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DECENTRALIZED DOMESTIC WASTEWATER TREATMENT USING A NOVEL HYBRID UPFLOW ANAEROBIC SLUDGE BLANKET FOLLOWED BY SAND FILTRATION

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Abstract- The aim of this study is to develop an innovative pilot plant compact system for decentralized treatment and reuse of domestic wastewater. The design, construction, operation and performance of the system are presented. The system is modular; it could serve from 1,000 to 5,000 capita. The pilot plant comprises of three successive compartments namely; hybrid up flow anaerobic sludge blanket (H-UASB) packed with innovative non-woven polyester fabric (NWPF), inclined plate settler (IPS) and a slow sand filtration unit (SSF). Characterization of NWPF was carried out using scanning election microscope. In addition toxicity test of the packing material was carried out using daphnia magna as a test organism. The NWPF has a specific area of 2000 m^2/m^3 and an average pore size of 43.8 μm. The overall efficiency of the treatment system, running for almost one year, resulted inconsiderable reductions of COD (86.6%), BOD (90.3%) and TSS (96.8%). In addition, great removal of nutrients and pathogens were also achieved. The results obtained proved the advantage of using the innovative packing material (NWPF) in the UASB reactor. The NWPF have pleated and rough surface, which can retain more biomass rather than the plain surface. Its high surface area and high porosity enhanced the strong adhesion of microbial biomass onto the packing media promoting the effective physical entrapment/adsorption and subsequent bonding between the biomass and media. In conclusion, the proposed treatment system produced a very high quality effluent, which can be applied in rural area and small communities.

Keywords- Wastewater, anaerobic treatment, packing material, rural areas, small communities.

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Introduction

Anaerobic treatment of wastewater is nowadays widely accepted as a proved technology and extensively used. One of the most common technologies is the anaerobic hybrid reactor, which consists of a sludge bed in the low part and an anaerobic filter in the upper part. This system combines the advantage of up flow anaerobic sludge blanket and anaerobic filter reactor, while minimizing their limitations [1]. The reactor is efficient in the treatment of dilute to high strength wastewater at high organic loading rate and short hydraulic retention time [2,3].

High rate bioreactors include the UASB, packed bed and fluidized bed reactors, based on the mechanism used to achieve biomass retention within the bioreactor. These bioreactors provide a high reaction rate per unit reactor volume thus reducing reactor volume and ultimately allowing the application of high volumetric loading rates [4-6]. The filter zone in the anaerobic hybrid reactor, in addition to its physical role for biomass retention, has some biological activity contributing to COD reduction in a zone which is lacking biomass in a classical UASB reactor. Increased stability and performance in anaerobic reactors can be achieved if the microbial consortium is retained in the reactor. The packing medium in the packed bed reactor serves as a filter preventing bacterial washout and also providing a large surface area for faster biofilm development and improved methanogensis. Specific surface area, porosity, surface roughness, pore size, orientation of packing material were found to play an important role in the anaerobic reactor performance. Oriented and porous media in the anaerobic filter reactor provide better performance in comparison with random and non-porous media [7].

