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# Anaerobic reactor/high rate pond combined technology for sewage treatment in the Mediterranean area

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**Abstract**
Two high-rate, anaerobic/aerobic units were used to treat the sewage of the IAV campus in a 1,100 $m^2$-plant designed for 1,500 e.p. and receiving 63 $m^3$ per day. The anaerobic pre-treatment consisted of a two-stage up flow anaerobic reactor (TSUAR) comprising two reactors and one external settler all in series. The aerobic line, or post-treatment, consisted of a high-rate algal (HRAP) and one maturation pond in series. The system totalized a hydraulic retention time (HRT) of 9 days. A gravel filter (GF) was constructed behind the TSUAR to trap low-density particles. The TSUAR removed 80% of COD and 90% of SS within 48 h. Solids retention time in the reactors averaged 32 d with a specific sludge production of 0.28 g VSS $g^{-1}$ COD removed. Almost 93% of the sludge evacuated from the settler was stabilized. Specific Biogas production from both reactors was 0.25 $m^3$ $kg^{-1}$ COD removed. Used in this configuration, the HRAP lost its BOD removal activity and increased its nutrients and pathogens removal capabilities (tertiary treatment). Results showed that 85% of total nitrogen and 48% of total phosphorus were removed by the HRAP. Land area requirement of this combination was less than 1$m^2$ per capita and filtered final effluent was of excellent quality (COD, 82 mg/l; TKN, 8.3 mg/l; total P, 2.7 mg/l, faecal coliforms, 2.4 $10^3$/100 ml and zero helminths eggs).

**Keywords**
Sewage treatment ; Two-step up flow anaerobic reactor ; high rate algal pond ; nutrients removal ; pathogens removal ; first-order reaction rate constant ; Mediterranean area.

## INTRODUCTION

High rate anaerobic reactors have been actively investigated for sewage treatment over the last two decades. Large scale plants were implemented in tropical climates mainly in India and Latin America (van Haandel & Lettinga, 1994; Hulshoff Pol *et al*., 1997). Sewage pre-treatment in these systems presents many advantages. They can achieve high removal rates of organic matter and SS in relatively short HRTs, they produce less sludge than equivalent aerobic systems, require small land areas and have moderate operation and construction costs. Other advantages of anaerobic reactors are biogas recovery and use for energy purposes (Malina, 1962; McCarty, 1964; Lettinga *et al*., 1980).

Pilot scale units implemented in temperate climates did not give satisfactory results. Investigations have shown that the low temperatures slow down the hydrolysis rate and favour the accumulation of an impairing mass of SS in the reactor (Wang, 1994). To overcome this limitation, it was proposed to switch to two step reactors, with the first unit mainly operating as a trap and as a “hydrolyser” for SS (Van Lier *et al*., 1997; Zeeman & Lettinga, 1999; Elmitwalli *et al*., 2002).

The post-treatment is a stage where N, P and, in some instances faecal coliforms, are removed. Many systems can fulfil this function going from intensive to extensive units depending on the particular conditions of projects (van Haandel & Lettinga, 1994 ; Lettinga *et al.*, 1997 ; Zeeman and Lettinga, 1999). The high-rate algal pond (HRAP) associated with MPs could play such a role. The HRAP has been tested for sewage and farm effluent treatment (Oswald & Glueke, 1959 ; Azov and Shelef, 1982, Picot & *al.*, 1992; Green and Oswald, 1993 ; El Hamouri *et al.*, 1994 ; Craggs *et al.,2003* ; Evans *et al.*, 2003). The HRAP was presented as an alternative system to facultative ponds to minimize the land area requirement and construction cost (El Hamouri *et al.*, 2003). Basically, the HRAP has a three fold role: i) biological degradation of organic matter using algae evolved oxygen (secondary treatment), ii) removal of nitrogen and phosphorus and iii) exacerbation of faecal pathogen die-off conditions. These three functions are taking place simultaneously, making the overall treatment performance be dictated by the slowest function.

This paper describes a new approach to treat domestic sewage. The TSUAR, developed for organic matter degradation and SS removal, is associated with an HRAP, in which organic matter degradation (secondary treatment) is dropped off while the rates of nutrients and pathogens removals (tertiary treatment) are increased.

## MATERIALS AND METHODS

Average temperatures during the reporting period were 14°C and 24°C respectively for the cold and the hot season. The average wastewater flow was 63 $m^3d^{-1}$. The plant included a pre-treatment line based on a duplicated TSUAR line receiving 31.5 $m^3d^{-1}$ each. The post-treatment line included a high-rate algal pond (HRAP) and two maturation ponds (MP), all in series.

