

Feasibility of a Filtration-Adsorption Grey Water Treatment System for Developing Countries

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Abstract

The performance and economic viability of a simple inexpensive grey water treatment system consisting of a filtration unit and an adsorption unit was evaluated. At steady state, the overall performance of the combined system was 85.68% BOD removal, 57.09% COD removal and 70.74% TSS removal. Most of the BOD removal (83.6%) was achieved in the filtration unit, while most of the fecal coliform removal was achieved in the adsorption chamber. The pH of the entire system remained stable (7.6 ± 0.29) throughout the experiment. The dissolved oxygen concentration of the final effluent was 1.3 ± 0.28 , indicating the need for aeration. Problems with carbon particle washout were observed in the adsorption chamber. Generally, the final effluent was found to be suitable for a range of uses such as toilet flushing, irrigation and fire protection. An economic analysis showed that 77.5% savings in water expenditure can be achieved if a simple greywater treatment is installed for toilet flushing.

Keywords: Grey water; Reuse; Toilet flushing; Filtration; Adsorption

Introduction

As pressures on freshwater resources grow around the world and as new sources of supply become increasingly scarce, expensive, or politically controversial, efforts are underway to identify new ways of meeting water needs. Of special note are efforts to reduce water demand by increasing the efficiency of water use and to expand the usefulness of alternative sources of water previously considered unusable. Among these potential sources of supply are greywater reuse, desalination and rainwater harvesting. Of the three mentioned above, greywater reuse is less favoured and acceptable because of aesthetics and health considerations. Due to the low level of treatment (sedimentation, filtration and adsorption) to be applied to the greywater which invariably reduces the cost of treatment, the possible reuse options for the treated water are urinal and toilet flushing, irrigation of lawns (college campuses, athletic fields, cemeteries, parks and golf courses, domestic gardens), washing of vehicles and windows, fire protection, boiler feed water, concrete production, develop and preserve wetlands, infiltrate into the ground (for recharge of aquifers), agriculture and viticulture reuse. However, the impact of greywater on soils and the sanitary implications of reusing greywater on edible crops, salinity status of agricultural lands and groundwater quality remain of concern. In many places throughout Nigeria, lower income communities live without access to household water connection. In these communities, women and children often have to walk long distances or wait in line in order to access water which then needs to be carried home. In these households, the water that is brought to the home is highly valuable because of the amount of labor invested and the cost relative to household income. This high level of water stress has driven many low and middle income earners to take the initiative of unconventional (untreated) greywater re-use. However, the level of hygiene in the way the greywater is reused may pose some health risks to the users. On-site greywater reuse within the urban and rural sectors may have a significant role in reducing the overall water consumption, leading towards more sustainable urban water utilization [1], and easing water stress in several areas of the world. Greywater reuse for toilet flushing in homes can significantly reduce the in-house net water demand. This means that a country like Nigeria, with a population of about 160 million, can save about 5.6 million cubic meters of water

per day by greywater reuse for flushing toilets. Based upon previous studies, factors identified to have significant influence on the successful implementation of greywater reuse systems are: economic status, geographical location, population size, public health considerations, religious practices and social acceptability. The factors determining level of public acceptance of greywater reuse include: perceived health risk, perceived cost, operation regime and environmental awareness. There has also been some perception that greywater reuse is not compatible with Islamic religious beliefs, although in 1978 the Council of Leading Islamic Scholars (CLIS) in Saudi Arabia found that treated wastewater can be reused as long as it does not present a health risk [2].

It is surprising that while many developed countries have gone ahead to encourage greywater re-use by formulating appropriate legislative framework, many developing countries are yet to officially recognized the need for this option. Grey water reuse is illegal in some Middle Eastern countries [3], yet extensive re-use occurs in households in the Middle East regardless of its legality [4]. Australia, Korea and Cyprus have incentive programs for greywater re-use. Australia has developed guidelines for greywater reuse, and reuse is encouraged through a program that offers \$500 rebates for the installation of a greywater system. In Tokyo, Japan, not only are there incentives for installing greywater systems, but they are mandatory for buildings with an area of over 30,000 square meters, or with a potential to reuse 100 cubic meters per day (CSBE 2003). Several municipalities of Spain, including Sant Cugat del Vallès near Barcelona and several other municipalities in Catalonia, have passed regulations to promote greywater reuse in multistory buildings [5]. Systems that reuse sink water to fill toilet tanks are sold primarily in Japan, Australia, Europe,

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Received June 18, 2013; Accepted July 18, 2013; Published July 24, 2013

Citation: Nnaji CC, Mama CN, Ekwueme A, Utsev T (2013) Feasibility of a Filtration-Adsorption Grey Water Treatment System for Developing Countries. Hydrol Current Res S1: 006. doi:[10.4172/2157-7587.S1-006](https://doi.org/10.4172/2157-7587.S1-006)

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and North America by a variety of manufacturers [6]. In Berlin, Germany, a 60 square meter engineered wetland constructed in the courtyard of a housing settlement has been successfully used for grey water treatment [7]. Sheikh estimates that only about 0.01% of greywater systems in California are permitted.