In packed bed reactors wastewater is passed in either up flow or down flow mode over a population of microorganisms attached to an inlet solid support carrier e.g. gravel, plastic carriers, ceramic rings, glass beads or baked clay [8,9]. Also, they have an advantage over UASB in that they are not susceptible to biomass washout by hydraulic shock loads. Elmitwalli, et al. [10] compared the performances of a hybrid UASB-filter and a classical UASB reactor at 13°C. The hybrid UASB-filter reactor reached 64% COD removal, 4% better removal than the classical UASB. This may be due to the attachment of biomass on the filter. Huysman, et al. [11] reported that reticulated polyurethane foam (porous media) offers an excellent colonization matrix for the anaerobic filter reactor. Selvamurgan, et al. [12] used up flow anaerobic hybrid reactor packed with PVC frill sheet to treat coffee processing wastewater at 18 HRT with organic loading rate of 9.55 Kg COD/m^3/day, the removal efficiency for COD, BOD and TSS were 61%, 66% and 58%, respectively. Abou-Elela, et al. [13] treat low strength wastewater using an integrated pilot plant system consists of P-UASB packed with lamella plastic sheets at an average organic loading rate of 2.5 Kg COD/m^3/day, HLR 6m^3/day and low HRT of 4Hrs. in P-UASB. The quality of treated effluent in terms of the removal rates of COD, BOD and TSS removal rates were 78%, 79% and 91%, respectively. Also, Rajakumar, et al. [14] used a 5.4 L hybrid UASB packed with PVC rings for treating poultry slaughterhouse waste under mesophilic conditions and they achieved TCOD and SCOD removal efficiency of 86% and 92.4%, respectively at OLR of 9.27 Kg COD m^3/day. However, the residual concentrations of COD, BOD and microbiological pollutants (Fecal coliforms) in the anaerobic reactor effluent usually exceed the maximum permissible level prescribed by the effluent discharge. Thus a post treatment is required. Sand filtration could be considered as one of the most promising treatment options which can remove BOD, TSS, turbidity and total coliforms up to 86%, 68%, 88% and over 99%, respectively. Also, it is a cost effective technique which requires less skilled man power due to its simple design [15].

The aim of this study is to develop a cost effective integrated decentralized wastewater treatment system suitable for implementation in small communities and rural areas. It consists of hybrid upflow anaerobic sludge blanket (HUASB) packed with an innovative packing material (non-woven polyester fabric) followed by inclined plate settler (IPS) then sand filtration unit (SSF) as a post treatment step.

Materials and Methods

Description of the Treatment System

A schematic flow diagram of the treatment system, its design criteria and operating conditions are shown in [Fig-1] and[Table-1].

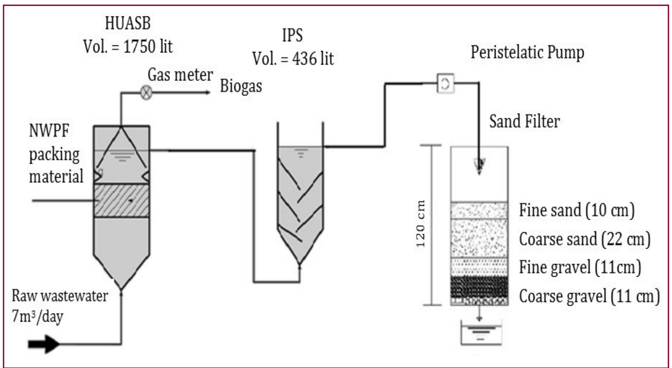

Fig. 1- Schematic flow diagram for the treatment system

Table 1- Design criteria and operating conditions of the treatment system

Parameters	P-UASB	IPS	SSF
Temperature (°C)	17-35	17-35	17-35
Flow rate (m^3/day)	7	7	--
Volume (m^3)	1.75	0.54	--
OLR (Kg COD m^3/day)	1.42	--	--
HRT (hr)	6	2.6	--
Surface loading rate/rate of filtration (m^3/m^2/h)	--	19.44	0.00064
Packing material	NWPF framed in cylindrical frames	Provided by plastic inclined sheets (60° inclination)	Coarse and fine gravel followed by coarse and fine sand

The treatment system consists of three successive compartments namely; hybrid up-flow anaerobic sludge blanket (HUASB) with internal dimensions of 114 x 102 cm and height of 191 cm packed with non-woven polyester fabric (NWPF), operated with an average OLR of 1.42 Kg COD/m^3/day and HLR of 7 m^3/day, inclined plate settler with internal dimensions of 60x60 cm and height of 150 cm and a slow sand filtration unit. The system is made of PVC of 8 mm thickness.

Packing Material

Non-woven Polyester Fabric

A non-woven polyester fabric (NWPF) was used as a biomass holder (packing material in UASB). This material was used for the first time for such purpose. It is purchased from the local market as sheets (1×1m) with a thickness of 0.8-1cm. The NWPF sheets were cut into square pieces (5×5 cm), then shaped into rolls and fixed in plastic cylindrical frames. The rolled NWPF was retained in a stainless steel basket and fixed in the upper part of the up-flow anaerobic sludge blanket at a distance of 60 cm under the gas-liquid-solid separator (GLS). The height of the packing material was 30 cm occupying a volume of 0.3 m^3.

