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# Development of a two-stage biofilter system to enhance the effluent quality of a UASB pretreated domestic sewage

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**Abstract**

This paper proposes a new development in post-treatment technology entailing a pilot-scale anaerobic upflow anaerobic sludge blanket (UASB) followed by a two-stage biofilter system. As filter media, local crushed recycled plastic and anthracite were used in the anaerobic filter (AF) and passive aerated rapid filter (RF) respectively. Domestic sewage from Birzeit town was treated at an average flow rate of 0.50m$^3$/d under variable organic loading rates (OLRs) and hydraulic retention times (HRTs). The applied HRTs for the treatment chain (UASB-AF-RF) along three run phases were (32.5, 2.2 and 1 h), (19.5, 1.3 and 0.7 h) and (14, 1, and 0.4 h). The applied OLR (kgCOD/m$^3$.d) were (0.16, 1.90 and 6.97), (1.53, 10.68 and 10.54) and (0.57, 6.17 and 20.40) respectively. The overall removal efficiency of the treatment chain for $COD_t$ was (42, 83 and 50%) respectively, however the achieved $COD_t$ removal efficiency by the UASB alone was (18.5, 53 and 29%). The suspended solids removal efficiency for the complete treatment chain was (70, 65 and 55%) at variable OLR and HRT, the UASB suspended solids removal efficacy was around (35, 27 and 21%) for the three run phases respectively. During the first run phase (Highest HRT), an average removal efficiency of 8 and 14% for ammonia and phosphorous in the RF was achieved, high OLR applied during the second and third run phases might be behind low nutrients removal efficiency. Removal of Kjeldahl nitrogen (TKN) in the AF and RF was associated with similar reduction tendency in BOD. The proper design and adequate operation of the UASB reactor appeared to be the main efficacy-limiting factors of the developed post treatment system.

**Keywords**

Anaerobic treatment, biofilter, fixed film material, nutrients removal, onsite treatment, post-treatment, UASB

## Introduction

The house sanitation is not a problem in the Palestinian territories in terms of collection of household excreta. But the problem is the safe disposal of the collected septage and/or sewage. Together with the geographical distribution, scattered nature of the houses and limited financial resources make it very difficult to construct urban sewerage and treatment systems in rural and semi-urban communities, were about 60% of the households in Palestine (West Bank and Gaza Strip) have cesspits tanks. Therefore, a rapid action should take place to protect the ground water [1].

Hence, the implementation of master plan to protect the only available water resource (ground water aquifer) from getting tolerated, only through the implementation of decentralized treatment system with anaerobic treatment as the core of this system. The decentralized concept will not only enhance the development of master plane, were alternative wastewater management can be integrated, it creates the possibilities to reuse treated wastewater in irrigation and fertilization, it offer the possibilities to separately collect and treat the different wastewater streams, thus less diluted streams can be reused in the household it self, and the more concentrated streams can be treated with a more appropriate technology [2], it serves as an alternative energy source, It protects the ground water aquifer from pollution [3].

The selected treatment technology in the urban sanitation should be chosen very carefully for an effective water management. Such technologies preferentially consist of integrated methods and are characterized by a minimum of consumptive use of the available resources (e.g. energy) and a maximum reuse of the treated water and the wastewater pollutants [4], were the running, operating and developing cost are minimum, at the same time the recovery of the treated effluent is very high, having the ability to treat wastewater at the highest concentration. It should be able to function independent from large infrastructure investment. And the selected system should meet the major objective of sustainability [5].

Anaerobic treatment dose not only remove solids, but also active biological stabilization of the majority of oxygen consuming substances through microbial degradation of organic particulate matter, colloidal and dissolved organic matter. Anaerobic treatment processes can achieve an effluent quality intermediate between the primary and secondary that can be classified as an enhanced primary treated effluent [6].

Typically, the residual nitrogenous oxygen demand in the effluent requires further treatment to be competitive with a conventional secondary treatment process. Depending on the composition of the raw wastewater, anaerobic reactors can achieve 65-85 percent removal of oxygen consuming substances and 60-80 percent removal of suspended solids [5].

The most popular form of the anaerobic treatment is the up flow anaerobic sludge blanket (UASB) technology. The sludge retention of the UASB reactor is based on the formation of the easily settling sludge aggregates (flocs or granules), and in the application of internal gas/liquid/solid separation system. The required good contact between wastewater and sludge is achieved by an even feed distribution over the bottom of the reactor and by the natural mixing of the sludge bed as a result of the gas production [7].

