Combined coagulation and intermittent sand filtration for on-site treatment of greywater

S Singh, M M Ahammed and I N Shaikh

Civil Engineering Department, S V National Institute of Technology, Surat, India

E-mail: shaikhirshad1990@gmail.com

Abstract. Performance of coagulation followed by intermittent saturated sand filtration system was evaluated for greywater treatment using real greywater. Filters with two different grain sizes were used to study the effect of media size on the removal. Filters were charged daily with 20 L of greywater coagulated with polyaluminium chloride (PACl). Performance of the filters were evaluated based on physicochemical and microbial parameters. Results showed that coagulation followed by sand filtration resulted in 94, 76 and 80% reduction in turbidity, BOD and COD respectively. Also, more than 99% of total and faecal coliform removal was observed. Sand filter with smaller grain size performed significantly better than the sand filter with coarser grain size. Coagulation followed by filtration showed stable and reliable performance as the effluent quality was insensitive to fluctuations in influent quality. Combined coagulation and sand filtration produced effluent conforming to different reuse standards.

1. Introduction

Water demand is increasing all over the world due to rapid industrialization, population growth and economic development. Due to this, alternative source of water for non-potable purposes are being investigated. Domestic wastewater originating typically from bathrooms, hand basins, kitchen and laundry is termed as greywater (GW). Greywater accounts for 50-80% of urban wastewater [1] and can play an important role, converting a significant fraction of wastewater to a valuable resource. Greywater has lower levels of solids, organic matter and pathogenic microorganisms compared to those in gross domestic wastewater and daily production of GW makes it a reliable source of water [2]. While GW can be treated by various physical, chemical, biological and natural systems [3], GW characteristics along with local conditions such as temperature, available space and finance will decide the GW treatment technology to be selected and each of these systems has its own advantages and drawbacks.

Granular filtration is a simple filtration technique involving use of media for filtration and is good at removal of solids, moderate at removal of organisms. Granular filtration system has the advantage of being compact and can be accommodated even at a small place [4]. Cost associated with the physical treatment system is very low as most of the materials used are locally available. Granular filters are suitable with respect to energy consumption, land requirement, sludge generation, and are also durable and robust as fluctuations in GW composition do not affect their efficiency [3].

Number of studies have been reported in the literature on the efficiency of granular filtration for GW treatment [5]. These filters remove up to 38-98 % of organics, and 58-99% of suspended solids [3]. However, filtration alone cannot meet the GW reuse standards [6] and this shows the need for some pre-treatment. Settling and chemical coagulation can be used as pre-treatment for filtration. Filters can be operated under saturated [7] or unsaturated conditions [2]. Ghaitidak and Yadav [8] reported 88, 99 and 98% reduction in BOD, turbidity and faecal coliforms (FC) respectively, in continuously operated...
saturated sand filter. Only a few studies reported physicochemical treatment of GW [6,7] and considered effect of grain size on the performance of filters [5].

In the present study the performance of intermittently operated saturated filters were evaluated using real GW coagulated with polyaluminium chloride (PACl). Filters with two different grain sizes were used to study the effect of media size on the contaminant removal. Performance of the filters were evaluated based on physicochemical and microbial parameters.

2. Materials and methods

2.1. Materials

Naturally occurring river sand passing through 0.80 mm and retained on 0.40 mm was used as filtration media in filter 1 named as SF1 and sand size of 0.80-1.18 mm was used in filter 2 named as SF2. Coarse sand (1.18-4.75 mm) and gravel (4.75-12.00 mm) were used to support the sand filtration medium in both the filters. Particle size distribution was analysed according to [9]. The sand was washed several times using tap water until the wash water became clear and was sun dried. Polyaluminum chloride (PACl) was used as a coagulant in the present study.

Greywater generated from Mother Teresa Bhavan (girls hostel) located at Sardar Vallabhbhai National Institute of Technology, Surat, India was used in this study. The hostel has separate collection systems for blackwater and GW. Hand basins, bathrooms, showers and laundry were the sources of GW. Greywater was diverted from the collection pipe into a 500 L collecting tank where the GW was homogenously mixed. Since the peak generation of GW was found to occur between 6:00-8:00 am, samples were collected during this time. A total of 60 GW samples were collected during the period November 2018-January 2019.

