# APPLICATION OF A NOVEL PROCESS FOR EFFLUENT QUALITY IMPROVEMENT IN DUBAI'S WASTEWATER TREATMENT PLANT

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## ABSTRACT

Plans are underway to upgrade and expand the main wastewater treatment plant in Dubai with a design capacity of 130,000 $m^3$ $d^{-1}$. This study examined a novel anoxic/aerobic fixed-film system to upgrade the exsisting activated sludge process as to cope with increasing hydraulic/organic loadings and produce a treated effluent suitable for reuse in irrigation. A pilot plant, utilizing the Biolace media, was constructed and operated using both the aerobic submerged fixed film (ASFF) and the anoxic/aerobic submerged fixed film (A/ASFF) systems. The effect of loading on the removal of organics and ammonia was studied at loading rates in the range of 0.03 to 0.3 g BOD.$g^{-1}$ BVS.$d^{-1}$ corresponding to hydraulic retention times (HRT's) in the range of 0.7 to 8 h. The results obtained revealed that both the ASFF and the A/ASFF systems are viable, cost-effective, options to upgrade the activated sludge process for combined organic and ammonia removal with minimal excess sludge production. High removal efficiencies of up to 98% for BOD, 75% for COD, and 97% for ammonia were obtained over a wide range of loading rates. Both the ASFF and the A/ASFF processes proved to be technically feasible for improving the effluent quality but the A/ASFF process appears to be more capable of maintaining stable and efficient treatment at higher loading rates. The treated effluent quality obtained from either upgrading process is considerably better than that achieved by the existing activated sludge process. It satisfies the water quality requirements for reuse in irrigation and reduces the need for tertiary filtration.

**Keywords:** Effluent quality;fixed-film processes; wastewater treatment; water reuse.

## INTRODUCTION

Reuse of treated wastewater effluents in irrigation of agricultural lands and landscaping has gained considerable attention in arid and semi-arid regions of the world where fresh water resources are scarce. In the Arabian Gulf countries, while water consumption continues to increase, reuse of treated wastewater effluents will play an important role in supplementing fresh water resources. Therefore, the concerned authorities in these countries have implemented policies calling for construction of new wastewater treatment plants to cope with increasing flows and produce treated effluents suitable for reuse in irrigation. Currently, treated wastewater effluents in the Arabian Gulf countries are reused extensively in landscape and greenery irrigation and, to a lesser extent, in agricultural lands as reported by Hamoda [1]. In recognition of the importance of water reuse in the United Arab Emirates, the Dubai municipality has undertaken plans to improve the treated effluent quality and expand the treatment works in Dubai's main municipal wastewater treatment plant (WWTP) at Al-Awir.

The Al-Awir WWTP was originally designed to treat 130,000 $m^3 d^{-1}$ of municipal wastewater serving a population of 800,000 persons. The plant is currently overloaded and expansion works are underway to double its capacity and improve the quality of treated effluent produced to satisfy the requirements for water reuse in irrigation. Execution of such plans is very costly as the construction and installation of new treatment works is becoming more expensive. Another approach is to upgrade the exiting facilities to cope with increasing flows at a much reduced cost. This study investigated the possibility of upgrading the secondary treatment stage at Al-Awir WWTP in a cost-effective way.

Biological suspended-growth systems, such as the activated sludge process, are commonly used for the secondary treatment of municipal wastewaters. This is the case with Al-Awir WWTP, where the high-rate activated sludge (HRAS) process is used for aerobic treatment of wastewater following grit removal and primary sedimentation. The secondary biological treatment stage is the focus of this study as it constitutes the backbone of the plant. In this stage, the high rate activated sludge (HRAS) is primarily designed for the reduction of carbonaceous material present in the primary settled wastewater. It consists of three rectangular aeration tanks with capacity of 4820 $m^3$ each, designed for a peak hydraulic retention time of 1.33 hours, and organic loading of 0.3 Kg BOD $kg^{-1}$ dry solids. The HRAS operates at mixed liquor suspended solids (MLSS) of 5,600 mg $l^{-1}$. Up to the design capacity of the plant, the HRAS produced well-treated effluent with an overall BOD and COD removal efficiency of approximately 85-90% and 55-65%, respectively. However, the HRAS process has two main persistent operational difficulties since the facility was put in service in 1989. These are: (1) excessive sludge production reaching 0.85 to 1.0 kg sludge solids per kg BOD applied, and (2) poor sludge settleability and frequent rising sludge problems. It was, therefore, necessary to upgrade the biological treatment stage to overcome operational problems and to cope with increasing wastewater flow received at the plant. In this study, attempts were made to use an attached-growth system to upgrade the HRAS process since the attached-growth processes have the advantages of low sludge production, good sludge settleability and stable operation (Metcalf and Eddy [2]; Lessel [3]).

Attached-Growth (fixed-film) processes are biological systems in which the microorganisms responsible for biodegradation and stabilization of organic matter are attached or fixed to a solid inert media forming a biofilm. A number of innovative processes have been used such as the aerated submerged fixed-film (ASFF) process developed by Hamoda and Abd-El-Bary [4]. This process employs a four compartment-in-series reactor equipped with an array of submerged media (fixed ceramic plates) for biomass attachment that is maintained under continuous diffused aeration. Modification of the ASFF process (Hamoda [5]) to operate in the anoxic-aerobic (A/ASFF) mode could have some advantages based on studies on the activated sludge process conducted by Hao and Huang [6].

