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Full Length Research Paper

A two-stage decentralised system combining high rate activated sludge (HRAS) with alternating charcoal filters (ACF) for treating small community sewage to reusable standards for agriculture

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Water scarcity increasingly drives wastewater recovery. Campaigns towards re-use of wastewater are not very common in Africa among other factors, due to a lack of efficient and cost-effective technology to treat wastewater to re-usable standards. In this study, two treatment systems, a high rate activated sludge (HRAS) system and alternating charcoal filters (ACF) are combined and used to treat wastewater to standards fit for reuse in agriculture. The charcoal can upon saturation be dried and used as fuel. Two different ACF lines were used in parallel after the HRAS: ACF1 with a residence time of 2.5 h and ACF2 with residence time of 5 h. Results show no significant difference ($\alpha = 0.05$) in the performance of the two filter lines, hence ACF1 with a higher flow rate was considered as optimal. The HRAS effectively removed up to 65% of total suspended solids (TSS) and 59% of chemical oxygen demand (COD), while ACF1 removed up to 70% TSS and 58% COD. The combined treatment system of HRAS and ACF1 effectively decreased TSS and COD on average by 89 and 83%, respectively. Total ammonium nitrogen (TAN) and total phosphates (TP) were largely retained in the effluent with average removal percentages of 19.5 and 27.5%, respectively, encouraging reuse for plant growth.

Key words: A-stage, sustainable wastewater treatment, resource recovery, developing countries, water reuse, nutrient management, agriculture.

INTRODUCTION

Humans depend on water for nearly all aspects of life. The diverse utilization of water coupled with population explosion across many places in the world has made it a scarce resource. Moreover, the discharge of untreated or

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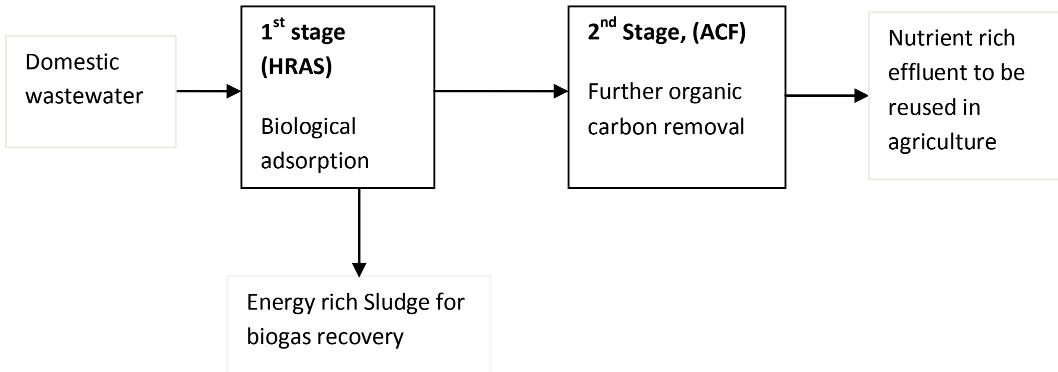

Figure 1. Representation of the combined processes treatment with use of high rate activated sludge (HRAS) system and the alternating charcoal filter (ACF).

inadequately treated wastewater leads to deterioration in the quality of fresh water sources and continues to deepen the water scarcity. Re-use of wastewater for some purposes such as agriculture is an indispensable part of integrated water management and would decrease water scarcity. This requires a change in perceptions as well as availability of simple, low cost and effective technologies. The treated wastewater should be sufficiently disinfected but not void of its nutrient content, so as to increase crop yields. In Uganda, reuse of wastewater is not widely reported; however, informal irrigation occurs in several parts of the country. For instance farmers in the Murchison Bay, which receives Kampala city's highest flow of wastewater effluent, are seen to cultivate a variety of crops. The main concern for reuse of wastewater is the health of both the farmers and the crop consumers. Unfortunately, some of the treatment methods used in developing countries may not attain sufficient disinfection, which limits reuse options (Nikiema et al., 2013) and may pose public health risks if improperly applied. Centralised systems common in the developing world are effective but very expensive and are not suitable for low density rural areas (Netter et al., 1993). These systems can cost up to € 40 per capita per year considering both capital and operational expenditure (Zessner et al., 2010). On the other hand, on-site systems are cheaper but have a number of limitations with regard to wastewater re-use. Also, some like pit latrines are known to increasingly pollute ground water sources (Katukiza et al., 2013, Nyenje et al., 2013). Therefore, efficacious and cost effective technology to boost wastewater reuse and recycling needs development for the developing world.