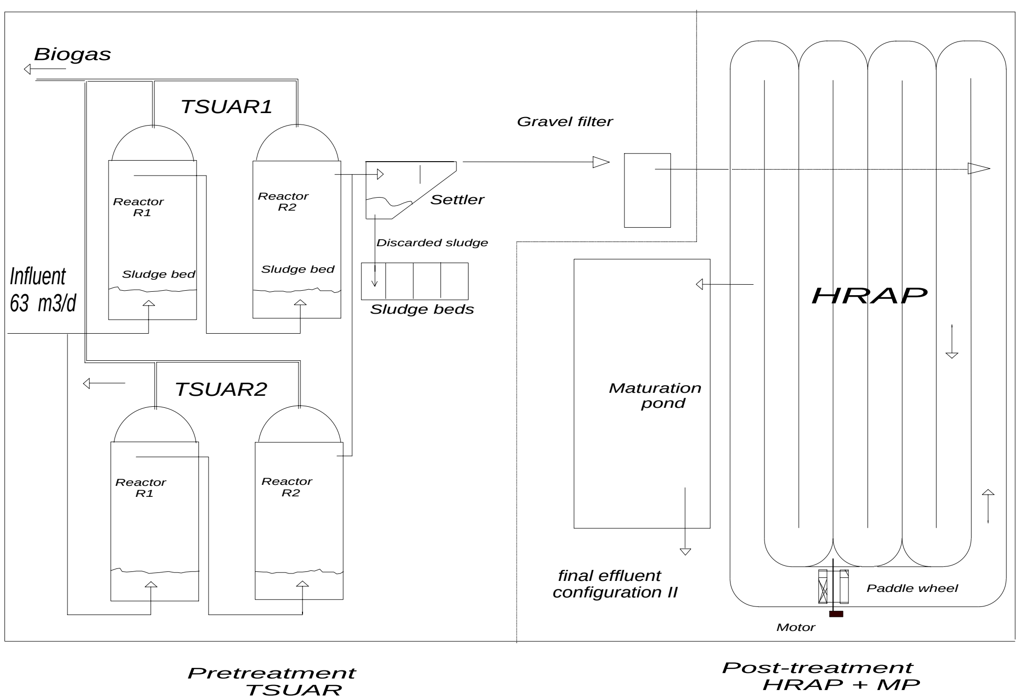



*Figure 1. Layout of the treatment plant*

The TSUAR included two reactors ($R_1$ and $R_2$), a settler (S) and a gravel filter (GF) (figure 1 and table 1). Biogas was collected using external cupola-shaped covers made of acid-resistant glass fibre. The base of the covers was inserted in a (40 cm width x 40 cm depth) channel surrounding the reactors and filled with treated effluent to act as a water seal, preventing odour and biogas release.

The post-treatment unit included a 790 $m^2$-HRAP with an HRT of 5.2 d and two maturation ponds ($MP_1$ and $MP_2$) with dimensions of 17 m length, 5 m width and 1 m depth for an HRT of 0.7 d each. Configuration I (TSAR+HRAP+$MP_1$+$MP_2$) had an overall HRT of 9 days, while configuration II (TSAR+GF+HRAP+$MP_1$) was obtained by introducing a gravel filter (GF) behind S and by by-passing MP2.

Table 1. Dimensions and operation parameters of reactors $R_1$ and $R_2$.

| | Unit | Reactor F | Reactor F |
|---|---|---|---|
| Depth | m | 5.30 | 5.00 |
| Diameter | m | 3.0 | 3.0 |
| Effective volume | $m^3$ | 33 | 31 |
| Average HRT | hour | 24 | 23 |
| Volumetric loading rate | kg COD $m^{-3}$ d | 0.76 | 0.4 |
| Up flow velocity | m $h^{-1}$ | 0.1 – 0.6 | 0.1 – 0.6 |

The settler S had dimensions of 2 m length, 0.7 m width and 1 m depth and was operated at an overflow rate of 1.5 m $h^{-1}$. Trapped sludge in S was removed daily to the sludge drying beds using hydrostatic pressure. The GF consisted of a 1-mm PVC film lined basin operated at a hydraulic loading rate of 1 m $d^{-1}$. The role of the GF was to remove low-density sludge particles escaping S.

24-hour composite samples were taken biweekly for main chemical characteristic analysis following Standard Methods (APHA, 1989) while daily *in situ* recording of temperature, pH, electrical conductivity (EC) and dissolved oxygen (DO) were also carried out. Settled COD (CODst) represented the fraction of CODt which did not settle down in 30 min in a 2-litres cylinder. Chlorophyll-a (Chl-a) was analysed following the method described by Pearson *et al*., (1987). The sludge velocity index (SVI) was determined following APHA (1989) and sludge granulometry of particles following the method of Laguna *et al*. (1999). Faecal coliforms (FC) were counted on grab samples using the MPN method (APHA, 1989) and helminth eggs were counted on composite samples following the flotation method described by Arther *et al*., (1981).