There are certain advantages with the fixed-film processes depending on the system used for attached growth (Grady and Lim [7]; Liu et al. [8]; Chudoba and Pujol [9]). These include simplicity, low sludge production, no foam or sludge bulking, long solids retention, stable operation and resistance against shock loads as compared to suspended-growth systems. Combining both attached growth and suspended growth of microorganisms has become a viable option to upgrade the activated sludge process (Rogalla et al.[10]; Odegaard and Rusten [11]; Su and Ouyang [12]; Hamoda and Al-Sharekh [13]).

This study was conducted in order to investigate the feasibility of upgrading the high rate activated sludge process using the ASFF and A/ASFF systems and to examine the effect of increased loading rate on process performance and effluent quality.

## MATERIALS AND METHODS

### Description of the Reactor and Experimental Set-up

The aerated submerged fixed-film (ASFF) bioreactor was used for conducting the pilot-scale experiments. This reactor is made of 6 mm thick plexiglass sheets, and divided into four equal-size compartments connected in series. The length of the reactor is 72.5 cm, the width is 30 cm and the liquid depth is about 60 cm, providing a total liquid volume of 115 litres. A pilot plant was installed at Al-Awir WWTP (Fig. 1). The experimental program involved in-parallel testing of ASFF and A/ASFF reactors, each was packed with the “Biolace” support medium. Biolace is a structured medium composed of cross-linked textile fibres with a great number of woven rings. It is fixed vertically and stretched in a high-grade stainless steel cage. Five (5) sheets of the Biolace (each is 390 mm long and 230 mm wide), spaced at 25 mm were fixed in each cage. Each compartment of the reactor housed one cage occupying approximately 44% of the compartment’s volume. The biolace is manufactured by UTS, Germany.

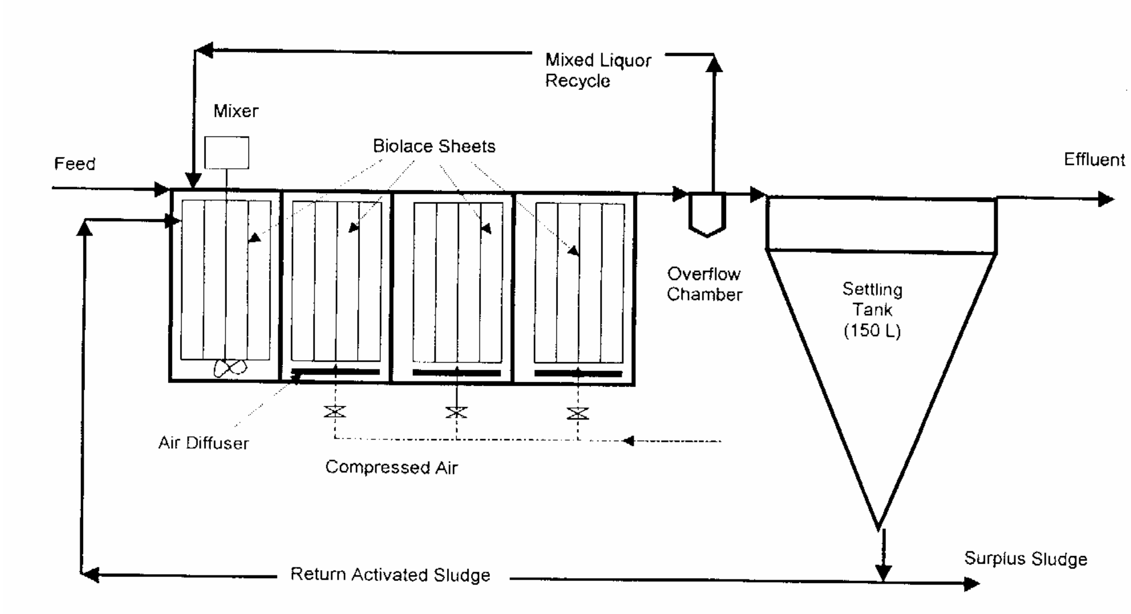


**Figure 1. Schematic diagram of the experimental set-up**

The reactors were operated at similar hydraulic retention times (HRT's), i.e. same hydraulic loading rates (HLR's). Each reactor was operated continuously at a preset feed flow rate. Different flow rates were tested in each reactor over a total period of nine months to obtain HRT's in the range of 0.7 to 8 hours. All experiments were conducted under normal weather conditions except for installing shade over the pilot plant to minimize algal growth from interfering with the normal microbial activities in the reactors. Primary settled wastewater was pumped into the reactor and no control was imposed on the feed's strength, i.e. BOD, COD, ammonia, suspended solids, etc. All reactors were initially seeded with activated sludge withdrawn from the return line of the plant's aeration tank to promote biofilm growth on the support media.. Aeration of the reactors was provided through medium-to-fine tubular- membrane air diffusers placed underneath the media. Two equal length diffusers were arranged per compartment. Compressed air was maintained at a constant pressure of approximately 2-2.5 bar. Designated terminal control valves regulated airflow into each compartment. Reactor's overflow was collected by gravity and analyzed in the plant's laboratory.