Verstraete and Vlaeminck (2011) proposed a new approach for optimal resource recovery, as opposed to the conventional wastewater management. In this approach which they label as the M & M treatment system, the wastewater is separated as near as possible to the source into two distinct streams: the major line (up to 90% of the flow) and the minor line (about 10% of the flow). The major water stream is treated to reusable standards while the minor concentrated stream can undergo additional treatment to recover energy and nutrients. Small-scale decentralised systems designed for a small number of households could provide a cost-effective method for that purpose. Such systems should focus on optimising the pre-concentration methods and further treatment of the two separate streams, to maximize resource recovery. Methods of solids pre-concentration may include the biological adsorption in a high-rate activated sludge stage (HRAS), also referred to as the A-stage of the A/B Verfahren system (Böhnke, 1977). This activated sludge process operates at high sludge loading rates (2 to 10 g bCOD $gVSS^{-1}$ d^{-1}) and low sludge retention times (hours to days), while a short hydraulic retention time of under 30 min selects for rapid incorporation of organic matter into sludge without extensive oxidation (Bohnke, 1977). Moreover, the 'young' A-stage sludge is easily digestible by anaerobic digestion (De Vrieze et al., 2013) to recover energy. The effluent from the A-stage can be further treated to achieve reusable standards by methods such as trickling filters or sand filters. For the developing world, it is important to explore locally available materials and simple technologies in order to achieve cost effective and sustainable systems. Charcoal is such a material and it is ubiquitously available in Uganda. The use of charcoal for wastewater treatment has been widely studied (Abe et al., 1993; Samkutty and Gough, 2002; Scholz and Xu, 2002; Ochieng et al., 2004; Sirianuntapiboon et al., 2007; Nkwonta et al., 2010; Ahamad and Jawed, 2011). Its performance compared well with other media like gravel, sand rocks and zeolite, however, attaining its continued use is still a challenge.

For this reason, this study proposes and investigates the concept of the state-of-the-art of low cost small scale wastewater treatment plant which also allows for wastewater reuse. It combines two wastewater treatment systems (Figure 1). The first stage is a HRAS system similar to the A-stage, to achieve pre-concentration and

Table 1. Average operating parameters of the high rate activated sludge (HRAS), the alternating charcoal filter 1(ACF1) with a retention time of 2.5 h and the alternating charcoal filters 2 (ACF2) with a retention time of 5 h and the removal efficiency of the HRAS combined with each of the alternating filter options.

Parameter	Raw wastewater	HRAS reactor	HRAS effluent	ACF1 effluent	ACF2 effluent	HRAS+ACF1 Average total removal (%)	HRAS+ACF2 Average total removal (%)
TSS (mg/mL)	0.322±0.163	2.174±0.932	0.102±0.049	0.032±0.022	0.026±0.019	0.089± 0.007	0.091±0.006
COD total (mg/mL)	0.613±0.244		0.233±0.106	0.093±0.045	0.091±0.047	0.083±0.008	0.084±0.008
COD soluble (mg/mL)	0.128±0.057		0.111±0.061	0.073±0.030	0.068±0.030	0.046±0.024	0.048±0.024
TAN (mg/mL)	0.036±0.011		0.033±0.010	0.030±0.009	0.029±0.009	0.019±0.016	0.020±0.010
P_{total} (mg/mL)	0.026±0.013		0.022±0.010	0.019±0.009	0.019±0.008	0.027±0.015	0.028±0.014
pH	7.2±0.2	7.4±0.2	7.5±0.2	7.6±0.1	7.6±0.1		
Temperature		21.9±0.7					
DO (mg/mL)		3.7±1.6					

major organics removal, and the second stage is filtration of the liquid fraction with use of alternating charcoal filters. The wastewater is treated to meet reusable standards for agriculture. The sludge from the process is to be used for biogas recovery in a subsequent study. Upon saturation the charcoal is replaced which allows for continuity of the system, the charcoal could then be dried and finally used as fuel, which originally was its primary use. This system is suitable for small communities.

MATERIALS AND METHODS

Sample collection

Raw domestic wastewater was collected from Bugolobi Sewage treatment plant (STP) in Kampala (Uganda) every two to three days for four months (June 2013 to October 2013). The Bugolobi STP managed by National Water and Sewerage Corporation (NWSC), is the largest sewage treatment plant in Uganda. It employs physical and biological treatment by use of screens, detritus basin, primary settling tanks, trickling filters and secondary clarifiers in that order. The plant has an average inflow of 12,000 m^3 per day mainly via the centralised sewerage pipe network. However, about 300 m^3 of the inflow is received via cesspool trucks that deliver septage from septic tanks and pit latrines around Kampala City and its outskirts. The cesspool dumping usually accounts for a sudden change in the influent wastewater quality. In this study, the wastewater was collected after the screens and grit chamber and stored in a 200 L container which continuously fed the HRAS experiment. Selected parameters of the raw wastewater characteristics and outflow of the HRAS stage were determined and are shown in Table 1. The values indicate that the Bugolobi STP wastewater is generally of high strength (for a comparison Metcalf and Eddy, 1991). The maximum values of total suspended solids (TSS), total phosphates (TP), total ammonium nitrogen (TAN) and chemical oxygen demand (COD) of the Bugolobi STP wastewater sampled at different times were 0.794, 0.066, 0.061 and 0.116 mg mL^{-1}, respectively. The faecal coliform (FC) colony forming units (CFU) in the influent ranged from $3.13x10^2$ to $2.01x10^6$ CFU mL^{-1}. The wastewater characteristics are known to vary depending on the weather conditions. The variation can also be attributed to the small daily volumes (300 m^3 day^{-1}) of high strength septage received by the plant throughout the day. The reactor sludge was obtained by autonomous growth during an acclimation period of 10 days of reactor operation. The charcoal used in the study was bought from the open market, crushed into pieces ranging from 0.5 to 1.5 cm. It was then washed to remove the dust before packing it in plastic columns in the Laboratory. The porosity and dry bulk density of the packed charcoal after crushing were determined.