Greywater contains many of the same contaminants as sewage water, and while generally present in lower concentrations than in sewage water, they can be well above international drinking, bathing, and irrigation water standards [8]. Despite the relatively low concentrations of contaminants, greywater constituents are known to be recalcitrant [9]. Greywater can contain pathogens derived from fecal contamination, food handling, and opportunistic pathogens such as those found on the skin [10]. Greywater in areas with very low consumption tend to have particularly low greywater quality, as contaminants are concentrated in the small quantities of water used [11]. The treatment technologies for greywater include membrane filters to remove contaminants, bacteria, and viruses along with aerobic biological treatment. One common method of aerobic biological treatment uses a rotating biological contactor (RBC) that cycles discs in and out of greywater tanks. Biological greywater treatment also includes membrane bioreactors (MBR). Physical and chemical greywater treatment systems primarily utilize disinfection and filtration to remove contaminants while biological treatment uses aeration and membrane bioreactors. Ultra violet disinfection has been included as a final safety measure before the use in toilet flushing [6,12,13].

Though there are treatment technologies available for the greywater reuse options, these technologies are at present expensive and are not well known among the members of the communities. Hence, the objectives of this research work are to (i) design a filtration-adsorption system for the treatment of greywater, (ii) to test the performance of the system and (iii) to determine the economic viability of the system.

Methodology

Diversion system

The experiment was set up in residential quarters (Umeano

Quarter) located within Nsukka vicinity. The wastewater treated in this experiment was conducted from two residential apartments (flats), each of the apartments has an average of six (residents), the sanitary installation comprises a bathroom in each apartment. The two flats chosen are located on the first and second floor of the building. This was done so that there would be enough head to drive the flow of greywater to the treatment setup. The sewer pipes are $\frac{3}{4}$ PVC pipes which were used to channel bathroom wastewater coming from two residential apartments (flats) to the setup. This pipe was then connected to the set up. The set up is composed of six (6) $\frac{3}{4}$ PVC pipes running from the bathrooms to the outskirts of the building where the treatment plant was setup (Figure 1).

Grey water treatment setup

The treatment process comprises of an equalization unit, sedimentation unit, filtration unit, receiving unit, adsorption unit and storage unit. The equalization unit regulates between raw greywater inflows and outflows to the treatment system, and equalizes the quality and temperature of the raw greywater. This unit has a volume of 120ltrs and receives raw greywater directly from the bathrooms. The sedimentation unit is a 50-litre bucket which receives raw greywater from the equalization unit. In this unit the particles are allowed to settle under gravity without the addition of coagulants as this would disturb the biological process in the filter. This sedimentation unit also serves as a sampling point to test for the level of contamination of the greywater. The filtration unit is a 120-liter black bucket filled with gravel acting as drain with size range of 2–16 mm to a height of 100mm from the bottom of the unit. A sand filter media with $d_{10}=0.19$, $d_{60}=0.55$ and uniformity coefficient, $C_u=2.89$ was laid on top the gravel under-drains to a height of 300mm (Figure 2).

The sand screens off particles larger than its pore size while the gravel acts as a drainage system to let off filtered greywater. The intermediate storage unit mainly receives filtered water from the filtration unit. This is so that the water coming from the filtration chamber doesn't go directly to the adsorption chamber before testing

