduce the pollution effect of discharging untreated wastewater to the environment and produces treated effluent water that can be further reused for irrigation. Results of operating the system can be summarized in the following points: -

1. Using a woven cotton textile media above the sand layer increased filter efficiency and makes the .filter cleaning easier
2. Flux rate of 3.0 m/day is the most efficient rate of slow sand filter and achieved the longest operating period up to 52 days yet the removal efficiencies varied negligibly compared with other flux rates.
3. The system has a magnificent overall removal efficiency of up to 99% for TSS, BOD_5 and COD.
4. The system has an acceptable removal ratio up to (85-90)% for TN, NH_4-H and TP.
5. Slow sand filter with woven cotton layer has a stunning removal ratio of microbial content up to 99%.
6. In case of filter clogging the woven cotton textile layer can be removed, washed, and reused again without any extra cost.
7. Sludge production by the system was very low and negligible due to the anaerobic digestion in the UASB.
8. The gas produced by the UASB reactor can utilized as a source of energy which can be taken as an add-up economic value for the system.

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