Recent results obtained by [8] and [9] indicated that pre-treating of domestic and black wastewater in a modified UASB-septic tank technology removed only COD and suspended solid. Despite of the UASB advantages such as low cost, operational simplicity and low biosolids production, together with the environmental condition in Palestine, will contribute to highlight the anaerobic treatment of domestic sewage, the UASB technology has difficulties in producing effluents that can comply with the environmental standards, hence, it is of great importance to consider a post-treatment for the UASB effluent.

The main objectives of post-treatment are to complement the organic matter removal, as well as to promote the removal of nutrients and pathogens, which are barely affected by the anaerobic treatment [10].

According to [11] and [12], anaerobic filter (AF) is one of the anaerobic treatment systems, which is based on relatively simple technology, it can be considered as a column or tower filled with support media for the growth of biomass. It is operated in vertical flow mode either up flow or down flow where high biomass retention can be achieved for efficient and stable operation, by immobilizing microorganism as biofilm attached on the support it does not required the formation of a granular sludge which was initially designed to immobilize the biomass and to achieve good system performances in terms of organic matter removal. A variety of natural packing materials can be used for attachment and growth of anaerobic biomass, these media have voids for the passage of wastewater and also for the accumulation of suspended biomass [13].

The combination of the two systems (UASB and AF) could become a very promising alternative for the treatment of domestic sewage [14]; the removal efficiency in terms of COD for the UASB effluent was almost 80%, they also observed that combination of both systems UASB and AF was capable of promoting additional removal rate of COD load (85-90%). At the same time, it is often impossible to gain the desired quality of effluent with an AF alone, and some additional treatment is required.

Rapid filter (RF) commonly applied to large volumes of raw water or treated wastewater with low solids concentrations and the characteristics future of deep bed filtration is the deposition of solids through the filter media. In addition the conversion, adsorption of nutrients by the biofilm attached to the surface of packing materials [15]. And consequently, the suspended solid concentration level of the effluent is very low. The filter bed is considered; therefore, to have functions of both biological treatment and filtration, hence this process was designated as a biofilm filtration process [16].

Post-treatment for nitrogen removal is usually a two-step process. The first steps known as nitrification were the oxidation of ammonia to nitrate. It is an aerobic biological process carried out by autotrophic bacteria. The second step in the nitrogen removal process involves the reduction of nitrate and nitrite to nitrogen gas. Under anoxic conditions, the denitrifiers use nitrate as a terminal electron acceptor, utilizing organic matter as a carbon source [17].

Pre-denitrification using the organic carbon of the municipal wastewater is more attractive from both an economic and environmental point of view, since their is less sludge production, less air consumption, no need or reduced need of an external carbon source, improvement of alkalinity balance. Furthermore, biofiltration nowadays represents a well-proven and robust process. It is particularly suited to sites where a compact or modular design is required e.g. urban, coastal or mountain areas [18]**.**

Seyfried and Hippen [19] Reported that biological methods for the treatment of wastewater with high nitrogen loads are facing the problem in achieving high nitrification rates. They realized that COD/N ratios below 4 increases the denitrification volume by a factor of 1.5 to 1.7, with a ratio below 2.5, sufficient denitrification cannot be achieved at all without the use of external carbon sources. Inhibition of the nitrification up to the nitrite stage can be very useful because the denitrification can begin with the nitrite, which allows dispensing with one step for either oxidation or reduction. In this way, up to 25% of the oxygen demand and 40% of the carbon demand can be saved.

The results of a research conducted on the filtration of the primary septic tanks and settler effluent by [20] indicated that, in a single stage biofilter, the removal of nitrogen compound could be achieved through nitrification and denitrification. Nitrification and carbon removal took place in the upper part of the filter, whereas denitrification in the lower anoxic part.

In upgrading the Stockholm wastewater treatment plant (conventional activated sludge), [21] the efficiency of rapid Filter (RF) had been studied as a post treatment stage. RF reduced the nitrate and phosphorus concentration in the effluent to a range between 2-3 mg N/L, and 0.1-0.2 mg P/L. The main removal mechanisms of nitrate and phosphorous in the filter were mainly due to sedimentation and biological activities.

**Materials and methods**

The experimental work was conducted from 29th April to 06th August. 2002 at Birzeit University campus wastewater treatment plant, the experimental work was divided into three experimental run phases as in (Table 1), where the UASB reactor was fed with the domestic sewage, delivered by tankers from septic tanks of residential houses in Birzeit town., The raw wastewater was stored in a holding tank, which was refilled every three days.