Characteristics of Packing Material (NWPF) using Scanning Electron Microscope

Samples of NWPF before and after entrapment by microorganisms were cut into small pieces and fixed in 0.2 M sodium cacodylate buffer (pH 7.3) containing 4% glutaraldehyde for 4 hours, followed by post fixation in osmium tetraoxide (OsO_4) for 2 hours. Then rinsed three times in the same buffer solution (sodium cacodylate buffer). The tissue pieces were dehydrated through washing with a graded ethanol series from 10 to100% for 10 minutes intervals except for the final step (100%) is dehydrated for 30 minutes. The dehydrated processes are repeated three times, then tissue pieces are dehydrated by using Critical Point Dried instrument with liquid carbon dioxide CO_2.The treated tissue pieces are mounted on cupper stubs with double- sided adhesive tape, coated with gold using S150A Sputter Coater-Edwards-England. The specimens viewed in a scanning electron microscope JXA-840A Electron Probe Micro analyzer-JEOL- Japan.

Toxicity Test for NWPF

In the UASB it was found necessary to carry out a toxicity test of NWPF before using it as a packing material in the UASB. Toxicity test for the NWPF was done using *Daphnia magna* as a test organism in a synthetic fresh water medium [16]. Gravid females were transferred at regular intervals to 1-L glass beakers in which the holding medium was renewed three times a week. The animals were fed three times a week with 14X10^{7}coenobia/ml of the green micro alga *Scenedesmusobliquus*for rearing. The daphnids were kept at a temperature 22±2°C.

Short term (48 Hrs. Acute) Toxicity Test

Forty-eight hours acute toxicity tests (static system) were conducted with less than 24h old daphnis. Pieces of NWPF were soaked in synthetic freshwater medium for ten days. Ten daphnis were employed in each replicate with 100 ml of the test water (soaking medium) and introduced in 250-ml glass beaker. Three replicates were conducted per each test. Control test was run in parallel. The number of live organisms after the elapse of 48Hrs. was recorded. Acute toxicity tests were run without food addition as recommended by the standard toxicity testing [17].

Site Description and Wastewater Characterization

The treatment system was located in a nearby wastewater treatment plant, North Giza. The system is fed continuously with a pre-screened real domestic wastewater using a submerged pump. The main characteristics of feeding wastewater are summarized in [Table-2].

*Table 2- Wastewater characterization**

Parameters	Unit	Mean	SD(±)
pH-value	--	7.25-7.43	0.12
Turbidity	NTU	122	31
Total Chemical Oxygen Demand	mgO_2/l	350	83
Soluble Chemical Oxygen Demand	mgO_2/l	138.9	44
Biological Oxygen Demand	mgO_2/l	194.9	19
Total Suspended Solids	mg/l	178.8	44
Volatile Suspended Solids	mg/l	115	33
Total Kjeldahal Nitrogen	mgN/l	32	6
Ammonia	mgN/l	20	5
Total Phosphorous	mgP/l	4	2
Oil & Grease and all Extractable Matters by Chloroform	mg/l	71	46
Hydrogen Sulphide	mg/l	6	2
Total Coliform	MPN/100 ml	4.6×10^7	--
Fecal Coliform	MPN/100 ml	1.5×10^6	--
Fecal Streptococci	MPN/100 ml	2.1×10^5	--

Mean values during one year operation

Samples Collection and Analysis

Samples of raw wastewater, H-UASB, IPS and SSFeffluents were collected and analyzed. The physico-chemical analysis covered: pH, turbidity, total chemical oxygen demand (TCOD), soluble chemical oxygen demand (SCOD), biological oxygen demand (BOD), total suspended solids (TSS), total kjeldahl nitrogen (TKN), ammonia (NH_3), total phosphorous (TP), hydrogen sulphide (H_2S) and oil & grease. Sludge analysis including total solids (TSS) and volatile suspended solids (VSS) were also analyzed. Microbiological parameters were measured in the influent and effluents of each treatment units as per standard methods [17].