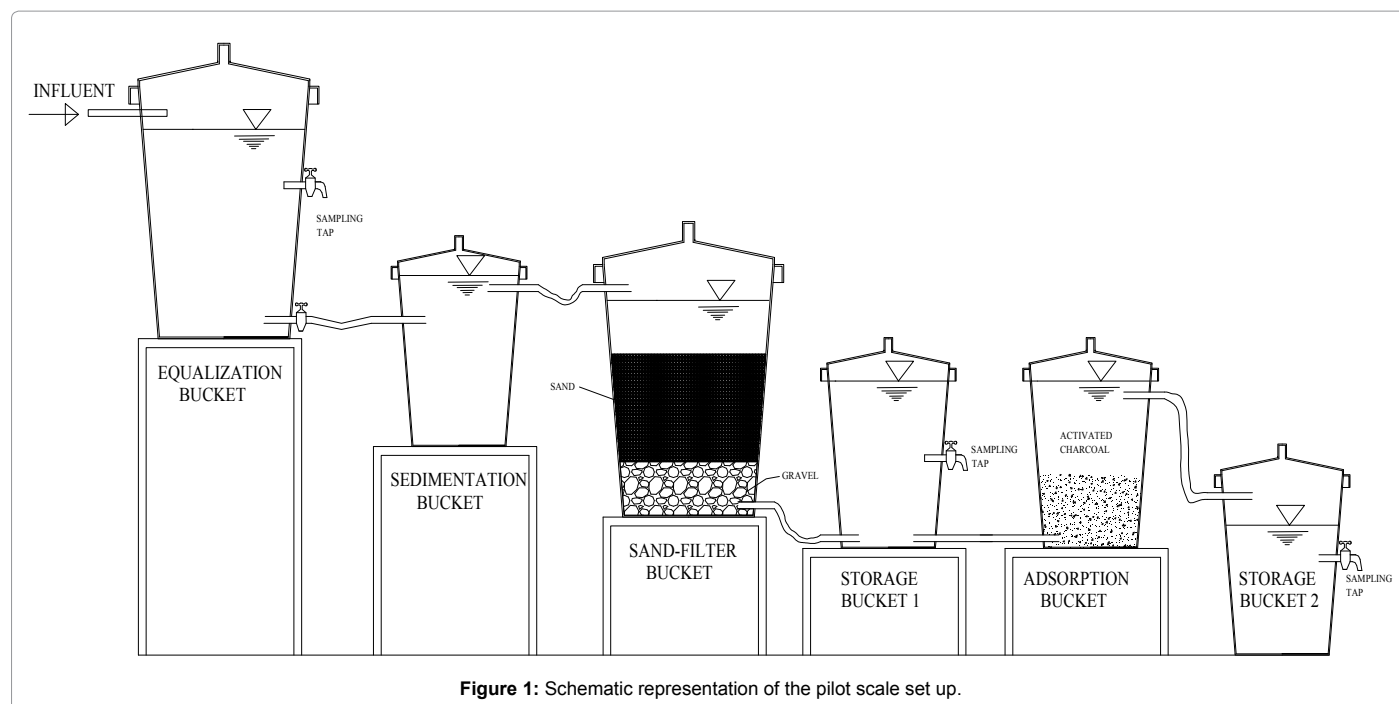
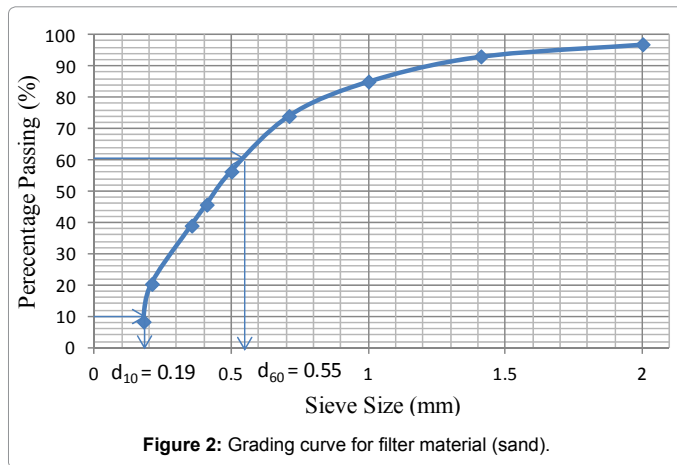


Figure 1: Schematic representation of the pilot scale set up.



so that the efficiency of the filtration as well as adsorption processes can be determined independently. This is why this unit is a sampling point to test the performance of the filtration. This adsorption unit contains activated charcoal for the removal of chemical and organic impurities from the filtered water. The procedure for the activation is as follows. 7kg of charcoal was weighed and placed into a metallic bucket. 500g of zinc chloride was dissolved in 6 liters of water and emptied into the bucket. This bucket was placed on top a heater and heated to boiling. After boiling, the charcoal was removed from the solution and allowed to cool, then after cooling was placed inside a furnace at 450–500°C for a period of an hour. The activated charcoal was allowed to cool, rinsed with water and afterwards baggage for use.