## Analytical Methods and Procedures

Samples were collected daily from each reactor and analyzed on the same day of collection. The samples were filtered using Whatman's Qualitative Filters size 4. The following parameters were determined on the filtrate: $BOD_5$, COD, Ammonia ($NH_3$-N), Nitrites ($NO_2$-N), Nitrates ($NO_3$-N), and Total Oxidized Nitrogen (TON). Unfiltered samples were used for other measurements such as Suspended Solids (SS) and Volatile Suspended Solids (VSS). The pH, dissolved oxygen concentration (DO) and temperature were measured on all samples collected. Compartmental attached biofilm mass was determined at the end of each experimental run. Representative compartmental samples of each medium were collected and oven dried at 105ºC. The volatile (organic) fraction of the attached and suspended solids was determined by further burning the samples at 550ºC. The final effluent was also analyzed to determine Total Dissolved Solids (TDS), conductivity, alkalinity, phosphates, chlorides, sulfates, calcium, magnesium, sodium, and potassium. All laboratory analyses were performed according to Standard Methods [14].

## Plant Operation

The operational parameters applied in the ASFF and the A/ASFF bioreactors are summarized in Table 1. The mass loadings were based on filtered (soluble) BOD and COD concentrations. There are some major differences between the two systems compared in this study; the ASFF bioreactor and the A/ASFF bioreactor in terms of estimating the hydraulic and mass loadings. The ASFF bioreactor is classified as an "attached-growth process" with minimal suspended growth. In contrast, the A/ASFF bioreactor involves a hybrid-growth biological process where both "attached and suspended growth patterns" exist and could efficiently contribute to the process performance. Therefore, estimation of loading rates based on available surface area for fixed-film growth, could not be applied to the A/ASFF bioreactor. It will however undermine the clear contribution of the suspended growth biomass, and will not represent the actual loading rates applied. Thus, loading rates were calculated per total biomass present in the system, i.e., per total attached and suspended volatile biomass solids. Mixed Liquor Volatile Suspended Solids (MLVSS) and Attached Volatile Solids (AVS) are added-up to express the Biomass Volatile Solids (BVS). Hence, hydraulic loading was estimated as $m^3$ per kg BVS per day and mass loading as g BOD or g COD per g BVS per d.

The other issue related to the implementation of anoxic process is the application of internal recirculation streams. First, recycling of nitrified sludge obtained from settling of the effluent mixed liquor and returning the thickened nitrified sludge (NRS) into the anoxic zone (1$^{st}$ compartment) was practiced to support anoxic conditions. Secondly, recycling of the effluent nitrified mixed-liquor (NML) into the 1$^{st}$ compartment was also carried out to further support the anoxic process especially at the shorter HRTs of 1 h and less. Therefore, such internal loading was considered in the overall hydraulic loading applied to the system. Organic (mass) loading, on the contrary , was only estimated based on feed (primary settled sewage) concentration since the mass loading contributed by both internal streams (NRS and NML) was relatively small and could be neglected. During this study, the mean temperature of incoming sewage at the main plant varied between 33 and 37°C. However, feed inflow to the pilot plant was often lower by 2 to 3 degrees, due to retention time in the head works, i.e. preliminary (mechanical) treatment stages. On the other hand, a two-degree temperature drop was mostly experienced across the A/ASFF or the ASFF bioreactors.

Dissolved oxygen profiles were determined at all HRTs. The $1^{st}$ compartment had DO concentrations between 0.1 to 0.2 mg $l^{-1}$. Due to long retention time in settling tank, return sludge was recycled with low DO. Evidence was clearly noticed from observed signs of denitrification, sludge flotation on water surface, and loss of nitrate concentration in return sludge as compared to effluent mixed liquor flowing into the settling tank. The NML on the other hand was recycled with high DO concentration of approximately 4-5 mg $l^{-1}$, but no drawback on the anoxic process was observed at the short HRTs applied of 1 and 0.7 h. On the other hand, low DO concentration in the $1^{st}$ compartment was a good sign of attaining anoxic condition. This had been a great advantage of implementing the anoxic process where the carbonaceous substrate (BOD and COD) can be removed without any outside energy source (oxygen) and without encountering any operational difficulties such as attached growth bridging (excessive biomass growth).

In the aerated compartments; $2^{nd}$, $3^{rd}$ and $4^{th}$, DO concentrations increased rapidly to 6 mg $l^{-1}$. In general, high DO concentrations were always prevailing at all HRTs regardless of loading. Usually, as the case observed with the ASFF bioreactor, longer HRTs result in longer contact period between substrate and microorganisms as compared with shorter HRTs, thus allowing better removal efficiencies and exhibiting higher DO concentrations. Oxygen limitations were not experienced with the A/ASFF, as all compartments achieved exceptionally good removal, and no sign of overloading was noticed.