2.2. Filter installation

Two identical plastic containers (internal diameter 0.42 m, height 0.80 m) brought from the local market were used in the study. The filter columns were filled with distilled water to allow uniform media packing and then manually packed to a depth of 5 cm with a gravel layer followed by 5 cm layer of coarse sand and 40 cm layer of fine sand and coarse sand in SF1 and SF2, respectively. Presence of water inside the filter before loading the sand was to avoid the development of air pockets and short circuiting. A perforated plastic jar (0.40 m internal diameter and 0.20 m height) was used as a diffuser to avoid disturbance to the top layer of the media during the charging of the filters as sudden pouring of GW may detach the microbial mass developed on the media in the top layer of the filter. The outlet was provided in such a manner that a water depth of 5 cm was maintained over the filter media. Figure 1 represents schematic diagram and photograph of the filter.

2.3. Filter operation

Chemically coagulated GW was used as the feed to both the filters. Optimum coagulant dose was determined daily using jar test (DBK instruments, Mumbai, India). For this PACl was dosed in increasing concentration to six 1000 ml jars filled with raw GW, then samples were rapidly mixed at 100 rpm for 2 minutes, followed by gentle mixing at 30 rpm for 10 minutes, and then after settled for 30 minutes. Residual turbidity was measured, and the optimal coagulant dose was derived. A 60 L container was used to coagulate the GW before feeding into the filters. Both the filter columns were operated in downflow mode and were manually charged daily once with 20 L of coagulated real GW. Flow rates were measured daily for initial one minute of filter operation immediately after the filters were charged. Filter operation was stopped after 60 days due to filter clogging.
2.4. Analytical methods
Greywater samples were analysed for turbidity, total solids (TS), total suspended solids (TSS), pH, electrical conductivity (EC), total chemical oxygen demand (COD), biochemical oxygen demand (BOD), according to standard methods [10]. pH and EC were measured using portable Hanna instruments (HI 98130), while calibration was performed using standard solutions. Turbidity was measured with Systronics turbidity meter 135. COD was analysed using closed reflux titrimetric method (5220 C). Sterilised bottles were used to collect samples for microbial testing and were analysed for total and faecal coliforms using multiple tube fermentation method as per standard methods [10]. Statistical software SPSS 10.0 was used for the statistical evaluation of the results.

3. Results and discussion
3.1. Raw greywater characteristics and effect of coagulation
The summary of the raw and coagulated greywater (GW) characteristics considered throughout the study period of two months in terms of mean, SD and range are presented in Table 1. It is seen that most of the parameters were within the range of values reported by various authors [1,6,8]. The GW used can be considered as of medium strength in terms of organic contents. It may be noted that wide variations in the characteristics was observed as indicated by the range and SD values even though the source of collection was the same. This large variation in the characteristics is one of the important issues to be considered while selecting the treatment options for GW [6]. The relatively high COD/BOD ratio (>2.0) observed in the raw GW indicates the suitability of physicochemical treatment of GW.

The optimum coagulant dose varied in the range of 140-260 mg/L with a mean value of 190 ± 30 mg/L. In PACl treatment, mean turbidity of GW dropped from 84 NTU to 12 NTU (removal 86%). Vinitha et al. [1] reported turbidity removal from 83 to 4 NTU (removal 93%) in investigating mixed GW. While Ghaïtidak and Yadav [11] reported turbidity removal in the range of 96-98% at different PACl doses with the pH range of 5.5-8.5. In the present study the turbidity removal was less than the range reported in the literature which could be attributed to pH adjustment in those studies.

Significant drop in pH was observed after dosing the GW with the coagulant. The mean pH value of raw GW was 7.92 ± 0.18 and it was dropped to 7.04 ± 0.26 after coagulation. pH of coagulated GW increased with increase in pH of raw GW as observed by Vinitha et al. [1] and pH drop was proportional...
to the coagulant dose. pH decreases after coagulation due to the release of H + ions in the hydrolysis reaction. When an aluminium-based coagulant is added as PACl in the water, the metal ion is hydrolysed to form aluminium hydroxide flocs, as well as hydrogen ions as shown in equation 1 [4].