In a slow sand filter, the velocity of flow per square area of the bed is dependent on the depth of the sand media. For grey water and filter media of given characteristics, head loss can be expressed as a function of filter depth as follows

$$h_f = \alpha L$$

$$\text{Where } \alpha = \frac{V_a^2}{g} \left(\frac{1-e}{\phi e^3} \right) \sum (f x / d) \quad (1)$$

$$f = \frac{150(1-e)}{\text{Re}} + 1.75; \text{Re} = \frac{\phi(\rho v d)}{\mu}$$

Where, h_f =head loss, F =friction factor, L =depth of filter, d =geometric mean diameter between sieves, V_a =approach velocity, Φ =shape factor (1 for perfectly spherical particles), μ =dynamic viscosity, e =porosity, x =weight fraction of particles passing the sieves, g =acceleration due to gravity, ρ =density of water (1000kg/m³ @ room temperature and pressure). Figure 3 shows various filter depths and their expected head losses for a given flow velocity per square area of the filter bed. This was calculated with the Equations 1 and the values of the weight fraction of the particles as well as the geometric mean diameter between sieves. The following filter media parameters were used: $\mu=0.001\text{N}\cdot\text{s}/\text{m}^2$, $g=9.81\text{m}/\text{s}^2$, $\rho=1000\text{kg}/\text{m}^3$, $\phi=1$ and $e=0.38$. To facilitate process design, a chart of head loss versus filter depth for different ranges of filtration rate has been presented in Figure 3 below. Figure 3 is unique to sand of the same characteristics as that used in the setup. Such plots can be produced for other kinds of filter materials (Figures 4-6).

Sampling and testing

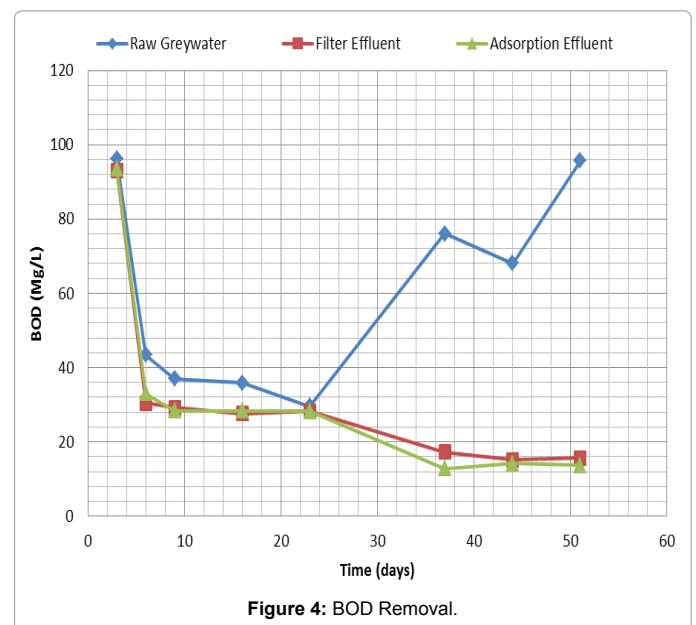
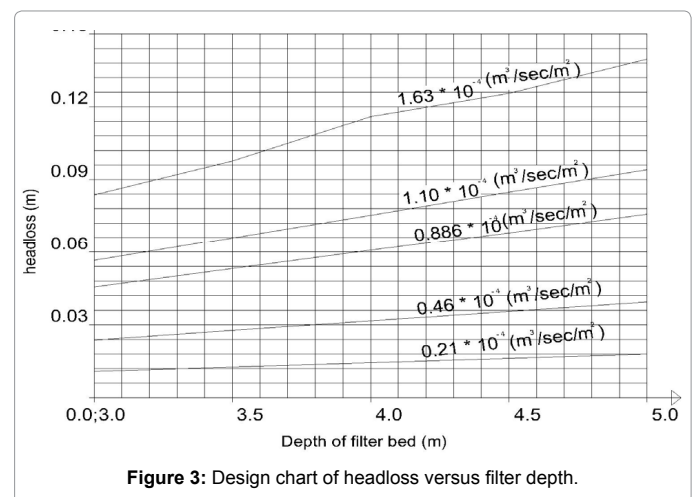
The greywater from the sewer PVC pipes empties into the