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**Table 1. Operational parameters applied to the pilot plant**

| HRT(1) | FEED | NRS (2) | NML(3) | Total Inflow | Recycle | BVS(4) | Hyd. Load | BOD Load | COD Load | $NH_3N$ Load |
|---|---|---|---|---|---|---|---|---|---|---|
| h | $m^3\ d^{-1}$ | $m^3\ d^{-1}$ | $m^3\ d^{-1}$ | $m^3\ d^{-1}$ | Ratio | g | $m^3.kg^{-1}$ BVS.$d^{-1}$ | g BOD.$g^{-1}$ BVS.$d^{-1}$ | g COD.$g^{-1}$ BVS.$d^{-1}$ | g $NH_3$-N.$g^{-1}$ BVS.$d^{-1}$ |
| **The ASFF Bioreactor** | | | | | | | | | | |
| 8 | 0.346 | N/A | N/A | 0.346 | N/A | 291.55 | 1.185 | 0.154 | 0.330 | 0.049 |
| 6 | 0.460 | N/A | N/A | 0.460 | N/A | 339.02 | 1.356 | 0.182 | 0.354 | 0.056 |
| 4 | 0.691 | N/A | N/A | 0.691 | N/A | 410.83 | 1.682 | 0.257 | 0.463 | 0.076 |
| 2 | 1.382 | N/A | N/A | 1.382 | N/A | 488.03 | 2.833 | 0.382 | 0.787 | 0.115 |
| **The A/ASFF Bioreactor** | | | | | | | | | | |
| 8 | 0.173 | 0.173 | N/A | 0.346 | 1.0 | 694.69 | 0.497 | 0.033 | 0.076 | 0.009 |
| 6 | 0.229 | 0.229 | N/A | 0.458 | 1.0 | 574.46 | 0.797 | 0.056 | 0.990 | 0.015 |
| 4 | 0.389 | 0.389 | N/A | 0.691 | 0.8 | 544.33 | 1.270 | 0.109 | 0.186 | 0.034 |
| 2 | 0.821 | 0.821 | N/A | 1.382 | 0.7 | 580.23 | 2.382 | 0.218 | 0.379 | 0.064 |
| 1.5 | 0.864 | 0.864 | N/A | 1.814 | 1.1 | 464.02 | 3.910 | 0.290 | 0.525 | 0.084 |
| 1 | 0.950 | 1.037 | 0.691 | 2.678 | 1.8 | 617.60 | 4.337 | 0.222 | 0.369 | 0.065 |
| 0.7 | 1.382 | 1.382 | 1.210 | 3.974 | 1.9 | 601.35 | 6.609 | 0.290 | 0.526 | 0.099 |

(1)Hydraulic retention time (2)Nitrified return sludge (3)Nitrified mixed liquor (4)Biomass volatile solids

The pH ranged between 7.0 to 7.6 in all compartments of the A/ASFF and the ASFF bioreactors. The total alkalinity of the liquid ranged between 100-300 mg $l^{-1}$ as $CaCO_3$ which indicates the good buffering capacity. No appreciable pH variations were observed during the operation of the A/ASFF although there was a slight increase in the pH value observed in the anoxic stage (1st compartment).

## RESULTS AND DISCUSSION

Major performance parameters such as organics removal, nitrogen transformations, and effluent quality were used to compare the behavior of the ASFF and A/ASFF bioreactors in upgrading the activated sludge process.

### Organics Removal

The organic removal profiles and removal efficiencies were determined for both the BOD and the COD parameters. Figure 2 shows mean (steady-state) BOD removal profiles, generated at all hydraulic retention times (HRT's). Similar patterns were observed in the ASFF bioreactor. Meanwhile, similar COD removal profiles were also observed in both bioreactors. It is clearly noticed that the majority of organic removal occurred in the 1st compartment.

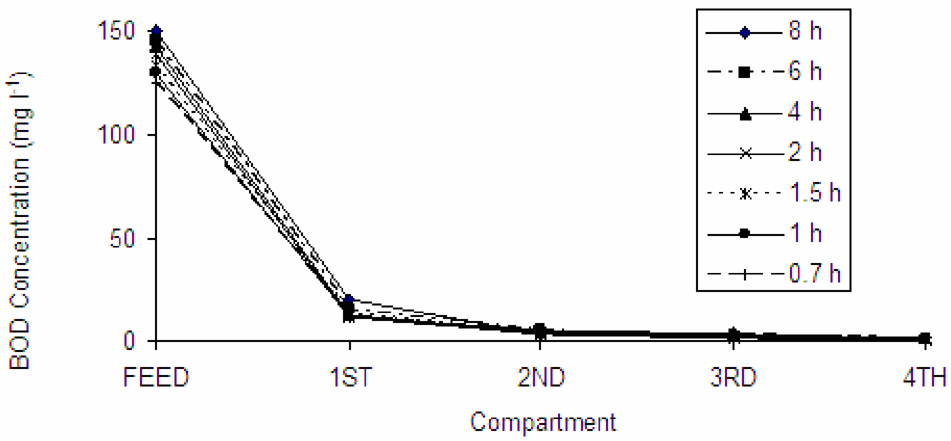


**Figure 2. Overall BOD removal profiles for the A/ASFF bioreactor**

The A/ASFF process is classified as single-sludge predenitrification system. The required carbon source is essential to support the denitrification process, and since the experiment was on treatment of domestic sewage, internal carbon source was readily available through the utilization of the sewage's carbonaceous substrate; expressed as BOD and/or COD. Additional carbon source was internally provided through recycling of return sludge biosolids. First compartment's organic removals ranged from 85-92% and 60-67% for BOD and COD, respectively. No appreciable removal occurred in the remaining compartments as the substrate removal followed a first-order kinetic model. This is clearly demonstrated in Tables 2 and 3 for BOD and COD removal, respectively. By combining the organic removal in all compartments, the overall BOD or COD removal efficiency was obtained in each case as shown in Tables 2 and 3, respectively. High “overall” removal percentages were obtained especially in the A/ASFF bioreactor which showed up to 98% for BOD removal and 75% for COD removal.