The pilot scale treatment train consists of Pre-treatment sections that consist of PVC holding tank of 1500-liter volume preceding the UASB of 350 litter capacity, UASB with reactor volume approximately 350 liters, effluent of the UASB had been directed to up flow AF with total height of 98cm and diameter of 20cm, the settling base height were around 20 cm, the internal filling packaging media (PM) was crushed PVC with a height were around 65cm, the spacing between the sampling taps around 15cm.

Rapid Filter (RF) with total height of around 70cm and internal diameter of 20cm, filled with anthracite PM with height around 50cm, with 15 cm between the sampling taps, the RF had been connected to the (AF) effluent thought plastic tube, where the admitted water on the form of drop aeration as in Figure 1.

The anaerobic filter had been seeded with 4 liters of anaerobic sludge form the bottom of the settling tank, to insure complete anaerobic start up condition. Biological seed for the AF contained a mixture of different active biomass to increase the spectrum of methanogenic genera. The inoculum's was a mixture of sludge from a digester of a municipal wastewater. And by slowly charging the RF through the outlet valve with clear water, allowing the air from the pores of the filter bed to escape upwards. The RF outlet valve had been open while admitting the AF effluent. With a flow rate of around 0.26 $m^3$/day, the RF inlet nozzle had been connected to the AF outlet tap via a plastic tube and it had been made in such a way to spray the inlet in the form of drops to increase the rate of contact between the air and inlet wastewater in the aeration zone.

Composite samples were taken from the inlet of each unit and from all bio-filters sampling taps along the reactor's height. Twice weekly samples were collected at midday and preserved icebox during the transportation to laboratory. The collected raw samples were analyzed in duplicate were all chemical and physical analysis had been conducted according to the standard methods for the examination of water and wastewater [22].

**Results and discussions**

The pH is one of the main factors which affect the rate and degree of hydrolysis in an anaerobic process. Average pH values along the sampling depth during the three run phases are plotted in Figure 2 for the complete treatment chain. It is clear from the Figure that the pH values had dropped more in the anaerobic stages (UASB+AF), specifically during the second run phase were the organic load compared with other run phases was high, and the increase in pH values in the third run phase was due to higher hydraulic load.

The pH of the passive aeration zone of the RF had been increased. The lowest pH value was recorded in the second run phase, where the highest organic loading rate was applied. The average values had increased in the initial aeration zone, which might indicate a partial CO2 striping. We can realize the drop in the pH value in the first sampling tap after the aeration step due the sedimentation of the organic matter on the surface of the packing media, where the anaerobic treatment process had been enhanced once again due to the hydrolysis of the organic matter and the low DO content.

During the three run phases, the pH range was found to be within the range of 7.5 -7.8. The average pH values obtained during all run phases for the UASB indicate that no steady state conditions were achieved. Hence, the hydrolysis stage was not reached fully, as the pH range between 7.55 and 8. From previous studies, it was found that the optimum pH for protein hydrolysis is in the neutral range (pH>6.3). On the other hand, the optimum pH for the hydrolysis of carbohydrates was found by [23] to be in the range of 5.6-6.5. the effect of drop aeration on the pH,

The average removal efficiency for COD fractions obtained during all run phases are listed in Table 3. During the start up phase, UASB show the lowest removal efficiency with an average of 18.5% of total COD compared to (52.6 and 28.5 %) respectively in second and third run phases.

The combination of UASB and AF showed higher removal efficiencies than UASB alone, where the removal efficiency had increased in the first and second run phases to (23.36nand 77.13%) respectively. However during the third run phase the removal efficiency of both units had decreased to 27.7%, which might be due to the low HRT in the AF. While the over all removal efficiency for the treatment chain (UASB+AF+RF), had reached an average of 41.6, 83.2 and 50.29% during the three run phases respectively.

From Figure 3 we can realize the effect of HRT, were the total COD concentration had increased in the AF depth as the HRT had decreased during the third run phase.

The COD fractions had been determined in the second and third run phases as in Table 3. The (Suspended COD) $COD_{ss}$ average removal efficiency in the UASB had reached 66% in second and third run phases were about 41.4%. The removal efficiency after the second treatment unit had reached (85.9 and 48.5 %), compared to the removal efficiency after the final treatment unit (87.4 and 67.8 %). From the gained results we can realize the negative impact of low HRT on the anaerobic units, at the same time OLR negative impact on the RF removal efficiency.

The obtained colloidal COD ($COD_{col}$) removal efficiency for the first treatment unit (UASB) were around -44 and 25.7 % in the second and third run phases. The combined removal efficiency of the (UASB+AF) was -26.2 and 9.7% and after the final unit (UASB+AF+RF) the removal efficiency reached a value of 25.6 and 33.8 %.From these results we can say that, the UASB showed a negative impact on removing the colloidal COD at higher organic load, while the AF negative results were due to the lower HRT. This could be due to due the smaller reactor volume as well as the seeded sludge in the anaerobic Filter.