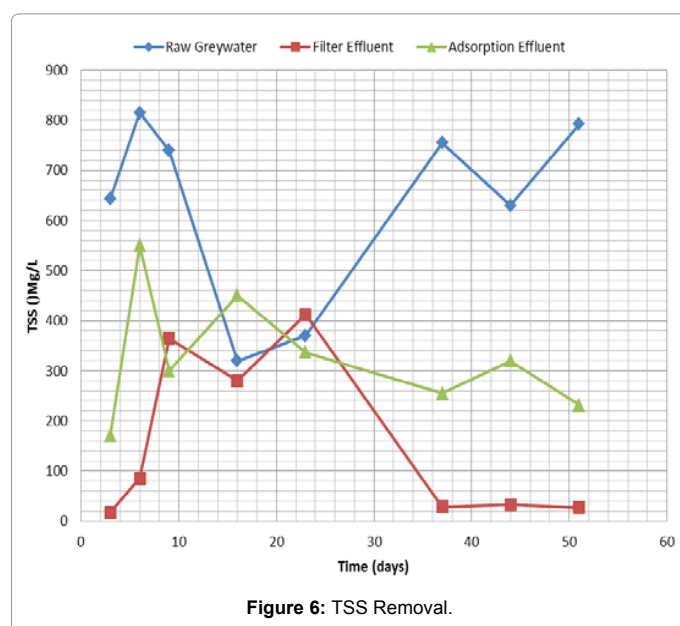
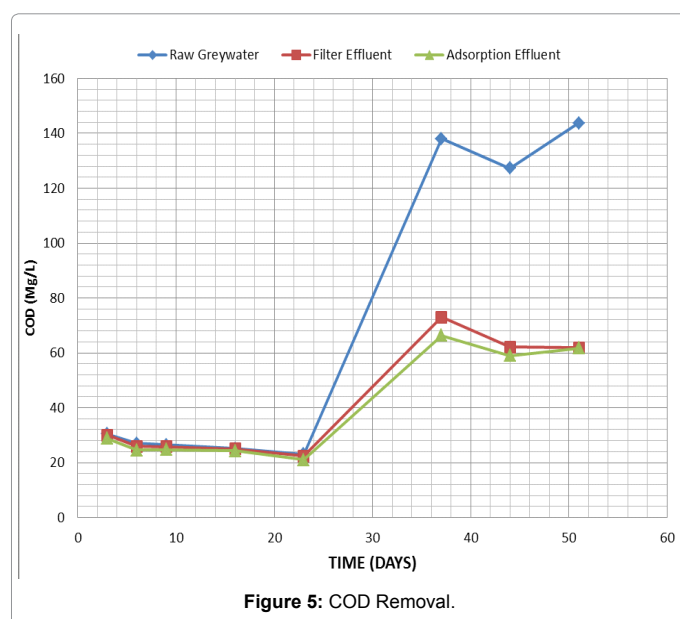
equalization unit which acts like a secondary storage tank before the sampling is conducted. At the start of the entire sampling operations, samples were taken at intervals of three (3) days for 3 consecutive samples. The reason for sampling at these three points (before filtration, after filtration and after adsorption) is to determine the degree of treatment achieved in each of the stages of treatment (filtration and adsorption) and also to check if the greywater was treated appreciably for the reuse options. The tests conducted on the samples are biochemical oxygen demand (BOD), chemical oxygen demand (COD), total suspended solids (TSS), dissolved oxygen (DO), pH and faecal coliform. Dissolved oxygen was determined in-situ using a Hanna potable DO meter.

Results and Discussion

Grey water treatment system performance

In the first three weeks of running the treatment system, the BOD removal was about an average of 15% while afterwards, a significant removal of as much as 85% was observed for the system. This trend is attributed to the increase in performance of sand filtration due to the





increase in the microfilm resulting in increased efficiency of the bio-filter. A very minute BOD removal was observed for the adsorption system. The same trends as in the BOD removal was also observed for the COD with an average removal efficiency of 6.6% after the first three weeks and up to 54% removal afterwards. The increase in performance is also attributed to the improved biological filter. Yet, minimal removal of COD was observed for the adsorption system. The sand filtration bed system performed significantly in total suspended solids removal to about 37% in the first three weeks even increasing to as much as 62% afterwards when the biological filter became much efficient. However, an increase in total suspended solids showing a negative TSS removal of about 52% was observed after adsorption. This is because some of the activated charcoal particles got suspended in the effluent water. The system performed optimally from the onset as regards fecal coliform with removal efficiency of roughly 100%. This performance is mainly contributed by the adsorption system which gave an overall

removal of 99.99% while the sand filtration bed system contributed an average of 9.6%. The PH of the influent and effluent greywater from the treatment system was relatively steady with an observed average of 7.7 with deviations of ± 0.35 for the raw greywater; an average of 7.6 for both after filtration and after adsorption with deviations of ± 0.36 and ± 0.29 respectively. The dissolved oxygen level in the influent and effluent greywater was also found to be steady (Table 1).