$$\text{Al}_2(\text{OH})_3\text{Cl} \rightarrow \text{Al}_2(\text{OH})_3^{3+} + 3\text{Cl}^- + 3\text{H}_2\text{O} \rightarrow 2\text{Al} (\text{OH})_3 + 3\text{H}^+ + 3\text{Cl}^- \quad (1)$$

| Parameter | Unit | n  | Raw greywater | Coagulated greywater | Removal (%) |
|-----------|------|----|---------------|----------------------|-------------|
| Turbidity | NTU  | 45 | 46-127        | 84 ± 22              | 85.7        |
| TS        | mg/L | 16 | 460-780       | 624 ± 99             | 22.4        |
| TSS       | mg/L | 16 | 60-380        | 212 ± 95             | 73.6        |
| pH        | -    | 60 | 7.32-8.36     | 7.92 ± 0.19          | -           |
| EC        | µS/cm| 60 | 506-1128      | 758 ± 114            | -           |
| Alkalinity| mg/L | 32 | 190-520       | 317 ± 87             | 40.1        |
| BOD       | mg/L | 12 | 27-168        | 110 ± 45             | 64.5        |
| COD       | mg/L | 5 | 165-280       | 230 ± 38             | 65.2        |
| TC        | MPN/10| 11 | 1.2x10⁶        | 4.7x10⁵ ± 2.1x10⁵ ± 8.0 | 95.53 |
| 0 mL      |      |    | 1.1x10⁷       | 3.5x10⁶ ± 10⁴        |             |
| FC        | MPN/10| 11 | 1.6x10⁵        | 4.0x10⁵ ± 1.7x10⁴ ± 95.75 |
| 0 mL      |      |    | 1.2x10⁶       | 3.9x10⁵ ± 8.6x10⁴   |             |

n, number of samples; SD, standard deviation

The hydrogen ions react with the alkalinity of the water and, in the process, lower the pH of the water [11]. Hence, lower alkalinity value in the coagulated GW. Coagulation resulted in an increase in EC of GW due to the addition of dissolved ions by PACl dosage. The mean BOD and COD removals achieved during PACl coagulation were 63 and 65% respectively. The organic content removal in present study agrees with Ghaitidak and Yadav [11] who reported 55-65% and 43-64% removal of BOD and COD in a study of mixed GW at pH range of 5.5-8.5.

Coagulation of GW significantly reduced total coliforms (TC) and fecal coliforms (FC) concentration with a mean 95% removal efficiency. The efficiency of coagulation system for TC and FC reduction observed in present study was less than that was reported by Ghaitidak and Yadav [11] who reported more 99% bacterial reduction at different pH values. Higher bacterial removal reported by this author was mainly because of the pH adjustment. By comparing the characteristics of the raw and coagulated GW with USEPA [12] and CPCB [13] standards, it was seen that this GW cannot be reused for any of the purposes without further treatment.

3.2. Performance of sand filters
Two identical saturated sand filters with two different grain sizes (SF1 and SF2) were used to study the effect of media size on the contaminant removal. The summary of the results is presented in Table 2 while variation in influent and effluent turbidity from the filters are given in Figure 2. Filtration rate in SF1 was reduced from 15.42 to 10.67 m²/m²/day while it was reduced from 33.70 to 21.66 m²/m²/day in SF2. Flow rate reduction was less in SF2 compared to SF1 which can be attributed to higher grain size of sand in SF2. Influent turbidity removal was 67 and 58% in SF1 and SF2 respectively indicating significantly better performance of SF1 compared to that of SF2 (Table 2). This was presumably due to longer retention time of GW in SF1 than SF2, which increases attachment of contaminants onto the media in SF1. Results are in agreement with Jenkins et al. [14] who reported higher turbidity removal when sand with effective size of 0.17 mm was used instead of 0.52 mm while treating surface water. The effluent turbidity from all the filters was fluctuating with influent turbidity values during the first
few days of filter operation and later it stabilized. This is because of accumulation of suspended solids in the voids and availability of uniform area for flow. Straining and sedimentation within the filter media are principal mechanisms responsible for removal of turbidity in filters [15]. Similar treatment performance of filters has been reported in the literature [6].