**Table 2. Compartmental percentage BOD removal in the A/ASFF and ASFF bioreactors**

| Reactor's Comp | A/ASFF bioreactor % BOD Removal | | | | | | | ASFF bioreactor % BOD Removal | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | HRT ( h ) | | | | | | | HRT ( h ) | | | |
| | 8 | 6 | 4 | 2 | 1.5 | 1 | 0.7 | 8 | 6 | 4 | 2 |
| 1st | 85.0 | 88.2 | 92.5 | 91.7 | 90.8 | 86.9 | 89.0 | 77.4 | 68.2 | 69.9 | 71.9 |
| 2nd | 11.4 | 9.30 | 5.03 | 6.01 | 6.84 | 10.3 | 5.4 | 15.0 | 21.5 | 17.6 | 7.9 |
| 3rd | 1.82 | 0.78 | 1.29 | 1.11 | 0.73 | 0.66 | 1.7 | 5.0 | 4.0 | 5.5 | 11.6 |
| 4th | 0.55 | 0.47 | 0.31 | 0.1 | 0.4 | 0.74 | 0.4 | 0.4 | 0.4 | 3.0 | 1.1 |
| overall | 97.5 | 97.0 | 98.5 | 98.0 | 96.5 | 95.5 | 96.4 | 96.8 | 93.2 | 95.5 | 92.0 |

**Table 3. Compartmental percentage COD removal in the A/ASFF and ASFF bioreactors**

| Reactor's Comp | A/ASFF bioreactor % COD Removal | | | | | | | ASFF bioreactor % COD Removal | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | HRT ( h ) | | | | | | | HRT ( h ) | | | |
| | 8 | 6 | 4 | 2 | 1.5 | 1 | 0.7 | 8 | 6 | 4 | 2 |
| 1st | 66.5 | 60.9 | 70.1 | 66.8 | 61.1 | 65.8 | 62.0 | 46.2 | 37.8 | 43.3 | 35.6 |
| 2nd | 8.95 | 8.38 | 1.79 | 4.75 | 5.73 | 8.25 | 7.1 | 11.4 | 14.9 | 9.5 | 8.8 |
| 3rd | 2.34 | 2.03 | 0.96 | 4.70 | 2.03 | 1.47 | 2.0 | 3.4 | 9.2 | 12.7 | 16.3 |
| 4th | 1.87 | 0.33 | 3.49 | 1.08 | 3.09 | 1.68 | 1.7 | 2.3 | 5.1 | 1.0 | 2.0 |
| overall | 78.5 | 72.1 | 77.5 | 78.2 | 72.5 | 78.0 | 74.5 | 67.1 | 67.5 | 67.3 | 63.0 |

Moreover, organic removal remained almost unaffected by variation in loading as no appreciable deviation was noticed between the different removal profiles. Comparing the ASFF and the A/ASFF removal profiles clearly illustrate the superiority of the anoxic stage, as the A/ASFF process consistently achieved excellent carbonaceous substrate removals at all loadings. More important, the anoxic process consistently produced almost complete removal of carbonaceous substrates in the 1st compartment thus allowing full utilization of the remaining aerated compartments for nitrification. Although the A/ASFF bioreactor was operated at about double the hydraulic loading applied to the ASFF bioreactor, the A/ASFF bioreactor's organic removal profiles, were more stable and showed better performance.

No signs of overloading were observed either in the 1st compartment or in the other compartments. Therefore, typical problems encountered with the ASFF bioreactor were not observed in the A/ASFF bioreactor. In addition to prominent appearance of anaerobic biofilm growth especially at higher loadings, as was experienced during operation of the ASFF bioreactor, healthy brownish colour for both attached and suspended biomass growth was always prevailing in the A/ASFF bioreactor's aerobic compartments (2nd, 3rd, and 4th).

Apart from the advantage of implementing the anoxic stage in improving the carbonaceous substrate removal, having high mixed liquor solids concentration resulting from recirculation of return sludge and additional recycling of mixed-liquor solids, had greatly helped supporting high removal rates where the process could be classified as hybrid growth (i.e. attached and suspended growth). Analysis of the specific oxygen consumption rate for the aerobic compartments have shown that suspended growth was superior in the removal efficiency especially at high loadings. This in turn had a positive impact in maintaining thinner fixed-films that allow for better substrate and oxygen penetration; thus higher removal capacity as compared to the thick biofilms.

Comparison between the ASFF and the A/ASFF reactors' overall removal efficiency for organic matter (BOD) is shown in Tables 2 and 3. The superiority of the A/ASFF bioreactor is apparent in achieving exceptionally high carbonaceous removal at the excessive hydraulic loading rates applied. Although both reactors showed minimal effect due to variation in hydraulic loading, the A/ASFF bioreactor's BOD overall removal was slightly higher (96-98%) and dropped by approximately 1-2% going from HRT of 8 h down to 0.7 h. In contrast, the ASFF's BOD overall removal was generally between 92-97.5% for the applied loadings. Similarly, better COD removal was achieved with the A/ASFF bioreactor with an overall removal efficiency ranging from 73% to 80%. The ASFF bioreactor however, achieved COD removal efficiency in the range of 63% to 67%. This could be due to further utilization of the "hardly biodegradable" COD portion as a carbon source for the denitrification process in the anoxic stage of the A/ASFF bioreactor. In general, BOD removal was more stable than the COD removal due to fluctuations in the COD biodegradable fraction.