Despite the fledging and unsteady performance of the system at the start of the experiment, the system approached a steady state with a performance of 85.68% BOD removal, 57.09% COD removal, 70.74% TSS removal and 99.99% fecal coliform removal. From Table 2, it can be seen that most of the biological and physical treatment occurred in the filtration unit. The filtration unit attained 83.6% BOD removal, 57.2% COD removal and 70.74% TSS removal. A high BOD removal did not translate into a correspondingly high COD and TSS removal. This can be explained by the fact that a reasonable amount of greywater constituents is not easily biodegradable.

The reduction in the treatment efficiency of the adsorption unit with respect to TSS can be attributed to carryover of carbon particle from the adsorption chamber, owing to unforeseen process problems. However, the adsorption chamber was found very effective in fecal coliform removal, reducing the fecal coliform concentration from 2.4×10^9 cfu/100 ml to 2400cfu/100ml. The filtration unit was not as effective in fecal coliform removal. Hence, the two units played complementary roles in greywater treatment. However, as observed by

parameters		Raw greywater	Filtration effluent	Adsorption effluent	Total effluent removal
BOD (mg/L)	Average	60.23	32.09	29.90	
	STD	± 27.3	± 25.48	± 26.4	
	Removal (%)	-	46.72%	6.8%	50.35%
COD (mg/L)	Average	67.64	38.51	38.8	
	STD	± 57.1	± 21.1	± 19.7	
	Removal (%)	-	43%	-	43%
TSS (mg/L)	Average	633.23	156.2	327	
	STD	± 189.8	± 167.8	± 122.2	
	Removal (%)	-	75.33%	-52.23%	48.4%
FECAL COLIFORM (cfu/100ml)	Average	6.97×10^9	6.3×10^9	2.0×10^5	
	STD	$\pm 6.76 \times 10^9$	$\pm 6.13 \times 10^9$	$\pm 5.4 \times 10^5$	
	Removal (%)		9.6%	99.99%	$\approx 100\%$
PH	Average	7.7	7.6	7.6	
	STD	± 0.35	± 0.36	± 0.29	
D.O. (mg/L)	Average	1.2	1.1	1.3	
	STD	± 0.26	± 0.3	± 0.28	

Table 1: Average Performance of Treatment System.

Parameters	Raw Greywater	After Filtration		After Adsorption	
	Influent (mg/l)	Effluent (mg/l)	Efficiency (%)	Effluent (mg/l)	Efficiency (%)
BOD	95.7	15.7	83.6	13.7	85.68
COD	143.8	61.8	57.2	61.7	57.09
TSS	792.8	27	70.74	232	70.74
Fecal Coliform	2.4×10^9	-	-	2400	99.99

Table 2: Performance of Treatment System at the End of Experiment.

Kariuki et al. [14], Figures 7 and 8 show that greywater treatment has little or no effect on pH and dissolved oxygen.

Economic analysis of a pilot scale grey water treatment and re-use system

The practice of greywater reuse has been shown to be sustainable and holistic. However, there is the need to justify this claim by proving the viability of investments in greywater treatment system. Though, this approach only recognizes immediate monetary benefits without accounting for benefits in the form of reduced environmental pollutions and also possible hazards like disease infections. To carry out feasibility studies on the greywater treatment system, a typical (pilot scale) greywater treatment system shown is considered. The capacity of the treatment system is so designed to treat bathroom

greywater produced from a 6-unit residential apartment. Each of the apartments was assumed to have a family of six members and producing a total 120liters of greywater per day. This amounts to a total greywater effluent of 720 liters of greywater per day and 262,800 liters per annum from the entire 6-unit residential apartments. This quantity is considered sufficient for toilet flushing at 20lpcd. It should be noted that water consumption and wastewater generation varies from country to country, with the margin gaping between developed and developing countries. Apart from water demand for drinking and flushing toilet (for fully plumbed areas), the water consumption in developing countries trails far behind that of developed countries. Domestic water consumption in developed countries is around 150lpcd and above, but it has been shown that average domestic water consumption per capita in a typical semi-urban Nigerian city is about 34.9lpcd (Nnaji et al, 2013). Hence it is reasonable to assume toilet flushing water demand of 20lpcd. Using locally obtainable prices, such a system was estimated to cost ₦286,190.00. The interest rate obtainable in the Nigeria capital market is 12% per annum. Maintenance costs are ₦12,000.00 per annum. The maintenance of the system which is to be done twice per annum to remove aggregates and charcoal, wash the tanks and replace with fresh materials supplies which are readily available and affordable locally; does not require any specialized personnel to carry out. Eight (8) working man hours is sufficient to carry out a full maintenance work on the system (Figures 9 and 10). The system was designed to harness gravitational flow force hence requiring pumping only for treated water extraction. Operational costs resulted from the use of electricity to pump treated greywater. Pump capacity=150gallons per minute=680 liters per min. If the pump is operating @ 50% efficiency, the time t , taken to pump 720 liters of treated grey water is given by

$$t = \frac{\{720\}}{\{0.50 \times 680\}} = 2.2 \text{ mins per day} \gg 805 \text{ mins per year}$$