Start-up of the Treatment System

The treatment system was fed with a real wastewater for almost one year at a temperature ranged from 17-35°C. The flow rate was gradually increased from 3 m^3/day to 7 m^3/day until it reached the steady state condition. The start-up period was almost 120 days. The performance of the treatment system was monitored at regular intervals via physico-chemical and microbiological analysis.

Retained Biomass and Wasted Sludge

Fixed number of NPWF media in the P-UASB was harvested after 240 days from operation. The collected NPWF media was squeezed and washed with water until it was apparently clean. The eluted biomass was collected in a porcelain dishes. The concentration of TS and VS of the squeezed sludge was analyzed corresponding to the size of the NWPF taken out. The biomass content per liter of the NWPF was calculated according to [Eq-1]. The experiment was repeated several times to take the average of retained biomass in the packing media.

$$\text{Re tained Sludge (NWPF)}\left(\frac{g}{L}\right) = \frac{\text{TSS or VSS}}{\text{NWPF Volume}} \qquad (1)$$

Excess sludge production from P-UASB was collected every month for analysis. Sludge volume, total solids and volatile solids were measured according to APHA, [17]. The sludge yield coefficient was calculated according to [Eq-2].

$$\text{Sludge yield coeffcient}\left(\frac{\text{kg TSS}}{\text{kg COD removed}}\right) = \frac{\text{TSS or VSS(kg)}}{COD_{Influent} - COD_{Effluent}} \qquad (2)$$

Results and Discussion

Characteristics of NWPF used in the UASB as a Packing Material

Examination of the NWPF before and after loading with biofilm using SEM are shown in [Photo-1] [Photo-2]. It is obvious from [Photo-2] that the biofilm developed in the NWPF media for a duration of 12 month, act as a filter preventing the washout and also providing a large surface area for faster biofilm development and consequently improved methanogensis in the H-UASB, [Table-3] summarizes the NWPF characteristics.

Table 3- Characteristics of NWPF

Parameters	Unit	Value
Shape	--	Rolled NWPF, thickness 0.81 cm cut into small pieces (5x5cm) and fixed in plastic cylindrical frames
Specific surface area	m^2/m^3	2000
Pore size	µm	Range from 21.2 µm - 66.5 µm with an average pore size of 43.8 µm