## Nitrogen Transformations

Nitrogen undergoes some transformations during the course of treatment in both the ASFF and the A/ASFF bioreactors by the nitrification and the denitrification processes. Nitrification is a two-step oxidation process to convert ammonia nitrogen to nitrite nitrogen ($NO_2$ –N) and further to nitrate nitrogen ($NO_3$-N) in the presence of oxygen. On the other hand, nitrate nitrogen can be biologically reduced by two means :assimilating and dissimilating or denitrification process. In the assimilating process , nitrate is reduced to ammonia for the use in cell synthesis. It proceeds independent of oxygen, and in absence of ammonia. The denitrification (dissimilating) process reduces the nitrate to more reduced forms such as $N_2O$ and NO, and more preferably to Nitrogen ($N_2$) gas. As the total nitrogen discharge limits become more stringent, total nitrogen removal by biological processes is much required. However, since the treated effluent is intended for reuse in landscaping and greenery irrigation purposes, removal of ammonia becomes the primary concern of nitrogen transformations in most wastewater treatment plants.

In this study, the compartmental percentage ammonia removal and the total oxidized nitrogen (TON) production of the A/ASFF bioreactor were determined as illustrated in Table 4. Generally, the observed compartmental efficiency clearly suggests the presence of active nitrifying microorganisms mainly in the $2^{nd}$ and the $3^{rd}$ compartments at all loading rates. This allowed the $4^{th}$ compartment of the A/ASFF bioreactor to contribute to process stabilization and to act as a buffering zone to make-up for any fluctuations in performance. Therefore, the A/ASFF bioreactor would offer stable nitrification performance and quickly adapt to fluctuations in the organic and hydraulic loading rates applied on the system. In contrast, nitrification in the ASFF bioreactor was mainly accomplished in the $3^{rd}$ and $4^{th}$ compartments.

**Table 4. Compartmental mean (steady state) percentage NH3-N removal and TON production in the A/ASFF bioreactor**

| HRT (h) | $2^{nd}$ Comp. | | $3^{rd}$ Comp. | | $4^{th}$ Comp. | |
|---|---|---|---|---|---|---|
| | % $NH_3$-N Removal | % TON Prod. | % $NH_3$-N Removal | % TON Prod. | % $NH_3$-N Removal | % TON Prod. |
| 8 | 31.40 | 52.52 | 17.68 | 43.31 | 2.55 | -2.85 |
| 6 | 33.02 | 54.93 | 13.23 | 33.80 | 1.56 | 4.38 |
| 4 | 19.81 | 55.60 | 17.98 | 33.78 | 0.64 | 5.33 |
| 2 | 25.14 | 34.33 | 26.12 | 67.17 | 0.79 | -11.10 |
| 1.5 | 19.00 | 26.20 | 17.00 | 57.50 | 2.60 | 10.60 |
| 1.0 | 20.00 | 11.60 | 19.00 | 66.00 | 2.20 | 4.07 |
| 0.7 | 12.00 | 18.60 | 13.00 | 51.50 | 4.50 | 14.10 |

The denitrification process was apparently not limited by the TON concentration at all runs as can be seen in Table 5 where the TON concentrations in the effluents of the $1^{st}$ compartment remained around 1 mg $l^{-1}$ at all HRT's in the A/ASFF bioreactor. Meanwhile, the reactor's final effluent TON concentrations were fairly constant and did not drop below an average of 10 mg $l^{-1}$ indicating high and stable ammonia removal at all loading rates.

**Table 5. Mean ( steady state ) OLR and TON concentration -1st compartment in the A/ASFF bioreactor**

| HRT ( h ) | Organic Loading Rate (OLR) | | TON ( mg $l^{-1}$ ) | |
|---|---|---|---|---|
| | gBOD/gBVS d | gCOD/gBVSd | IN | OUT |
| 8 | 0.133 | 0.306 | 11.6 | 1.0 |
| 6 | 0.368 | 0.647 | 14.90 | 1.10 |
| 4 | 0.388 | 0.664 | 8.2 | 0.6 |
| 2 | 1.000 | 1.737 | 7.0 | 0.95 |
| 1.5 | 1.245 | 2.250 | 5.7 | 0.6 |
| 1 | 0.837 | 1.395 | 5.26 | 1.8 |
| 0.7 | 1.360 | 2.471 | 7.32 | 1.7 |

Ammonia removal efficiencies were higher in the A/ASFF bioreactor as compared with those observed in the ASFF bioreactor especially at shorter HRT's. This is illustrated in Figure 2 which shows percentage ammonia removals of up to 97 % HRT's of 6-8 h. Meanwhile, Figure 3 illustrates the mean concentrations of nitrates obtained in all compatments of the A/ASFF bioreactor at all HRT's. Presence of nitrates in the aerobic compartments ( 2nd, 3rd, and 4th) confirms the activity of the nitrifying bacteria in these compatments. In contrast, only traces of nitrates were observed in the anoxic (1st) compartment where dentirification takes place.