![Figure 2. Variation of influent and effluent turbidity from the filters (Please note the different scales for influent and effluent values).](image)

The filtration results in increased pH and EC values in both the filters. Filter media leaching due to higher filtration velocity and extremely limited salt adsorption capacity of sand could be the reasons for the higher pH and EC value in the effluent [2]. EC after filtration was increased in both the filters due to increase in dissolved solids. Young-Rojanschi and Madramootoo [16] while treating drinking water using household biosand filter (BSF) found that in saturated filter both pH and EC increased during filtration. The effluent pH from both the filters was in the range 6.5-8.5 which meets both the USEPA [12] standard of urban reuse, restricted access area irrigation and agricultural reuse and CPCB [13] standard for discharge into inland surface water, discharge into land for irrigation and industrial cooling.

Performance of filters in terms of BOD and COD removal and variation of influent and effluent TC and FC from both the filters are presented in Figure 3. BOD and COD removals followed similar trends. SF1 gave the better performance with BOD and COD removal of 46 and 50%, respectively, while SF2 gave the poorer BOD and COD removals of 31 and 41%, respectively. SF1 performed better than SF2 in terms of organic content removal. This is due to smaller grain size which results in longer residence time of GW in the filters as a result of reduced flow rates in SF1 (data not shown). Ochoa et al. [5] also reported lower reduction in influent COD when effective size was increased to 0.6 mm from 0.3 mm while treating mixed GW in intermittent sand filters. The mean removals observed in the present study is lower than those reported in the literature for different types of filters treating GW. For example, Dalahmeh et al. [2] reported 75 and 72% removal of BOD and COD for synthetic GW when filter was operated in intermittent mode. These higher values could be attributed to the higher influent concentration in their study. It may be noted that the mean BOD and COD values in the influent was low as the filters received coagulated GW hence the poor removal of organics content was observed.

It may be noted from Figure 3a that BOD removal improved with time of operation in the filters and achieved almost constant values despite changes in the influent concentration. Over the period as the thickness increases the slime layer may act as a fine straining mat and improves the removal of fine particles contributing to BOD and COD removal [17]. Along with physical straining, sedimentation, adsorption and biological process through the formation of biofilm layer on the upper surface of sand are responsible for removal of organic content from influent GW [17].
Figure 3. Changes in influent and effluent BOD, COD, TC and FC from different filters.

Young-Rojanschi and Madramootoo [16] while treating water reported that performance of saturated filters improved significantly with time due to development and maturity of biolayer. Effluent from all the filters during all the runs of experimental study was below USEPA [12] standards for restricted access area irrigation and construction (BOD<30 mg/L) and CPCB [13] standards (BOD<30 mg/L) for discharge into inland surface water and discharge into land for irrigation.

Table 2. Characteristics of treated greywater in coagulation and filtration

| Parameter | Unit | n | Influent | SF1 | SF2 |
|-----------|------|---|----------|-----|-----|
|           |      |   | Mean ± SD| Mean ± SD| Removal (%)| Mean ± SD| Removal (%)|
| Turbidity | NTU  | 45| 12 ± 5   | 4 ± 2   | 66.7 (95.2)  | 5 ± 2   | 58.3 (94.0)  |
| pH        |      | 60| 7.04 ± 0.26 | 7.62 ± 0.23 | - | 7.51 ± 0.19 | - |
| EC        | µS/cm| 60| 815 ± 119 | 898 ± 128 | - | 883 ± 141 | - |
| BOD       | mg/L | 12| 39 ± 14  | 21 ± 9  | 46.2 (80.9)  | 27 ± 10 | 30.8 (75.5)  |
| COD       | mg/L | 10| 80 ± 21  | 40 ± 13 | 50.0 (82.6)  | 47 ± 13 | 41.3 (80.0)  |
| TC        | MPN/10 mL | 11| 2.1x10^5 ± 5.3x10^3 | 97.48 | 9.1x10^3 ± 6.8x10^3 | 95.67 |
| FC        | MPN/10 mL | 11| 1.7x10^4 ± 2.0x10^3 | 98.82 | 3.7x10^2 ± 1.3x10^2 | 97.82 |

n, number of samples; SD, standard deviation; values in the parenthesis indicate overall removal (i.e. combined coagulation and filtration system)