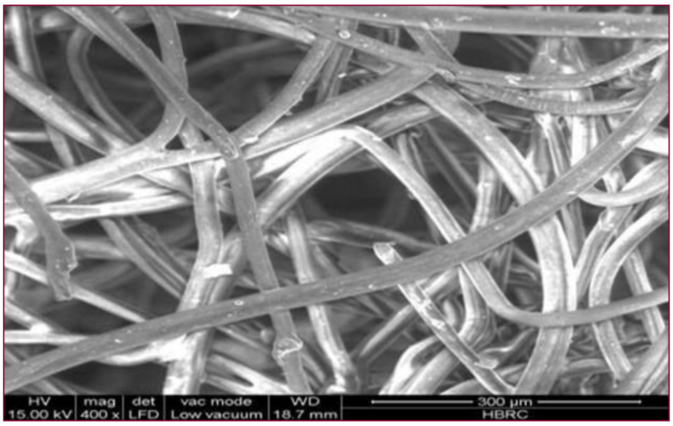

Photo 1- SEM of NWPF before operation

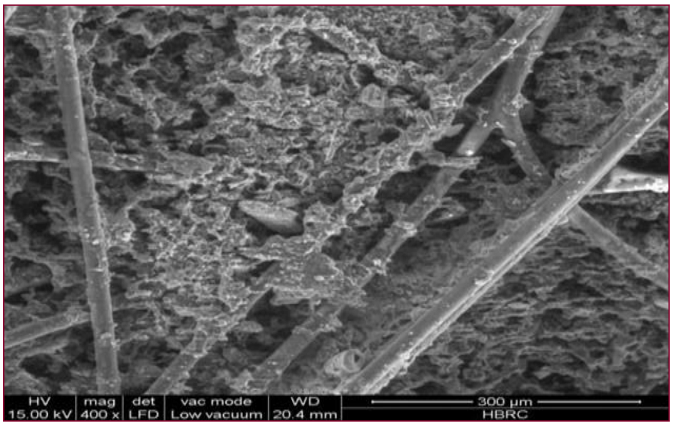

Photo 2- SEM of NWPF after entrapment with microorganisms

Toxicity Test

A toxicity evaluation is an important parameter in wastewater quality monitoring, as it provides an overview of the response of test organisms to all the compounds in the wastewater [18]. To achieve a realistic estimation of the hazard of pollutants, toxicity effect must be investigated [19]. The water flea *Daphnia magna straus*is the most commonly used zooplankton in toxicological tests. Generally in toxicity test, death is a decisive criterion because it is easy to determine and has obvious biological and ecological significance [20]. The results depicted in [Table-4], after 48 hr. acute toxicity test revealed that the packing material used in this study was not toxic.

Table 4- Toxicity effect of NWPF soaking media on Daphnia magna

Fabric soaking media (Triplicates)	Concentration %	48h-Survival %
	Control	100
1	100	100
2	100	100
3	100	100

Effect of Packing Material on the Removal Rate of Organic Matters and Suspended Solids in H-UASB Alone Prior Sedimentation

The effect of using the new packing material (NWPF) was monitored through the measurements of TCOD, SCOD, BOD and TSS. The COD removal rate at the start-up of the reactor was relatively low and it reached 21.8%. This may be due to the clean conditions on the media (NWPF). It was increased gradually to 50% after almost 80 days. After reaching the steady state conditions (120 days), the removal efficiency of TCOD, SCOD, BOD and TSS were increased to 60%, 42%, 66% and 76.36% due to the entrapment and accumulation of biomass onto the NWPF surface. The high entrapment capacity of organic matter by the NWPF was due to the pleated rough surface, high specific surface area (2000m^2/m^3) and the low density. Moreover, the high porosity of the NWPF ranged between (21.2-66.5 μm) with an average porosity of 43.8 μm. All that leads to a strong adhesion of microbial biomass onto the NWPF, promoting the effective physical entrapment/ adsorption and subsequent bonding (chemical/ electrostatic and Vander Waals forces) between biomass and media which lead to immobilization of attached biomass. Also, all these could be the cause of the higher potentiality for biodegradation of both particulate and soluble organic matter in the HUASB reactor. In addition, the high removal rate of TSS (76.36%) may be attributed to the use of NWPF which overcomes the washout of suspended solids in the effluent and consequently increased the sludge residence time. The use of lamella sheets in the same UASB at the same operating conditions removed only 52% of COD and 62% of TSS [13] compared with 60% and 76.36% removals using NWPF. The results obtained indicated the advantage of using such porous surface (NWPF) compared with the smooth one (lamella sheets) used as packing material in the UASB reactor treating low strength wastewater [13].

Retained Biomass on the Surface of NWPF

Sludge analysis indicated that the sludge yield coefficient in the HUASB reactor was 0.33Kg SS/Kg COD removed per day. The attached biomass on the surface of NWPF in the HUASB reactor operated at an average OLR of 1.42kg COD m^3/day was 65.7 SS g/l and 28.9 VSS g/l. The SEM before and after entrapment showed the densely attached biomass on the pores of NWPF after one year of operation although there is still void spaces was not entrapped by the microorganisms in the NWPF as shown previously in [Photo-2].

Overall Efficiency of the Integrated Treatment System

The overall efficiency of the treatment system using HUASB-IPS then by SSF is shown in [Table-5] and [Fig-2], [Fig-4].