The PHCN (Power Holding Company of Nigeria) rate per KWH of electricity consumed is ₦14/KWH. 805 mins=13hrs, 25mins per annum. The operational cost of powering the electric pump is ₦200.00 per annum.

Let a be the annual return on investment made from the greywater treatment system used to pay off borrowed money, i is the interest rate in the capital market, P is the principal amount borrowed to make investment on the greywater system to be paid back after a period of n years; then a is given as:

$$a = P / \frac{1}{i} \left[1 - \frac{1}{(1+i)^n} \right] \quad (2)$$

For an annual maintenance cost of ₦12,000.00, the net present worth at an interest rate of 12% for 25 years is obtained as ₦94,117.67 (using Equation 2 transposed with P as subject). Hence, the total cost (capital, operation and maintenance) is ₦286,190+94,117.67=₦380,307.67. Using Equation 2, the total annual payment/cost of the system is

$$a = \frac{380307}{\frac{1}{0.12} \left[1 - \frac{1}{(1+0.12)^{25}} \right]} = \$48,489.13$$

Capacity of pilot scale=720liters/day. Volume of greywater treated in a fiscal period=720 × 365=262,800liters. This translates to ₦0.18/liter of greywater. Using an average cost of ₦0.8/litre of potable water (Nnaji et al, 2013), percent savings in water expenditure is

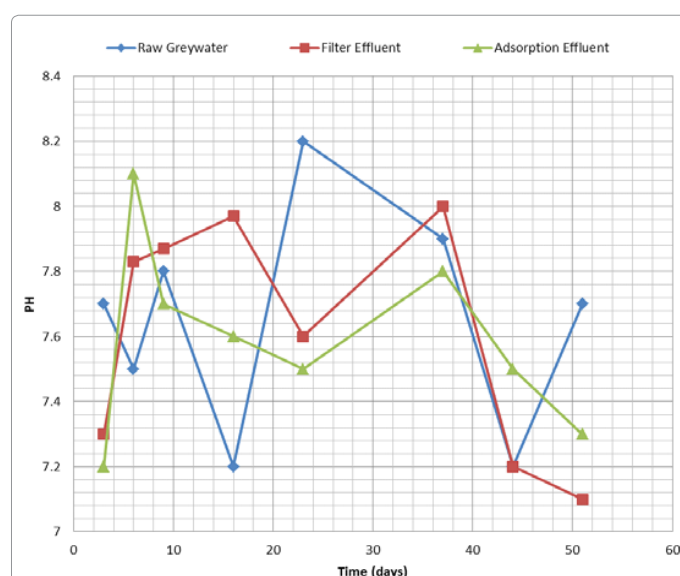


Figure 7: Variation of pH at different stages.