Experimental set-up

High-rate activated sludge (HRAS) experiment

A HRAS experiment was set up at laboratory scale as shown in Figure 2. It consisted of a continuous stirred tank reactor (CSTR) unit which was continuously aerated, a settling unit and a sludge return device. The CSTR unit had a volume of 4 L and an average hydraulic retention time (HRT) which begun at 0.5 h but was increased and maintained at 1 ± 0.3 h after 10 days. The average sludge retention time (SRT) of the CSTR was 1.5 ±0.3 days and it was loaded at an average sludge loading rate of 2.2 g bCOD/g SS per day. Two electrical aerators (Aquatic AP1, Interpet, United Kingdom) were used to supply oxygen into the CSTR which achieved an average concentration of dissolved oxygen (DO) of 3.7 ± 1.6 $x10^{-3}$ mg/mL. A mechanical stirrer (RW16 basic, IKA Labortechnik, Germany) was used to stir the CSTR unit. The settling unit had an effective volume of 8 L and an initial HRT of 1 h, which was increased and maintained at 2 ± 0.4 h after 10 days. The sludge from the settling unit was returned to the CSTR using a pump (Leroy Somer Varmeca, Belgium). The Recycle ratio ($Q_{return}/Q_{influent}$) of the CSTR was 1 and 2 L of sludge was wasted manually every day. The wasted sludge was kept in a 5 L container at 4°C where it settled further before the clear water was poured off and the settled sludge was used in another study. Selected parameters of the influent and effluent of the HRAS experiment were measured on the samples collected three times a week.

The alternating charcoal filter (ACF)

The effluent from the HRAS was fed into the ACF for further treatment as shown in Figure 3. It was fed into two separate ACF lines, each with three charcoal filter columns placed in series. The filter columns were 25 ± 3 cm long and had a volume of 1 L of charcoal. The charcoal particles in the filters ranged between 0.5 to

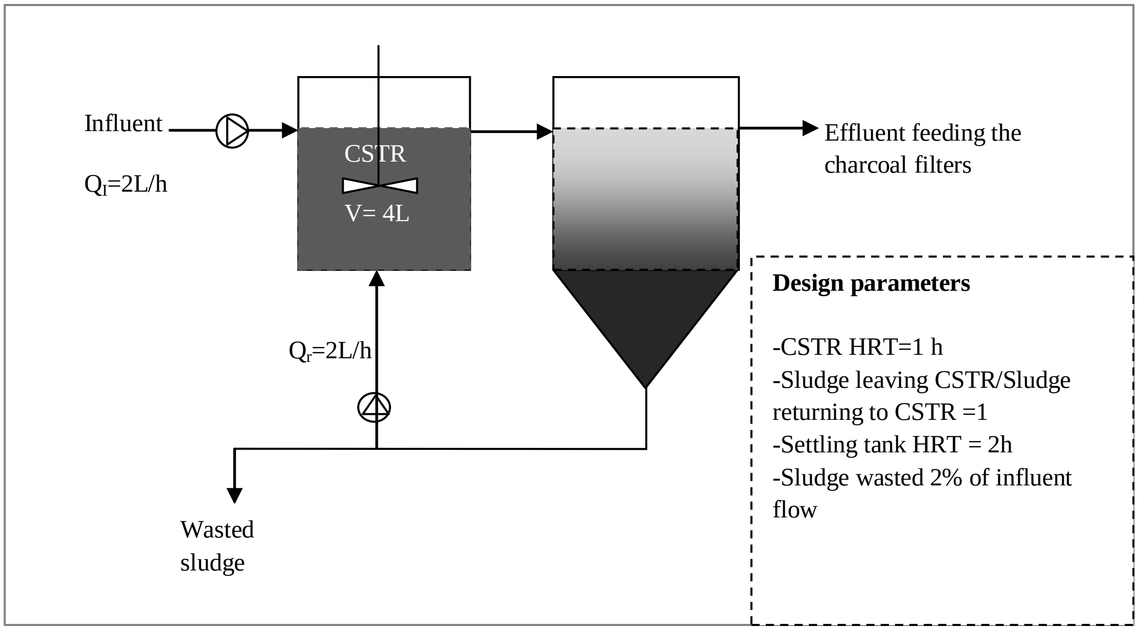

Figure 2. Schematic representation of the high-rate activated sludge (HRAS) set-up consisting of a completely mixed reactor (CSTR) in series with a settler.