The results revealed that the system achieved sustainable and satisfactory reductions in TCOD, SCOD and BOD. Their corresponding percentage removal values were 86.57 %, 78.32 % and 90.3%, respectively with residual concentrations of 47, 30 and 18.8 mgO_2/l. It is obvious that the IPS unit improves the quality of the anaerobically treated effluent due to the formation of a thin biofilm on the surface of the inclined plates which improve the bisorption of suspended and colloidal particles and consequently improves the degradation of organic matters. Moreover, further removals of TCOD, SCOD and BOD in sand filter were due to the straining and attachment of microorganisms to the sand media [13].

Table 5- Overall efficiency of the integrated treatment system

Parameters	Unit	Raw wastewater	HUASB effluent	IPS Effluent	SSF Effluent	Overall Efficiency % Removal
pH-value	--	7.34	7.16	7.62	7.74	--
Turbidity	NTU	122	93	9	4	96.72
TCOD	mgO_2/l	350	140.91	68.18	47	86.57
SCOD	mgO_2/l	138.9	80.91	44.09	30	78.32
BOD	mgO_2/l	194.9	66.91	31.27	18	90.3
TSS	mg/l	178.8	42.27	12.73	5.56	96.8
VSS	mg/l	115	23	5	1	99
TKN	mgN/l	32	25.23	17.18	12	62.5
NH_4-H	mgN/l	21.13	16.28	10.3	7.08	66.5
TP	mgP/l	4	2.5	1.48	1	91
Oil & Grease	mg/l	73.92	26.63	14.38	6.25	91.5
H_2S	mg/l	4.87	9.13	1.8	0.47	90.3
TC	MPN/100 ml [1]	4.7×10^7	1.8×10^5	1.5×10^3	2.8×10^2	99.99
FC	MPN/100 ml [2]	1.5×10^6	7.42×10^4	1.5×10^2	1.1×10	99.99
FS	MPN/100 ml [3]	2.1×10^5	1.5×10^4	2.0×10^2	1.1×10	99.99