The dissolved COD removal efficiency after the first treatment unit UASB were around (54.4 and 3.5%), while after the second treatment unit (UASB+AF) the removal efficiency had increased to (76 and 7.5%), and the average over removal efficiency are (53.3 and 35.3 %). The removal of dissolved COD showed a more pronounced increase because it improved from 3.5% for the UASB to 76% for the combination of (UASB+AF) while it had decreased to 53.3 % after the RF, this is might be due to the higher applied organic load on the RF surface area where some fractions of the suspended and colloidal COD had been converted to dissolved fraction by the physical and biological activities.

From the obtained dissolved COD results we can realize the HRT has negative effect on the AF. And as well as the OLR negative effect on the RF. The justification for this must be the poor biodegradability of the dissolved COD, because the average residence time of colloids and soluble compounds in principle is similar (unless the sludge would be very effective in entrapping colloidal matter). Elmitwalli et al., [6] Reported that the removal of dissolved matter can be increased by using sludge with a higher methanogenic activity, such as granular sludge, and by increasing the contact between wastewater and sludge by applying high up-flow velocity ($V_{up}$).

The average BOD removal efficiencies for the three run phases by the first treatment unit (UASB) are (32.5, 22.5 and 26.5%), while for the combined anaerobic units (UASB+AF) are (21.8, 29, and 10.4%) and for the over all units (UASB+AF+RF) are (48.5, 50 and 34.3%). From the above we can conclude that the maximum removal efficiency was in the second run phase, with the higher organic loading rate. In the first run phase, the AF removal efficiency were negative values due the seeding in the upper part as well as in the lower mixing zone of the filter. Due to that, the biomass was washed out, while in the last run phase where the HRT as well as the organic loading rate had decreased the removal efficiency.

The TSS removal efficiency of the first treatment unit (UASB) are (34.6, 27.4 and 21%), While in the combination of (UASB+AF) the removal efficiency had increased to (51.2 and 51.8%) in the seconds and third run phases but in the first run phase decreased to 23.3% due the wash out of the seeded anaerobic sludge. The over all treatment train efficiency (UASB+AF+RF) had increased to (70, 64, and 55%), from the obtained results we can realize that the removal efficiency of the RF in the first run were the highest due to lower organic load, where the SS effluent from the AF is lower if compared with other runs as seen in Figure 4. The UASB VSS removal efficiency for the three run phases were (43, 6, and 24%), while for the combined units (UASB+AF) the removal efficiency had increased to (14, 56.7 and 46.5%) and the average over all treatment chain (UASB+AF+RF) removal efficiency had increased to (78, 62.7 and 70%).

Ammonium concentration has increased during run phases by (5 mg/L) as in Table 3, this can be attributed to nitrate dissimilation pathway, where nitrate converted into ammonium, this has been observed by many authors [24], during conventional anaerobic digestion of biosolids. It is also known that the acid forming bacteria perform quite well known fermentation reactions. They convert sugars originating from the hydrolysis of polymers like starch, hemicellulose and cellulose into butyrate, propionate, acetate, lactate, ethanol, hydrogen and carbonate. In the conversion of proteins, amino acids, other organic acids, and ammonia and hydrogen sulphide is formed. [25] Found that 80% of the effluent TKN is $NH_3$-N, which they also showed that 70% of the influent Org-N converted to NH3 under anaerobic conditions.

During run phase 1 and 2, the Anaerobic Filter (AF) dynamic were reflected by a wake biochemical reaction with regard to hydrolysis of TKN. Only slight removal efficiency was observed during phase 2, where about 6.2% of TKN was obtained. This can be attributed to the biomass uptake. And the increase of TKN content during run phase three might be due to the biomass wash out and induced by inhibitory factors as high hydraulic loading rate or small solids retention time in the biofilter. But in the first run phase were the steady state conditions not reached yet, the increase in TKN content due to the wash out sludge seeding in the AF. It had been prove that the potential loss of nitrogen in the influent nitrogen due to the assimilation by biomass in the anaerobic filter [26].

Minimal increase in $NH_3$ concentration was detected during phase 1 and 3 which might be attributed to protein hydrolysis, this assumption was conformed by increase in TKN and SS, it has been frequently reported that AF can perform a good hydrolysis of organic nitrogen [6].