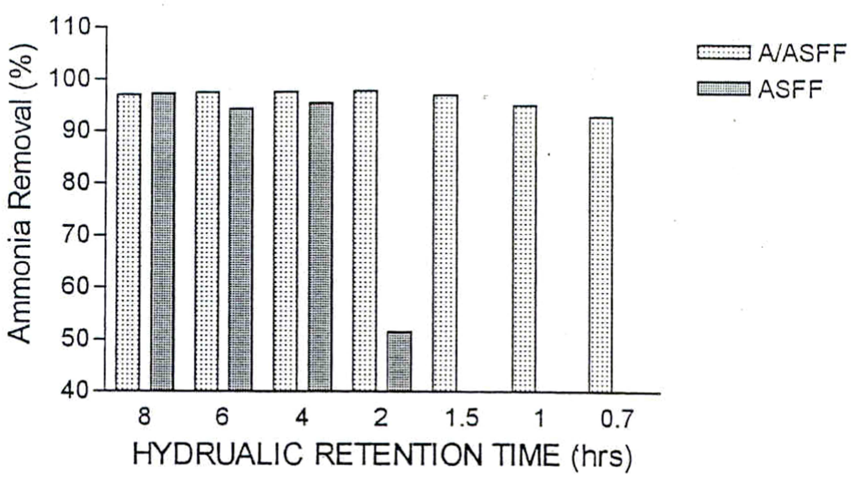


**Figure 3. Mean percentages of overall ammonia removal in the ASFF and A/ASFF bioreactors**

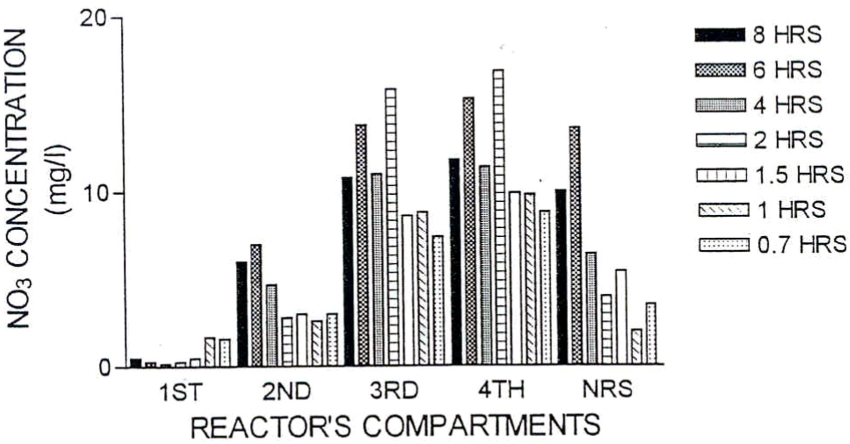


**Figure 4. Mean (steady state) nitrate concentrations in the A/ASFF bioreactor**

## Effluent Quality

The effluent quality (in terms of BOD and COD) obtained from the A/ASFF bioreactor is much better than that obtained from the ASSF bioreactor as shown in Table 6. Despite operating at higher hydraulic loadings, the A/ASFF bioreactor produced low effluent concentrations of BOD and COD. Only at HRT of 0.7 h, filtered BOD effluent concentration reached 4 mg $l^{-1}$ whereas it remained under 2 mg $l^{-1}$ for all remaining runs. Relatively higher concentrations were however, achieved by the ASFF bioreactor where a maximum BOD concentration over 10 mg $l^{-1}$ was obtained at HRT of 2 h. Similar observations were made for the COD concentration where the A/ASFF bioreactor's filtered effluent COD level fluctuated between 50 to 80 mg $l^{-1}$.

**Table 6. Mean (steady state) filtered effluent's characteristics of the A/ASFF and the ASFF bioreactors**

| HRT (h) | A/ASFF Bioreactor | | | ASFF Bioreactor | | |
|---|---|---|---|---|---|---|
| | BOD ($mg.l^{-1}$) | COD ($mg.l^{-1}$) | COD/BOD Ratio | BOD ($mg.l^{-1}$) | COD ($mg.l^{-1}$) | COD/BOD Ratio |
| 8 | 1.7 | 62 | 37.6 | 2.8 | 100 | 35.1 |
| 6 | 1.8 | 72 | 39.3 | 7.5 | 86 | 11.5 |
| 4 | 1.3 | 61 | 47.4 | 5.7 | 92 | 16.2 |
| 2 | 1.4 | 64 | 45.9 | 10.2 | 103 | 10.2 |
| 1.5 | 1.9 | 79 | 40.7 | - | - | - |
| 1.0 | 2.0 | 54 | 26.9 | - | - | - |
| 0.7 | 3.9 | 61 | 15.8 | - | - | - |

Higher COD concentrations were observed during runs with lesser biomass content as the case with runs at HRTs of 6 and 1.5 h where biomass volatile solids (BVS) obtained were approximately 87.8 g and 108 g, respectively. In addition to better utilization of complex biodegradable substrate through hydrolysis in the anoxic process, uptake of substrate biomass contributed to higher COD removal in the A/ASFF bioreactor as compared with the ASFF bioreactor. The COD/BOD ratio is indicative of the biodegradability of the trace organics escaping the biological treatment. The higher ratios show that only hard-to-degrade organics remained in the treated effluent and that the process was able to remove almost all of the biodegradable organics in the course of treatment.Table 7 presents several water quality parameters for effluent characterization and shows the suitability of the ASSF and A/ASSF process effluents for reuse in irrigation in comparisoin with the existing HRAS system.