Mean values during one year operation

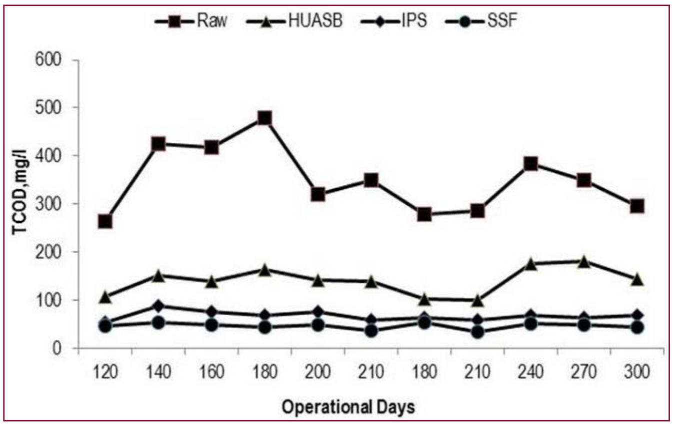

Fig. 2- Variations of TCOD in the treatment system

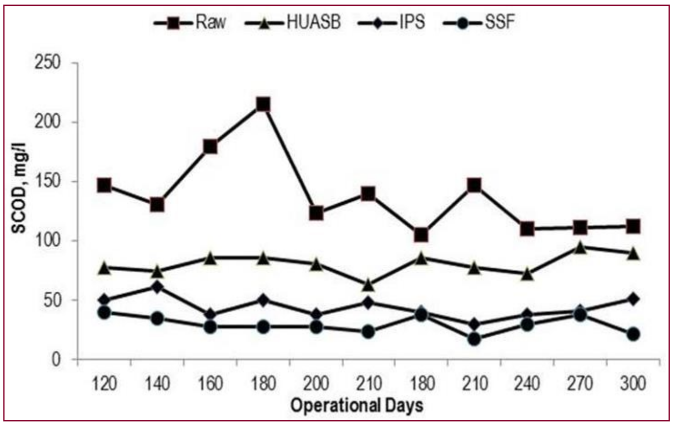

Fig. 3- Variations of SCOD in the treatment system

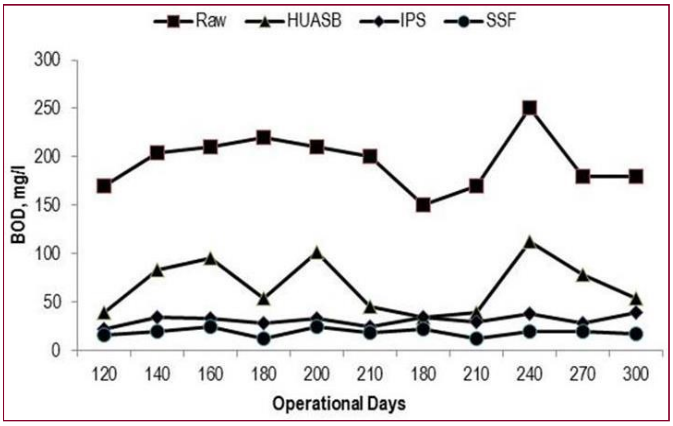

Fig. 4- Variations of BOD in the treatment system

Removal of TSS

The results depicted in [Fig-5] show that 76% from the suspended solids have been removed in the HUSB due to the presence of NWPF. Moreover, the use of inclined plate settler followed by sand filtration improved the quality of wastewater. The average residual concentration of TSS in the treated effluent was 5.5 mg/l with an average percentage removal rate of 96.89%. This may be attributed to the presence of IPS which is provided by plastic inclined sheets at 60◦ inclination with surface loading rate of 19.44 $m^3/m^2/day$. It improves the settliability of suspended solids (up to 92.88% removal of TSS) which is then accumulated and discharged with the sludge. Moreover, a biofilm is developed on the surface of IPS where biocatalysts exist on the surface of an inert media or adhere with other microorganisms [13]. This is in agreement with Latik, et al. [22] in which they stated that the lesser the angle of inclination, the more susceptible the separators becomes to plugging with solids. In addition, the mechanism of SS removal in the sand filter attributed to the straining and attachment to the media of sand [15].

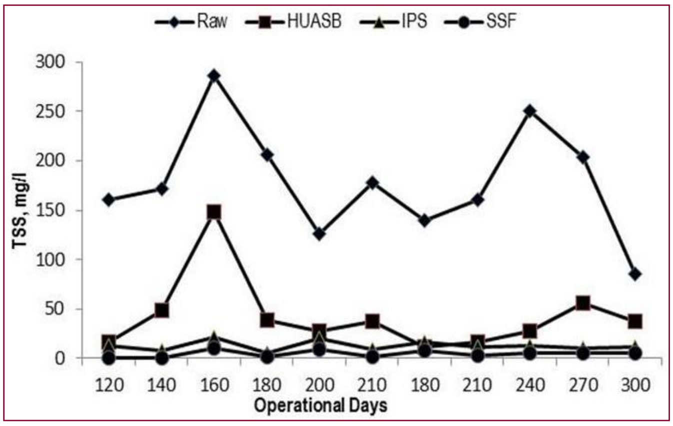

Fig. 5- Variations of TSS in the treatment system

Nutrient Removal

The integrated treatment unit displayed nutrient removal efficiency of 62.5 % for total organic nitrogen, 66.5% for ammonia and 91% for total phosphorous as shown in [Fig-6]. The average residual concentrations were 12 mgN/l, 7 mgN/l and 1 mgP/l. It was obvious in this study that most of ammonia was removed in the sand filtration unit. Sand filters are a biofilm driven processes were microorganisms established on sand grains that are responsible for biotransformation, biodegradation, mineralization and nutrient assimilation process involved in wastewater purification [22]. Also, phosphate removal could be due to the decomposition of some organic phosphorus compound from the wastewater and by various mechanisms such as asorption, precipitation and assimilation by the biofilm developed on sand media.