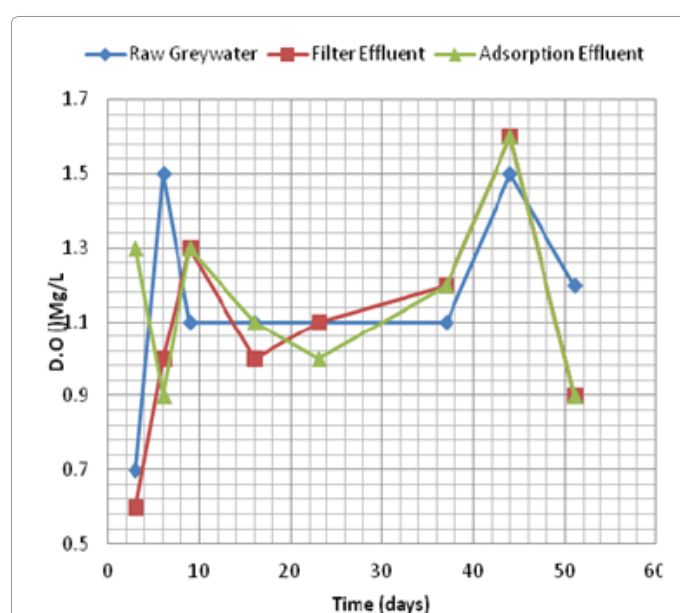
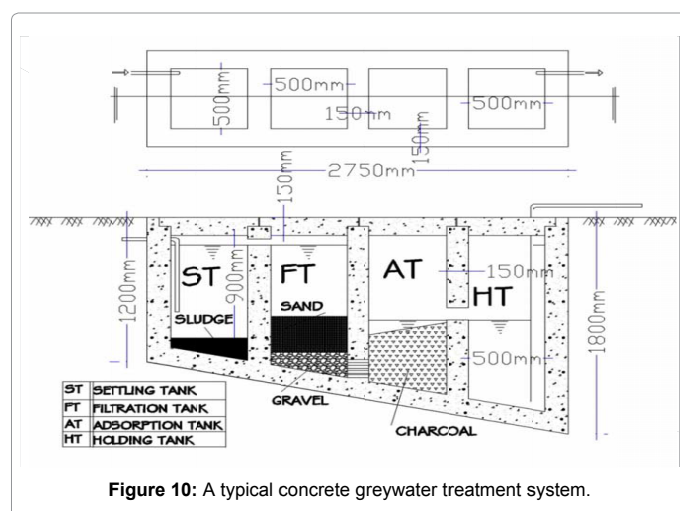
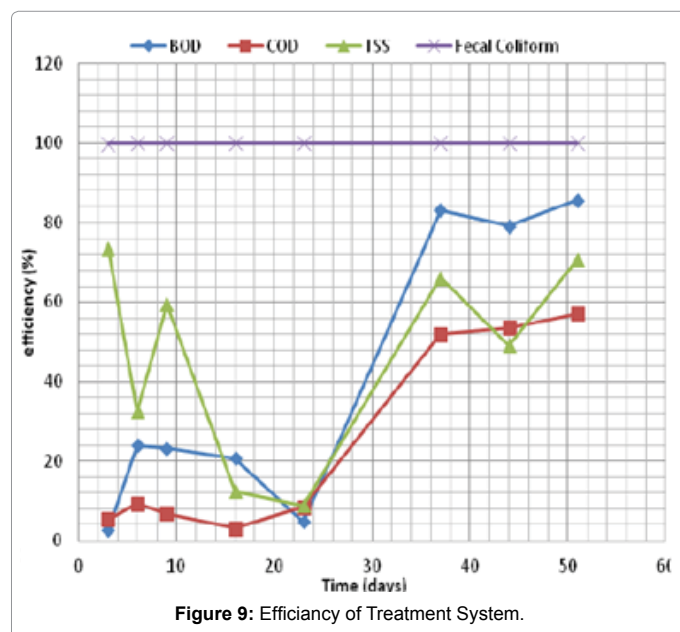


Figure 8: Variation of dissolved oxygen.



$$\text{Savings (\%)} = \frac{0.8 - 0.18}{0.8} = 77.5\%$$

The monetary savings per capita is ₦0.62/liter, and if approximately 20liter of water is required per capita for flushing toilet, the total savings per year for a family of six (6) is ₦27,156.00. This is a substantial sum considering that some people earn as low as ₦10,000.00/month or even less. When considered on a national scale, this translates to a whopping ₦2.17 trillion.

Conclusion

The overall performance of the pilot scale was commendable producing an appreciably improved quality of greywater. The final effluent at a steady state had a BOD of 13.7 mg/L which is close to values obtainable with some standardized water treatment technologies. This value is also very close to the 10mg/l limit recommended for urban reuse which includes toilet flushing, vehicle washing, landscape irrigation and fire protection. The total COD removal of about 57.09%

is much less compared to BOD removal which can be attributed to non-biodegradable impurities of soap origin. The COD and TSS concentrations of the effluent were above those obtainable with popular treatment units. However, the TSS value at steady state was well within the 30mg/l limit recommended for food crop irrigation. The overall removal of fecal coliform (≈100%) suggests an equivalent reduction of pathogenic organisms. The adsorption chamber suffered substantial instability in efficiency of TSS removal as a result of carbon particles washout. Installation of a greywater treatment/reuse system has dual benefits:

- I. It reduces the health hazards associated with reuse/handling of raw greywater which is a common practice in developing countries.
- II. It makes provision for storage of treated greywater such that it can be used when needed. If a greywater treatment system is not installed, there is always a tendency to waste excess raw greywater, since the quality rapidly deteriorates in just a matter of hours.
- III. Finally, as much as 77.5% savings in water expenditure is possible by the use of a simple inexpensive greywater reuse system.

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