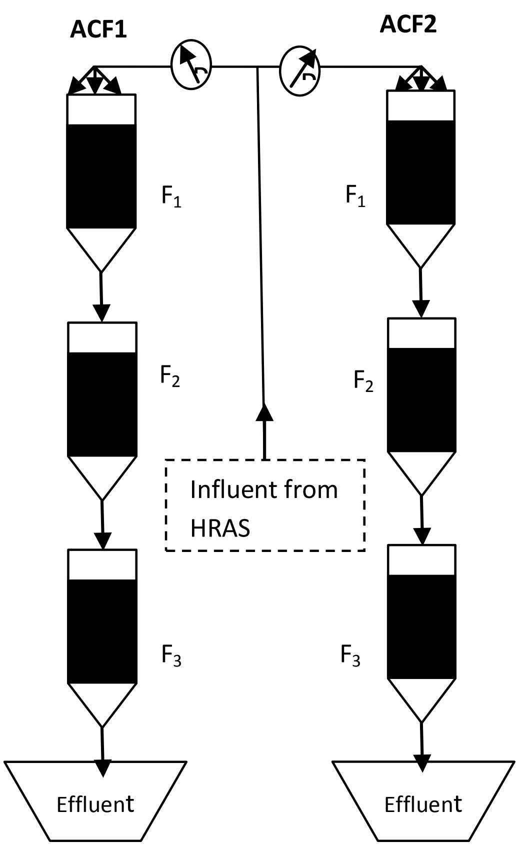

Figure 3. Schematic representation of the setup of the alternating charcoal filter 1 (ACF1) with a retention time of 2.5 h and the alternating charcoal filters 2 (ACF2) with a retention time of 5 h.

1.5 cm. The packed filters had porosity of 48% and dry bulk density of 0.3 g cm^{-3}. The residence time in the filter lines differed with filter line 1 (ACF1) having a residence time of 2.5 h, while filter line 2 (ACF2) had a residence time of 5 h. After every 30 days, the top filter column 1 (F_1) was emptied and refilled with fresh charcoal and moved to the last position in the series while filter column 2 (F_2) and filter column 3 (F_3) went a position up in the series to become F_1 and F_2, respectively. This means that all filters were replaced every 90 days and this continued for the rest of the experimental period. Wastewater samples were taken from the effluent of the last filter columns thrice a week; and chemical oxygen demand (COD), TSS, total ammonium nitrogen (TAN), Total phosphorus (TP), and CFU were measured.

Analytical methods

The influent and effluent samples of the HRAS and the ACF were measured for organic matter, total nitrogen and phosphorous. Total phosphorus (TP), chemical oxygen demand (COD) and total ammonium nitrogen (TAN) were analyzed using Hach DR 5000 Spectrometer as described in the standard methods (APHA, 2005). The pH was measured with a pH meter (Teledo, USA) while volatile Solids (VS) and total solids (TS) were analysed according to standard methods (APHA, 2005). The FC Bacteria were determined using the Colilert-18 protocol (Idexx Laboratories, 2012) and dissolved oxygen (DO) was determined with use of a DO meter (Hach, UK). The Kruskal-Wallis non-parametric test was used to verify if there was a significant difference between the measured influent and effluent parameters of the HRAS and the ACF.