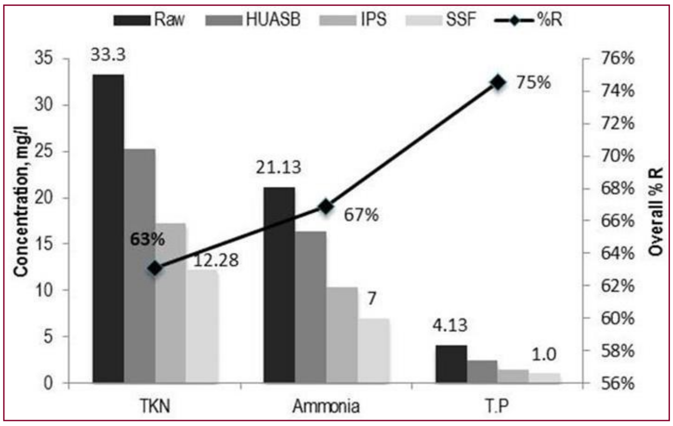

Fig. 6- Efficiency of the treatment system for nutrients removal

Bacterial removal

The average influent concentrations of Coliforms (Total coliforms, Faecal coliforms) and Fecal Streptococci were 4.6 x 10^7 and 1.5 x 10^6 and 2.1 x 10^5, respectively. Analysis of the treated effluent indicated the removal of 5 logs of Total coliforms, 5 logs of Faecal coliforms and 4 logs of Faecal streptococci. The residual values were 2.8x10^2, 1.1x10 and 1.1x10, respectively as shown in [Fig-7]. TC and FC counts were reduced by 2 logs in HUASB due to their entrapment in the UASB sludge bed and inside the packing material. Also, the HRT of 6Hrs. in HUASB was sufficient for TC and FC to get absorbed to the anaerobes/biomass. This is in agreement with [23]. Biological sand filter was used as a post treatment to remove the remaining fractions of pathogenic microorganism. TC and FC was reduced by 5 logs due to low filtration rate, the effective size of sand media and the biological processes which occur in the layer accumulated above the sand surface (schmutzdecke). The high growth of biomass in upper layer also contributed to high removal efficiency of COD, BOD, SS, TC, FC and FS. This is in agreement with [24].

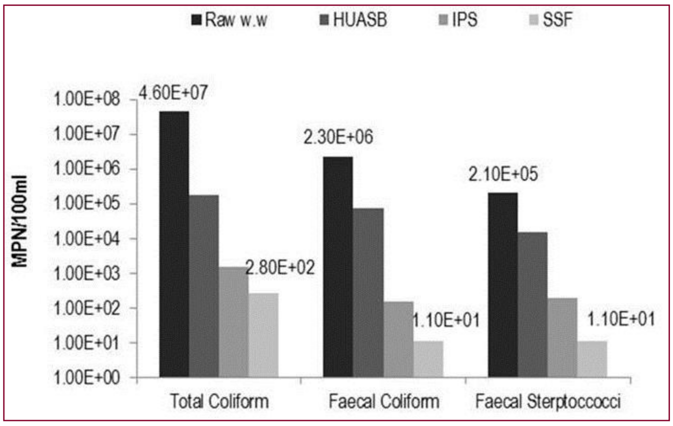

Fig. 7- Efficiency of the treatment system for pathogenic removal

Conclusion

The results obtained in this study revealed that the use of an integrated system namely; packed bed up-flow anaerobic sludge blanket, followed by inclined plate settler then slow sand filtration produced a high quality effluent in terms of physico-chemical and biological parameters. The COD, BOD and TSS removal rates reached 86.57%, 90.3% and 96.8%, respectively. In addition, over 99.99% removal of Total coliforms, Faecal coliforms and Fecal streptococci were achieved. The use of a novel packing material (NWPF) in the HUASB with high specific surface area (2000 m^2/m^3), high porosity (43.8μm) and rough surface enhanced the strong adhesion of microbial biomass onto the packing media promoting the effective physical entrapment/adsorption and subsequent bonding between the biomass and media and consequently improved the performance of the HUASB. The integrated treatment system produced a high quality effluent complying with the National Regulatory Standards for wastewater reuse in agriculture. The treatment system can be applied as a standalone system for wastewater treatment in rural areas and small communities.

Acknowledgment

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