From (Figure 5) and the obtained results in Table 3 we can realize the slight TKN and ammonia removal in the RF (passive aerated filter). The TKN has decreased by (8.2, 10 and 15%) respectively for the three run phases this is due to the nitrification process which took place within the first aerobic layer of the RF, an evidence for this hydrolysis activity is the decrease of pH value, however, due to high organic load and lack of DO concentration this activity was very week. [27] Studied the deep bed sand filter efficiency in removing the suspended and colloidal particles from the secondary effluent, the results show round 4% TKN removal.

From Figure 6 we can realize the filter back washing effect in ammonia removal, due to the filter washing of the accumulated biomass which had been deposit in the pore opening, which could affect the DO concentration along the filter depth and the rate of oxygen depletion will be fast. The result of filter back washing will result in increasing the pore volume, due to the expansion of the filter media, and cleaned from biomass, which create anaerobic conditions in the filter depth.

It had been proved by [28 & 17] that up to 30% of the ammonium reduction in the bio-filter was used for both autotrophic and heterotrophic cell synthesis during aerobic carbon removal and nitrification of anaerobicaly pre-treated effluent.

At higher COD/N ratios nitrogen removal efficiency will be limited by incomplete ammonia oxidation as nitrification was affected by the organic load and the complete oxidation require lower COD/N ratios, while at COD/N> 4 the denitrification activity will increase. Due to that heterotrophic biomass activity will resulted in the inhabitation of ammonia oxidizer. This fact had been proved by [28] where they investigate bio-filter consisting of three zones. Anaerobic, anoxic, and aerobic in partially aerated at varying loading rate.

From Figure 7 we can realize he COD/N variations for the three run phases in RF. In the first run phase the AF effluent value 1.9 it had been decreased to 1.5 at sampling tap RF T2 after that the ratio where almost constant, in the second run phase, the ratio had increased in the aeration Zone to 3.5 due to the higher organic load and the deposition of suspended in the surface of the PM, after that it had decreased to a value of 2.7 at the sampling tap RF T3 and finally in the third run phase the value had decreased from 3 in the aeration zone to 2 at sampling depth RF T2.

Hence from the plotted Figure 7 we can realize the optimum biomass growth, where the active biomass had been colonized at an average depth of 30cm. The average surface area for this depth around 17.5m2. Similar results obtained by [29] were they investigate the active biomass substrate in the infiltration percolation process by determining the depth of the media colonized by the biomass.

From the obtained results in Table 3, we can realize that PO4 concentration had increaser in the anaerobes stage effluent (UASB+AF) from (4.4, 7.7, and 5.6 mg/L) UASB influent to (9.2, 8.8 and 6.3 mg/L) AF effluent.

This is due to the Poly-phosphate accumulating organisms (PAOs) were they act differently, depending on weather they are exposed to anaerobic or aerobic/anoxic conditions. During anaerobic conditions they take up easily degradable organic matter and store it as mainly polyhydroxybutyrate (PHB) while releasing phosphate. During aerobic or anoxic conditions they degrade the stored organic matter while replenishing their internal poly-P-storage by taking up phosphate from the water [30].

From Figures 8 and the obtained results we can realise that UASB phosphors release in the effluent had increase in all the run phases, as well as in the first and second run phase AF effluent, but it had decreased in the AF third run phase due to the lower HRT and the higher up flow velocity which might caused the washout of Poly-phosphate accumulating organisms (PAOs).

The Ortho-phosphate removal efficiency in the RF had reached 14.4 and 7 % in the first and the second run phase, but it had decreed to a negative values in the last run, due to the higher AF effluent organic load, where biomass had been washout, in turn it had reached to the RF surface, due that anaerobic conditions occurred.

Nielsen *et al.,* [31] Reported the effect of filter packing materials chemical properties and it's impact on phosphorus removal, were in ferrous enriched sand it is possible to achieve removal efficiency of 70-90% of the Phosphors at concentration of 10-15 mg/L in the inlet, while the removal efficiency of the un-reached sand could reach around 40-60 % for the septic tank effluent.

The depth of intermediate sand filter packing materials and its effect on phosphors removal had been investigated by [29]. From the results they obtained, there was no increment in $PO_4$ removal after 30 cm layer. The removal efficiency had reached around 50%.

**Conclusion**

The objective of this study was to develop a two-stage biofilter system to reduce the organic and nutrient contents from the UASB effluent. Based on the results of the study, the following conclusions are drawn:

- The total COD removal efficiency in the anaerobic stages had increased with increasing the HRT and organic loading rate. UASB was inefficient in removing $COD_{col}$ at higher organic loading rates compared to the anaerobic filter, due to the higher attached biomass activity compared to flocculants biomass.