## Process Application

The wastewater received at the plant is classified as a "strong", almost septic, due to the long retention in the collection system in addition to the hot climate of the city of Dubai. Primary sedimentation slightly improves the effluent quality but the produced effluent fails to meet the guidelines for reuse in irrigation. On the other hand the current processes used for further treatment in the plant include the high rate activated sludge process followed by "polishing" trickling filtration and gravity settling for secondary treatment and sand filtration as well as chlorination for tertiary treatment. Such successive treatments can finally produce an effluent that satisfies the requirements for reuse in irrigation. Meanwhile, by using either the ASFF or the A/ASFF process (a single step) to upgrade the secondary treatment stage, an effluent suitable for reuse could be produced with no need for further polishing or sand filtration (Hamoda et al. [15]). This involves considerable cost savings taking into consideration that the ASFF and the A/ASFF processes require minimal capacity for secondary clarification.

Modification of the existing HRAS aeration tanks can be easily implemented by installing the Biolace media and necessary baffles at minimal cost, if compared with the construction of new tanks, to increase the capacity of Al-Awir WTTP with no delays. One of the benefits gained in adopting the anoxic step in the A/ASFF bioreactor is apparent in securing steady ammonia removal at higher hydraulic loading rates than applied in the ASFF bioreactor which gives an edge to the A/ASFF bioreactor as a biological nitrogen removal (BNR) process. Moreover, high removals of both the carbonaceous and nitrogenous matter achieved by the A/ASFF bioreactor are coupled with reductions of more than 25% in sludge production under the anoxic conditions as compared with the aerobic systems. At the same time, aeration requirements in the A/ASFF bioreactor are much lower. These features will certainly result in reduced operational cost of the A/ASFF bioreactor.

**Table 7. Characteristics of treated effluents at various stages of treatment**

| Parameter (1) | Raw Wastewater | Primary Settled Effluent | Secondary Treated Effluent | | | Tertiary Treated Effluent | Effluent Quality Guidelines for Irrigation |
|---|---|---|---|---|---|---|---|
| | | | HRAS(٢) | ASFF(3) | A/ASFF(4) | | |
| BOD | 420 | 290 | ١٩,١ | ٥,٧ | 1.8 | ٣,٧ | 10 |
| COD | 641 | 455 | 98 | ٩٢ | ٦١ | ٢٩,٥ | ٧٥ |
| SS | 850 | 393 | 25 | 10 | 10 | ٣,٩ | 10 |
| TDS | 1705 | 1800 | ND(5) | ND | ND | ١٢٣٠ | 2000 |
| Conductivity ( umhos/cm ) | 4250 | 4200 | ND | ND | ND | ١٩٢٠ | 750-2000 |
| $NH_3 - N$ | 48.5 | ND | 6.1 | ٢,٠ | ١,١ | 1.0 | 1 |
| $NO_3 - N$ | 2.2 | ND | 8.4 | 16.0 | 12.2 | ٨,٤ | 20 |
| $PO_4 - P$ | 20 | ND | 15.1 | 11.2 | 10.1 | ٩,٩ | 30 |
| ALK (as $CaCO_3$) | 348 | 400 | 320 | 340 | 350 | 350 | 700 |
| Cholorides | 930 | 939 | 260 | 240 | 235 | ٢3٠ | 140-350 |
| Sulfates | ND | 400 | 275 | 185 | 223 | ٢٢٠ | 100-380 |
| Calcium | ND | 69 | 59 | 51 | 59 | 5٦ | 45 |
| Magnesium | ND | 110 | 94 | 88 | 84 | 60 | ND |
| Sodium | ND | 625 | 210 | 138 | 130 | 123 | 70 |
| Potasium | ND | 73 | 23.5 | 17.2 | 15.9 | 15.1 | 25 |
| pH (units) | 7.9 | 8.2 | 7.9 | 7.5 | 7.6 | 7.1 | 6.5-8.5 |

(1) Average values in $mgl^{-1}$ unless otherwise indicated
(2) HRAS = High rate activated sludge process
(3) ASSFF =Aerobic submerged fixed film process
(4) A/ASFF = Anoxic / Aerobic submerged film process
(5) ND = Not determined

# CONCLUSIONS

Based on the experimental results obtained in this study, the following conclusions can be made:

1. Secondary treated effluent of the upgraded plant using either the ASFF or the A/ASFF process satisfies the water quality requirements for reuse in irrigation without tertiary filtration. Each process achieved high organic and nutrient removal efficiencies of up to 98% for BOD, 75% for COD and 97 % for ammonia.
2. Performance of the A/ASFF process was not adversely affected by a ten-fold increase in hydraulic/organic loading in the range of 0.5 to 6.6 $m^3$ $kg^{-1}$ BVS $d^{-1}$ (hydraulic) and in the range of 0.03 to 0.3 g BOD $g^{-1}$ BVS $d^{-1}$ (organic).
3. For nitrogen transformations, the A/ASFF process was superior to the ASFF process in ammonia oxidation by nitrification and nitrate reduction by denitrification, even at the shorter HRT's.
4. Success of the A/ASFF bioreactor was mainly due to the efficient performance of the anoxic stage incorporated in the $1^{st}$ compartment. More than 90% and 60% BOD and COD removal efficiencies were achieved in this stage, respectively.

5. The proposed system can be easily applied, with minimal required modifications, to the exiting aeration tanks to double their capacities provided that the plant adopts an efficient diffused aeration system and suitable media for biomass attachment.

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