RESULTS

Performance of the HRAS reactor

In the HRAS reactor, the wastewater had an average pH

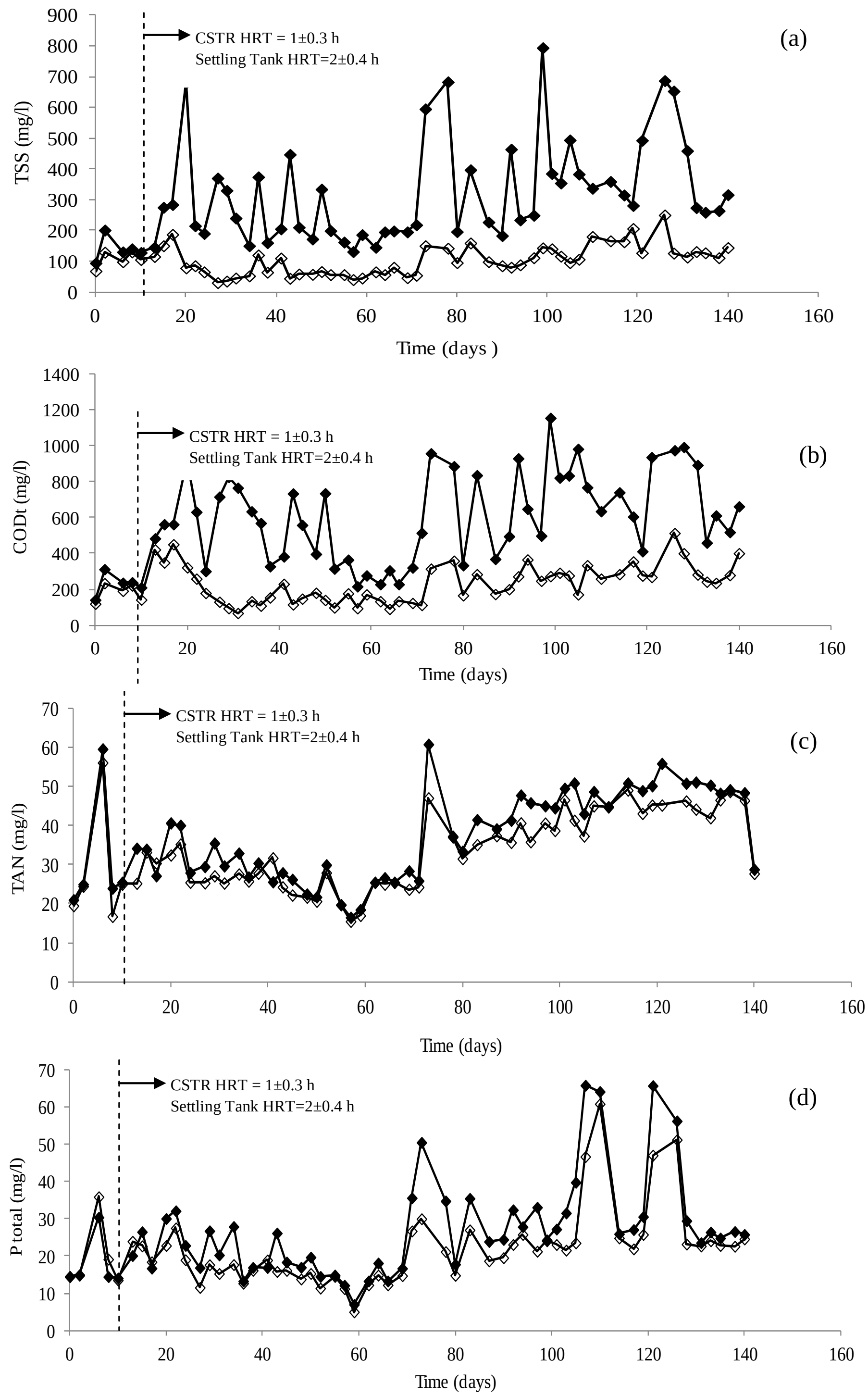

Figure 4. Influent (♦) and effluent (◊) concentrations of (a) the total suspended solids (TSS), (b) the total chemical oxygen demand (COD_t), (c) the total Ammonium nitrogen (TAN) and (d) the total phosphorous (P_{total}), in the high rate activated sludge system during the entire study period.

of 7.4 ± 0.2, dissolved oxygen of $3.7 \pm 1.6 \times 10^{-3}$ mg mL^{-1} and temperature of 21.9 ± 0.7°C (Table 1). Figure 4 shows the performance of the HRAS over the entire 140 days of the experimental run. To evaluate the performance of the HRAS, consideration is only given to the period after day 10 when the HRT in the CSTR and the sedimentation tank were maintained at 1 ± 0.3 and 2 ± 0.4 h, respectively. Regardless of the variation observed in the influent TSS concentration (0.131 to 0.794 mg mL^{-1}), the effluent concentrations were less variable ranging between 0.030 to 0.250 mg mL^{-1}. This corresponded to an average TSS removal of 65%. The average influent COD was 0.613 ± 0.244 mg mL^{-1} of which about 21% was soluble while the average effluent concentration was 0.233 ± 0.104 mg mL^{-1} of which about 48% was soluble COD. This led to an average removal efficiency of 59% for total COD and 15% for soluble COD. The HRAS slightly eliminated TAN and TP with an average removal efficiency of 11 and 17%, respectively.

Performance of the ACF reactor

The effluent of the HRAS was fed to two ACF reactors for further treatment. ACF1 had a residence time of 2.5 h while ACF2 had a residence time of 5 h. Figure 5 shows the performance of the two filter lines over the entire 140 days of the experiment. For consistency, the period after day 10 was considered for evaluation of the performance of the filters. The average TSS concentration of the effluent from ACF1 and ACF2 were 0.032 ± 0.022 and 0.026 ± 0.019 mg mL^{-1}, respectively. This corresponds to an average removal efficiency of 70% for ACF1 and 76% for ACF2. The concentration of total COD of the effluent from ACF1 was on average 0.093 ± 0.045 mg mL^{-1} of which 78% was soluble COD, for ACF2 the average total COD was 0.091 ± 0.047 mg L^{-1} of which 74% was soluble. This corresponds to a total COD removal efficiency of 58 and 60%, observed for ACF1 and ACF2, respectively, while for soluble COD, it was 27 and 30%, respectively. Like in the HRAS reactor, the removal of TAN and TP was low in both filter lines. The average removal of TAN was 11 and 13% in ACF1 and ACF2, respectively, while the average TP removal was 12% in ACF1 and 13% in ACF2. Statistical analysis showed that there was no significant difference (α =0.05) in the performance between ACF1 and ACF2 in removal of all the above considered parameters.

Overall performance of the combined treatment system

In general, the combination of the HRAS and ACF registered high COD and TSS removal efficiencies (Table 1). The overall average TSS removal was 89% ± 7 and 91% ± 6 when the HRAS was combined with ACF1 and ACF2, respectively. The same combinations attained average total COD removals of 83% ± 8 and 84% ± 8 and average soluble COD removal of 46% ± 24 and 48% ± 24, respectively. The overall removal of TP and TAN was generally lower compared to TSS and COD: the combination of HRAS with ACF1 obtained an average TAN removal of 19% ± 16 while with ACF2 it was 20% ± 10. TP removal was 27% ± 15 and 28% ± 14 for the HRAS combination with ACF1 and ACF2, respectively. There was no significant difference (α=0.05) in the performance of the two filters. CFU counts were monitored from day 34 up to the end of the experiment. The HRAS influent CFU counts varied widely from 3.13×10^2 to 2.01×10^6 CFU mL^{-1}. During the experimental study period, the HRAS system achieved on average 1 log decrease of CFU and a further 2 log decrease was achieved by the ACF treatment system.