- The rapid filter total COD removal efficiency had increased with increasing the HRT, but it had decreased with higher organic loading rates. The BOD removal efficiency increased with increasing the OLR in the anaerobic stages while it decreased in the RF.

- Suspended solids removal efficiency increased with increasing the anaerobic filter HRT, while the UASB removal efficiency decreased, due to the entrapment mechanisms of the filter packing materials. All rapid filter solids fractions removal efficiency had decreased with higher organic loading rate.

- There ammonia production increased in the anaerobic stages might due to the hydrolysis of proteins, and the reduction in TKN values might to the anammoxc process as well biomas built up. The ammonia and TKN removal efficiency reduced with increasing the RF organic loading rate due to the depletion of the dissolved oxygen in the RF.

- The maximum nutrients removal efficiency in the RF at depth of 30 cm with 17.5 $m^2$ and the maximum, and the organic load should not exceed (1 g COD/$m^2$.d), which equivalent to (26 g/d), it is almost equivalent to (100 mg/L), hence this value should be the basis for AF effluent ($C_e$) design calculation.

- The average substrate removal rate in the AF was around 0.46 kg COD/kg VSS.d. From the obtained removal rate we can obtain the optimum design for the AF effluent, which can satisfy the minimum requirement of organic load for the final treatment unit (RF).

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## Tables

**Table 1:** The dimension of the main treatment units for each run

| UNIT | Run | Run Period | Flow Rate ($m^3$/d) | Active Volume ($m^3$) | HRT (h) | Surface Area ($m^2/m^3$) |
|---|---|---|---|---|---|---|
| **UASB** | 1 | 29/04–9/05 | 0.26 | 0.35 | 32.41 | 8.45 |
| | 2 | 02/06–3/07 | 0.43 | 0.35 | 19.44 | 8.45 |
| | 3 | 17/07–06/08 | 0.60 | 0.35 | 13.89 | 8.45 |
| **AF** | 1 | 29/04–9/05 | 0.26 | 0.02 | 2.21 | 21.75 |
| | 2 | 02/06–13/07 | 0.43 | 0.02 | 1.32 | 21.75 |
| | 3 | 17/07–06/08 | 0.60 | 0.02 | 0.95 | 21.75 |
| **RF** | 1 | 29/04–9/05 | 0.26 | 0.01 | 1.00 | 28.87 |
| | 2 | 02/06–3/07 | 0.43 | 0.01 | 0.69 | 24.97 |
| | 3 | 17/07–06/08 | 0.60 | 0.01 | 0.38 | 23.99 |

**Table 2: P**hysical characteristic of the packing media (PM) used

| Material | Density kg/ml | Effective Size (mm) | Mean Diameter (mm) | Porosity | Specific Surface Area ($m^2/m^3$) |
|---|---|---|---|---|---|
| Anthracite | 1424.167 | 2 | 1.29 | 0.49 | 1313.30 |
| Crushed Plastic | 775 | 4.75 | 2.33 | 0.60 | 1030.04 |