Figure 3(c and d) presents variations in influent and effluent TC and FC from the filters. While the bacterial removal was low initially, with time it improved significantly in all the filters. The TC and FC removal in SF1 was 1.60 and 1.93 log compared to 1.36 and 1.66 log in SF2. Bacterial removal in SF1 was significantly (p<0.05) better than that of SF2 which could be attributed to the reduced flow rate and
corresponding increased retention time in SF1. Jenkins et al. [14] also reported 0.3 log higher bacterial removal when smaller grain size was used (d_{10} = 0.17 and 0.52 mm). Surface roughness, electrical double layer, hydration forces, macromolecular bridging, hydrophobic interactions and Van der Waals forces are factors/mechanisms responsible for bacterial adhesion in saturated filters [14]. Increasing days of filter operation was positively associated with bacterial removal in both the filters which can be attributed to formation and maturation of biolayer and results agrees with [14]. Most of the studies reported less bacterial removal compared to removals observed in the present study. For example, Zipf et al. [18] reported only 0.35 log FC removal in treatment of GW from hand basin in unsaturated continuous filter. The higher bacterial removal observed in present study could be due to the formation and maturation of biolayer. SF1 met the USEPA [12] and CPCB [13] standard for GW reuse in restricted access area irrigation and construction in terms of bacterial removal.

4. Conclusions
The study employed coagulation followed by sand filtration for treatment of real greywater where PACl was used as coagulant. Sand with two different grain sizes was used to study the effect of grain size on the performance of the filters. Both the filters were subjected to identical loading conditions during the study period. Results showed that coagulation results in significant reduction of turbidity, organic content and bacteria but did not achieve the reuse standards for agricultural and land irrigation. Sand filter with smaller grain size performed significantly better in reducing different pollutants compared to filter with coarse grain size. Physicochemical treatment of greywater could achieve the standard for reuse. Physicochemical treatment of greywater appears to be a reliable treatment method for greywater with a very low land footprint and minimal maintenance, thus making it suitable for wide range of geographical settings especially at decentralised levels.

References
[1] Vinitha E V, Mansoor Ahammed M and Gadekar M R 2018 Water Science and Technology 2017 869–77.
[2] Dalahmeh S S, Pell M, Hylander L D, Lalander C, Vinners B and Jonsson H 2014 Journal of Environmental Management 132 338-45.
[3] Shaikh I N, Mansoor Ahammed M and Sukanya Krishnan M P 2019 Sustainable Water and Wastewater Processing, ed C M Galanakis and E Agrafioti (Amsterdam: Elsevier) 19-54.
[4] Pidou M, Avery L, Stephenson T, Jeffrey P, Parsons S A, Liu S, Memon F A and Jefferson B 2008 Chemosphere 71 147-55.
[5] Ochoa S I C, Ushijima K, Hijikata N and Funamizu N 2015 Journal of Water Reuse and Desalination 5 39–49.
[6] Noutsopoulos C, Andreadakis A, Kouris N, Mendrinou P, Galani A Mantziaras I and Koumaki E 2017 Journal of Environmental Management 216 337–46.
[7] Friedler E and Alfiya Y 2010 Water Science and Technology 62 2357-63.
[8] Ghaitidak D M and Yadav K D 2016 Journal of Water reuse and Desalination 6 108–24.
[9] Manual on test sieving methods: guidelines for establishing sieve analysis procedures 1998 ed R P Charles (West Conshohocken: Lawrence) American Society for Testing and Materials (ASTM), Washington, DC.
[10] Standard Methods for the Examination of Water and Wastewater 2012 21st edn. American Public Health Association (APHA), American Water Works Association (AWWA) and Water Environment Federation (WEF), Washington, DC, USA.
[11] Ghaitidak D M and Yadav K D 2015 Desalination and Water Treatment 54 2410-21.
[12] Guidelines for Water Reuse 2004 Report EPA/625/ R-04/108, United States Environmental Protection Agency (USEPA), Washington, DC.
[13] Guidelines for Water Quality Management 2008 Environmental Standards-Water Quality Criteria, Central Pollution Control Board (CPCB), New Delhi, India.
[14] Jenkins M W, Tiwari S K and Darby J 2011 Water Research 45 6227–39.
[15] Katukiza A Y, Ronteltap M, Niwagaba C B, Kansiime F and Lens P N L 2014 Journal of Environmental Management 146 131–41.
[16] Young-Rojanschi C and Madramootoo C 2015 Journal of Water Supply: Research and Technology - AQUA 64 157–67.
[17] Verma S, Daverey A and Sharma A 2019 Environmental Science and Pollution Research 26 34148–56.
[18] Zipf M S, Pinheiro I G and Conegero M G 2016 Journal of Environmental Management 176 119-27.