DISCUSSION

High rate activated sludge (HRAS) system

Bohnke et al. (1997) proposed that the HRT of HRAS should be 30 min or less. However, at that HRT which was used in the first 10 days of the experiment, the performance of our HRAS unit was insufficient, with COD and TSS removals going below 40 and 45%, respectively, hence the HRT was increased to 1 h. The HRAS reactor thereafter effectively removed TSS and total COD by an average of 65 and 59%, respectively. The results in this study are similar to those observed in other studies (Zamalloa et al., 2013; Bohnke, 1977). Apart from biological uptake and degradation, removal in the HRAS systems is partially due to physico-chemical processes which include adsorption and bio-flocculation (Bohnke et al., 1997, 1998).

The contribution of physic-chemical processes on the overall removal is a result of the short SRT and high sludge loading rate of HRAS processes, which alter the kinetics of substrate removal (Larrea et al., 2002, Makinia et al., 2006). The adsorption of particulate substrates may act as a buffer against fluctuations in organic loads (Bunch and Griffin, 1987), which ensures that the effluent sent to the second stage had a more stable composition for optimal filter performance (Bohnke et al., 1997). TP and TAN were removed to a lower extent in comparison to TSS and COD. TAN and TP removal is generally known to be low in HRAS and other high rate activated sludge processes. To ensure sufficient removal of these compounds, additional treatment is typically incorporated after such systems.

Zamalloa et al. (2013) applied a flocculant in the HRAS to decrease phosphates while Bohnke et al. (1997) ensured TAN and TP removal in a second activated sludge stage at low sludge loading rates. For this study however, since the final effluent from the treatment system is proposed for reuse in agriculture, there would be no need for removal of TP and TAN. The sludge generated in the HRAS is known to be highly degradable (Hernandez Leal et al., 2010; De Vrieze et al., 2013) and will be anaerobically digested for energy recovery in a subsequent study.

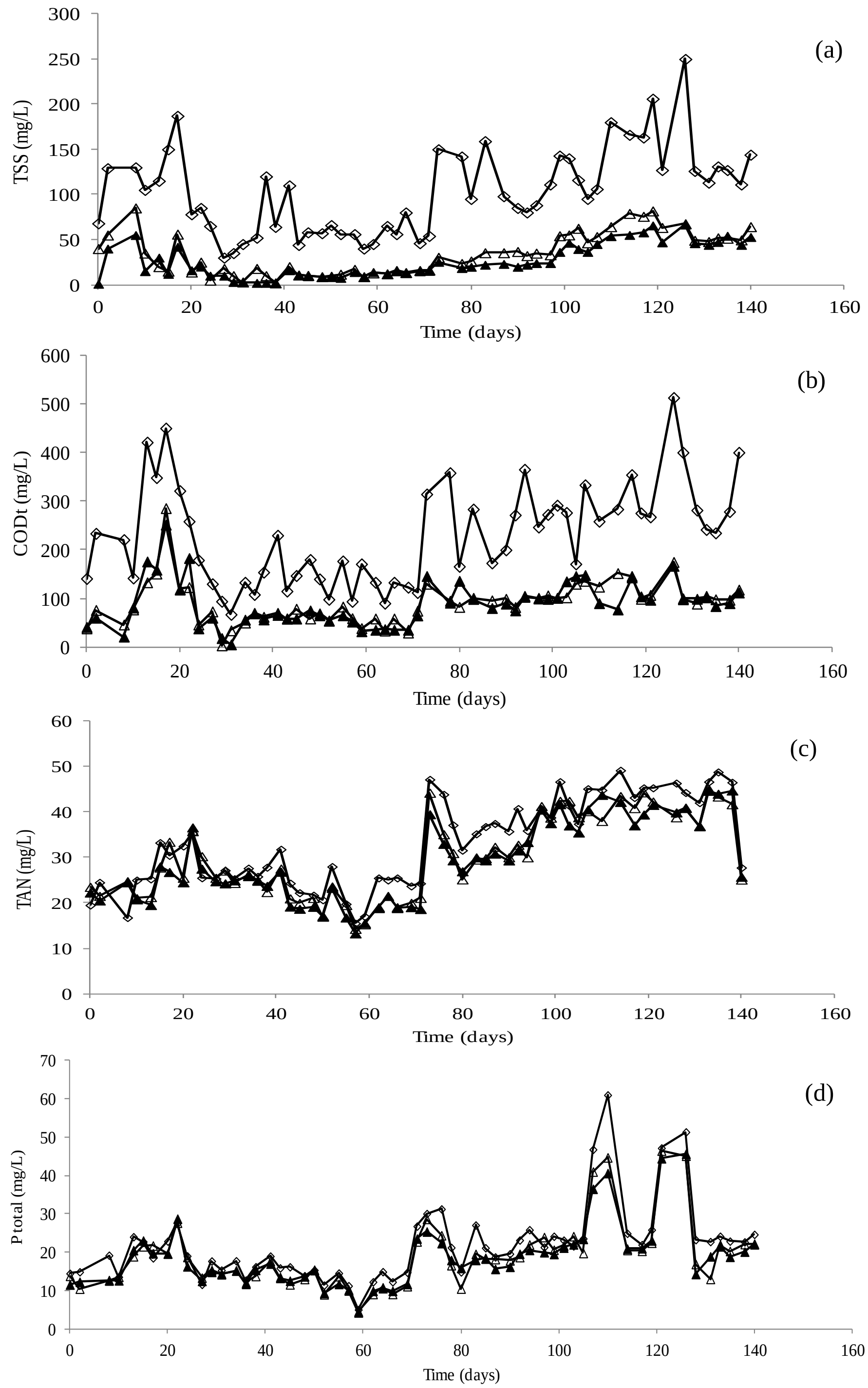

Figure 5. Concentrations of (a) the total suspended solids (TSS), (b) the total chemical oxygen demand (COD_t), (c) the total Ammonium nitrogen (TAN) and (d) the total phosphorous (P_{total}) in the Influent (◊), ACF1 Effluent (Δ) and ACF2 Effluent (▲) during the entire study period.