**Table 3**: average obtained results along the treatment chain

| Test | RUN | UASB IN mg/L | UASB OUT mg/L | AF OUT mg/L | RF OUT mg/L | UASB Eff (%) | AF Eff (%) | RF Eff (%) | Over all Eff (%) |
|---|---|---|---|---|---|---|---|---|---|
| T-COD | 1 | 214.00 | 174.50 | 164.00 | 125.00 | 18.46 | 6.02 | 23.78 | 41.59 |
| | 2 | 1242.13 | 589.29 | 284.04 | 209.29 | 52.56 | 51.80 | 26.32 | 83.15 |
| | 3 | 326.95 | 233.71 | 236.38 | 162.52 | 28.52 | -1.14 | 31.24 | 50.29 |
| S-COD | 2 | 1028.83 | 349.67 | 144.89 | 130.11 | 66.01 | 58.56 | 10.20 | 87.35 |
| | 3 | 155.43 | 91.10 | 80.00 | 50.05 | 41.39 | 12.18 | 37.44 | 67.80 |
| C-COD | 2 | 73.28 | 105.44 | 92.50 | 54.78 | -43.90 | 12.28 | 40.78 | 25.25 |
| | 3 | 103.29 | 76.76 | 93.24 | 68.33 | 25.68 | -21.46 | 26.71 | 33.84 |
| D-COD | 2 | 113.94 | 51.94 | 37.67 | 53.17 | 54.41 | 27.49 | -41.15 | 53.34 |
| | 3 | 68.24 | 65.86 | 63.14 | 44.14 | 3.49 | 4.12 | 30.09 | 35.31 |
| BOD | 1 | 106.95 | 72.18 | 83.64 | 55.13 | 32.52 | -15.88 | 34.09 | 48.46 |
| | 2 | 242.16 | 187.59 | 171.94 | 120.97 | 22.53 | 8.34 | 29.64 | 50.04 |
| | 3 | 176.40 | 129.76 | 158.17 | 115.83 | 26.44 | -21.89 | 26.77 | 34.34 |
| TS | 1 | 1044.00 | 998.00 | 1056.00 | 915.67 | 4.41 | -5.81 | 13.29 | 12.29 |
| | 2 | 1577.29 | 1222.57 | 1288.29 | 1246.00 | 22.49 | -5.38 | 3.28 | 21.00 |
| | 3 | 1461.33 | 1329.33 | 1464.33 | 1298.33 | 9.03 | -10.16 | 11.34 | 11.15 |
| SS | 1 | 521.50 | 341.25 | 400.25 | 156.25 | 34.56 | -17.29 | 60.96 | 70.04 |
| | 2 | 683.33 | 496.00 | 333.26 | 241.51 | 27.41 | 32.81 | 27.53 | 64.66 |
| | 3 | 719.16 | 569.64 | 346.67 | 322.67 | 20.79 | 39.14 | 6.92 | 55.13 |
| VSS | 1 | 326.50 | 186.00 | 280.50 | 70.75 | 43.03 | -50.81 | 74.78 | 78.33 |
| | 2 | 345.67 | 368.67 | 169.83 | 146.25 | -6.65 | 53.93 | 13.89 | 57.69 |
| | 3 | 489.03 | 370.98 | 261.87 | 147.00 | 24.14 | 29.41 | 43.86 | 69.94 |
| NH3 | 1 | 37.73 | 43.42 | 43.59 | 39.99 | -15.06 | -0.39 | 8.25 | -5.98 |
| | 2 | 52.91 | 57.76 | 55.61 | 57.90 | -9.16 | 3.72 | -4.13 | -9.44 |
| | 3 | 52.56 | 53.73 | 55.62 | 51.44 | -2.22 | -3.52 | 7.53 | 2.14 |
| TKN | 1 | 98.45 | 82.27 | 85.38 | 78.38 | 16.44 | -3.77 | 8.19 | 20.39 |
| | 2 | 104.88 | 94.48 | 88.58 | 79.73 | 9.92 | 6.24 | 9.99 | 23.98 |
| | 3 | 83.93 | 78.03 | 80.52 | 68.50 | 7.03 | -3.20 | 14.94 | 18.39 |
| NO3 | 1 | 1.11 | 1.23 | 1.07 | 1.46 | -10.71 | 12.83 | -35.98 | -31.23 |
| | 2 | 7.67 | 4.39 | 3.05 | 3.56 | 42.75 | 30.53 | -16.67 | 53.60 |
| | 3 | 5.65 | 5.60 | 5.56 | 5.08 | 0.81 | 0.71 | 8.63 | 10.02 |
| PO4 | 1 | 4.42 | 7.19 | 9.17 | 7.850032 | -62.73 | -27.55 | 14.41 | -77.66 |
| | 2 | 7.71 | 8.52 | 8.85 | 8.22 | -10.49 | -3.86 | 7.07 | -6.64 |
| | 3 | 5.69 | 6.61 | 6.29 | 6.406165 | -16.11 | 4.83 | -1.81 | -12.50 |