Alternating charcoal filters (ACF) system

The charcoal filters benefited from the HRAS stage which had an effective treatment and produced a more uniform effluent (TSS and COD did not vary as much as they did in the influent). The two filters had similar performance in which they effectively removed TSS and total COD by an average of 73 and 59%, respectively. Similar to the HRAS, a limited removal was observed for TAN and TP, so the final effluent still contained sufficient nutrients for plant growth. Removal mechanisms of pollutants by the charcoal filter are similar to those in other filters. These include physical filtration, sedimentation, adsorption and biological degradation due to biofilm development. When compared to other filter materials like gravel and rocks however, charcoal has a number of essential properties such as a high number of many micro pores on the surface, high porosity and a high specific surface area of 200 to 300 m^2/g (Darmstadt et al., 2000). The higher specific surface area and porosity in charcoal enhances sedimentation and other filtration processes in charcoal filters (Ochieng and Otieno, 2006) and the micro-pores provide good conditions for micro-organisms to attach. Also, like granulated carbon, charcoal is a good adsorbent and has been widely used as such in wastewater and water treatment (Abe et al., 1993; Khalfaoui et al., 1995, Kamal and Mohammad, 2012). Due to its adsorbent properties, charcoal can accumulate sufficient organic matter and nutrients for biomass to grow. It is believed that in the first few days before biofilm growth, adsorption is responsible for most of the COD removal. All these processes contribute to the high efficiency of TSS and COD removal observed throughout the filter's operation. In addition, the small-sized charcoal particles used in this study are cheap, light and easily available at charcoal making stores as waste, and hence offers a cost-effective filter medium for application in the developing world. Actually, the cost for regular replacement of the charcoal are quite reasonable, they are only of the order of 9% of the total cost $capita^{-1}$ $year^{-1}$. Unlike other media however, charcoal is not easy to clean in case of clogging, which would potentially limit its application for prolonged operation times. Therefore, it is proposed in this study that the charcoal filters be used in series and be moved up the chain as the first filter is replaced every month. As demonstrated in this study, such an alternating use of charcoal filters ensures consistently high removal efficiency for both TSS and COD. Interestingly, the spent charcoal can be sun dried and subsequently used for fuel. Thus, the charcoal can be used in a coherent sustainable way.

Overall performance

Overall, the combination of the HRAS with each of the filters showed an effective system for the removal of TSS and COD. It produced an effluent whose average values of TSS and COD met the National effluent standard as required by the National Environment Management Authority (NEMA). NEMA is the regulatory body of effluent discharge in Uganda and its standards require both the TSS and COD of the effluent to be below 0.1 mg mL^{-1}. The combination of the HRAS and the ACF also showed that it could on average achieve a 3 log decrease of CFU mL^{-1} from the influent. The removal efficiency of CFU is at least 60% in an activated sludge process or biofilm process (Farrell et al., 1990). The treatment system in this study performed as well as expected achieving 99.9% (3 log decrease) of CFU for the combined systems of the HRAS and the ACF. In porous media systems, pathogen removal is partially achieved by straining and sorption, which are largely determined by the filter pore sizes, hydraulic loading and clogging (Stevik et al., 2004). Straining would be predominant with small pore sizes (when bacteria sizes are bigger than the pore sizes), low hydraulic loading and where clogging has occurred, otherwise adsorption would take over. With the charcoal particle sizes up to 1.5 cm it is clear that adsorption was the most important mechanism of pathogen removal at the beginning of the experiment. However, with time, clogging brought about straining as the other pathogen removal mechanism. Also, the continued running of experiment allowed accumulation of macro-organisms which contribute to pathogen removal through predation. With the influent ranging from 3.13×10^2 to 2.01×10^6 FC mL^{-1}, it was possible to achieve the NEMA effluent standard of 10^2 CFU mL^{-1} for more than half of the samples (53%). Given that on average, a 2 log decrease of CFU can be achieved by the ACF system alone which consists of three filter columns, it would be possible to increase percentage of compliance by increasing the number of filter columns in the ACF system. Further studies could aim at optimising the system with regard to additional filters required to achieve 100% compliance of the CFU effluent to NEMA standards. Furthermore, with the effluent proposed to be reused in agriculture, it should also meet the standards for reuse. The World Health Organisation (WHO) guidelines require at least a 6 log decrease of pathogens from the wastewater source considering a level of contamination of 10^6 CFU mL^{-1} in the untreated wastewater (WHO, 2006). On the other hand, designing a plant to achieve a log decrease of 6 or more, only to eliminate pathogen contamination would be too expensive. It would include additional processes like chemical coagulation, flocculation and disinfection, which would generally preclude its application in many developing countries. It is therefore important that wastewater reuse strategies for pathogen removal are not just based on wastewater treatment alone. Instead, a multiple control approach should be adopted to effectively eliminate or inactivate the various microorganisms spread through different routes. WHO (2006) proposes different control measures such as cooking and washing of foods before consumption, that can be combined to achieve a total log decrease sufficient to eliminate risk of pathogen infection.