## Figures

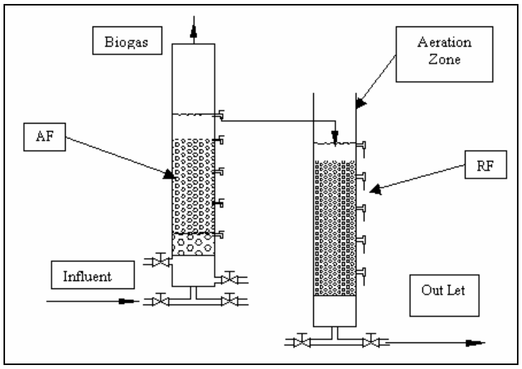


**Figure 1:** Schematic diagram of AF

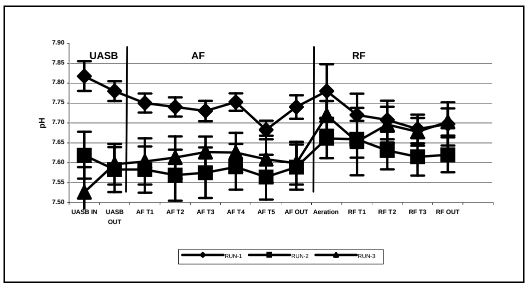


**Fig.2**: pH average values (± SE) along the sampling depth for the three run phases.

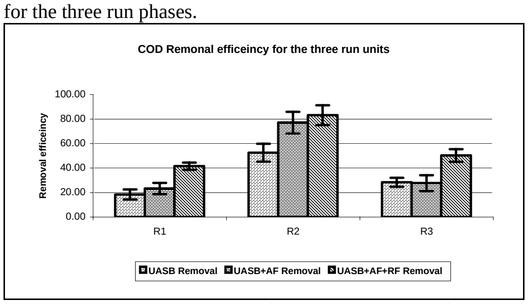


Fig 3: Average $COD_t$ removal efficiency with (± SE) for the three run phases.

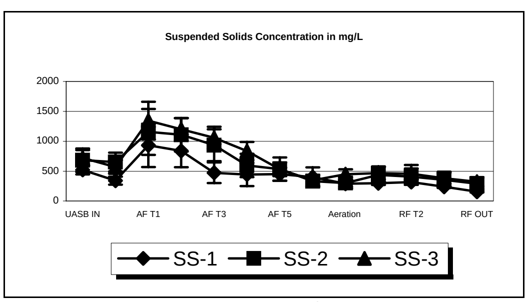


**Fig 4**: TSS average values (± SE) for each run along the sampling depth of the treatment chain

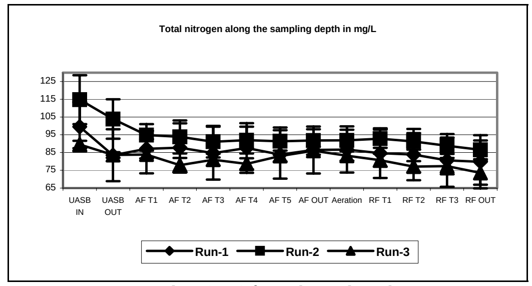


**Fig 5:** TKN average values (±SE) for each run along the treatment chain sampling taps.

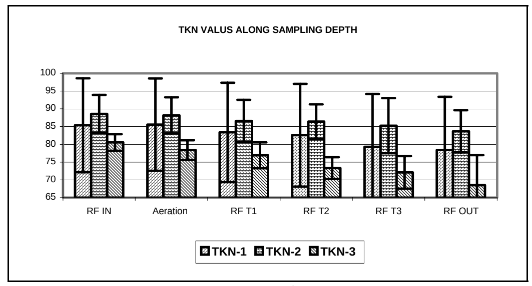


**Fig 6** TKN average values (± SE) for all run phases along RF sampling depth.

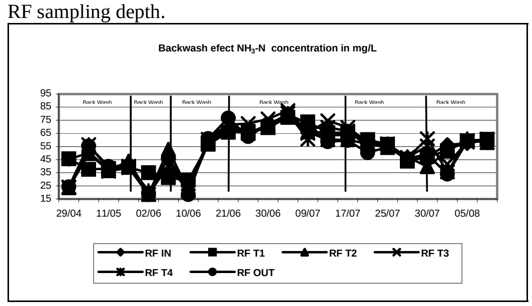


**Fig 7:** RF back washing and its effect in ammonia removal

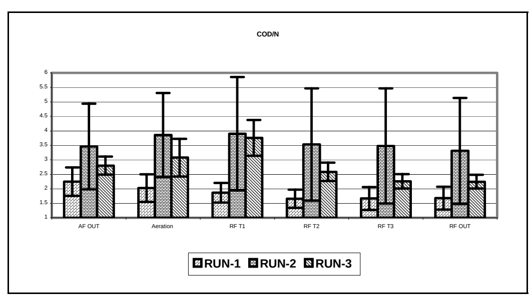


**Fig 8:** C/N average ratio (±SE) along the RF depth for the three run phases.

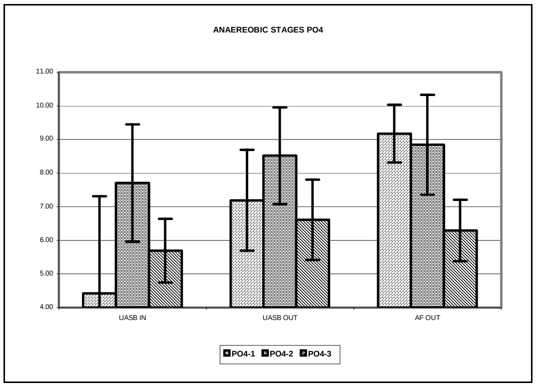


**Fig 9:** $PO_4$ average value (± SE) for anaerobic stages influent and effluent.