Preliminary estimation of costs

The preliminary cost estimates of the HRAS/ACF treatment system serving a small farming community of

Table 2. Capital and operational cost estimation of HRAS/ACF system. Assuming a small agricultural community of 10 houses, with 5 inhabitants producing 100 L of wastewater $IE^{-1}day^{-1}$.

Capital costs	€
HRAS CSTR[a]	60
HRAS Settler[b]	110
Charcoal filter[c]	114
Filter material[cd]	5
HRAS/ACF Instrumentation[e]	100
Total Capital cost	389
	7.8 € Capita-[1]
Operational costs	€/m^3/d
ACF material[df]	0.012
Electricity costs[g]	0.003
Labour costs[h]	0.093
Total operational cost	0.1
	3.6 € $Capita^{-1}$ $year^{-1}$
Annualised overall cost for the treatment system[i]	4.9 € $Capita^{-1}$ $year^{-1}$

[a]Wastewater flow rate plus recycle of 0.4 m^3h^{-1}, requires a durable plastic water tank of 0.5 m^3, volume price according to a local plastic water tank manufacturer is 60 €.[b]For a HRT of 2 h, the settling tank volume required is at least 0.8 m^3. Use a durable plastic water tank of 1 m^3 volume, local manufacture's price is 110 €. [c]For a flow rate of 0.2 m^3h^{-1} (no recycle), total charcoal volume required is 0.5 m^3 (0.2 m^3 per filter). Use 3 plastic tanks of 0.25 m^3 of a local price of € 38 each. [d]A bag of charcoal (0.33 m^3) costs between € 10 - 20 depending on the season. However, a bag of the small pieces (< 2 cm) arising from the charcoal making process is wasted or sold at 3 €. [e]HRAS/ACF instrumentation (pump, aerator and pipe work) is estimated at 100 €. [f]Material in only one filter is replaced monthly. [g]Based on a consumption of 0.018 KWhel/d/m^3 wastewater treated. Installed power of 6 W/m^3 reactor is assumed (10 m hydraulic head, for a flow rate of 5 m^3/d and a pump efficiency of 60%) and 3 h pumping at an electricity cost of 0.09 €/kWhel. [h]Cheap unskilled labour is required to monitor pump operation time and change material. [i]A life span of 10 years was considered and a real interest rate of 10%.

10 houses, each with 5 inhabitants is shown in Table 2. The costs are based on the lab-scale reactor operational conditions and use of locally available but durable material in Uganda. These estimations indicate that the system can treat wastewater at an overall (capital and operational) annualised cost of 5 € $capita^{-1}$ $year^{-1}$. This estimate excludes the sludge line treatment. If it is included, it could be possible to recover an additional value from electricity generated estimated at 1 € $capita^{-1}$ $year^{-1}$ for sludge with at least 3 to 5 kg DW/m^3 (Verstraete and Vlaeminck, 2011) through anaerobic digestion. The overall (capital and operational) cost of the HRAS/ACF system is less than a third the overall cost of a small scale (10,000 to 50,000 IE) conventional activated sludge system (CAS), which is estimated at about 18 to 24 € $capita^{-1}$ $year^{-1}$ (Zessner et al., 2010), excluding sludge treatment. It was also less than half the cost of the waste stabilisation pond (WSP) and the horizontal subsurface flow constructed wetlands (HSSF-CW) which can cost about 13 and 14 € $capita^{-1}$ $year^{-1}$, respectively, in East Africa (Mburu et al., 2013). Apart from the already mentioned added value that could arise from anaerobic digestion of the sludge, the proposed system offers the community other benefits which include fuel that can be derived from the sun dried used charcoal. Furthermore, a nutrient rich effluent would go a long way to boost crop productivity for farmers.

Conclusions

The results in this study have shown that a combination of the HRAS and the ACF can effectively remove TSS and COD from domestic wastewater to meet the NEMA discharge standards. The treatment system achieved the NEMA effluent standard for CFU for more than half of the samples. However, it would be possible to attain higher CFU removal if more filter columns are added in the ACF system. Further research is proposed to optimise the system in order to achieve 100% compliance to the CFU standard. TAN and TP were largely retained in the effluent, allowing nutrient reuse by crops. The proposed treatment system has an estimated cost which is less than half the cost of other systems such as, the small-scale CAS, WSP and HSSF-CW. It further offers a nutrient-rich effluent which will advance the re-use of wastewater for agriculture through generation of higher crop yields and profits. The novel design is therefore suggested for further development as a technology for wastewater treatment and reuse to benefit small agricultural communities. In order to effectively eliminate microorganisms and reduce pathogen transmission, it is recommended that the effluent be reused in an agricultural setting with a multi-barrier approach for example where food will be washed and or cooked before consumption.

Conflict of interests

The authors did not declare any conflict of interest.

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