## RESULTS AND DISCUSSION

### Pre- treatment, anaerobic reactor unit

Performance of the TSUAR presented here are to be analysed under the conditions generally prevailing in the wastewater treatment facilities of small communities, which are characterized by highly varying hydraulic and organic loads. Standard deviations (SD) shown on table 2 might be explained in this way. For instance, the flow had maximum and minimum values of 110 and 14 $m^3$ $d^{-1}$ respectively. Also, large variations were recorded within the day. Half the daily flow (30 $m^3$) was received within six hours, precisely between 8:00 and 14:00.

On the other hand, the deliberate choice not to remove manually any excess sludge, for operation simplicity, forced us to operate the reactors on “maximum sludge hold up” mode (van Haandel & Lettinga, 1994). Washout periods were followed by periods of sludge accumulation during which the sludge washout was at its minimum. The completion of a washout/accumulation cycle took 3 months with an average solid retention time of 32 days. Measurements of sludge bed thickness showed a permanent bed of at least 1 m at the bottom of each of the two reactors even during intensive SS washout periods. The average SS concentration was 23,000 mg/l, with a VSS/SS ratio of 0.79, in $R_1$ and 14,000 mg/l and 0.70 for $R_2$ (figure 2). Specific sludge production in the TSUAR was estimated to be 0.28 g SS $g^{-1}$ COD removed. Based on the extensive and continuous sampling analysis program achieved (136 sampling campaigns), a certain confidence is to be attributed to the average removal rates presented in table 2, stating that TSUAR with an organic loading rate (OLR) of 760 for $R_1$ and 400 g $m^{-3}$ $d^{-1}$ for $R_2$, and a global HRT of 48 h removed an average of 80% of CODst or 70% of $BOD_5$ (table 2). However, TSUAR performance in SS removal under configuration I was not satisfactory. The removal rate did not exceed 30% and might be explained by the maximum sludge hold up mode adopted and also by the occurrence of low-density particles for which the settler was ineffective. Indeed, particle distribution analysis of the bulk of SS leaving reactors $R_2$ was dominated by two types of particles: i) reticulated particles of 100 and 350 μ diameter having an SVI of 20 mg/l and ii) low-density particles (probably biological material in an advanced stage of digestion) of 60 μ diameter and an SVI of 35 mg/l. The settler was inefficient in trapping the 60 μ particles. They were carried away to the first component of the post-treatment unit, the HRAP, in which they reduce the light penetration through the water column and contributed in the build up of unwanted sediment in the pond (El Hafiane *et al.*, 2003). In configuration II, these troublesome particles were successfully stopped in the GF.

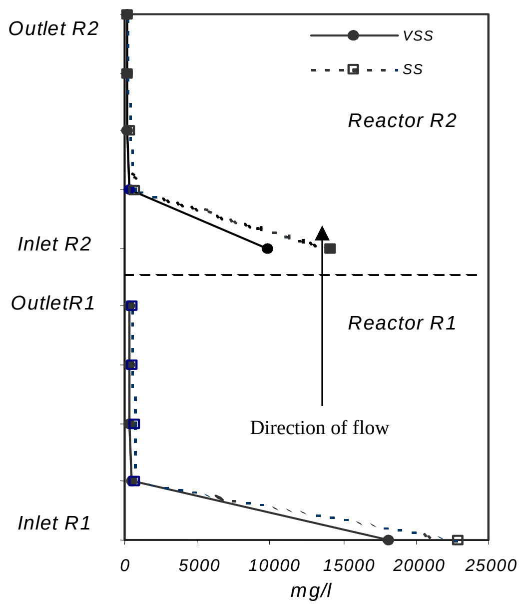



Figure 2. SS and VSS profiles in reactors $R_1$ and $R_2$

Table 2. TSUAR performance

| Parameter | Influent | Reactor 1 | | Reactor 2 | | Settler | | Global RR |
|---|---|---|---|---|---|---|---|---|
| | | Value | RR | Value | RR | Value | RR | |
| CODt ($mgO_2$/l) | 800 ± 202 | 530 ± 220 | 34 | 380 ± 180 | 28 | 310 ± 145 | 18 | 61 |
| CODst ($mgO_2$/l) | - | 285 ± 105 | - | 159 ± 79 | - | 159 ± 81 | - | 80(1) |
| CODs ($mgO_2$/l) | 420 ± 117 | 270 ± 97 | 36 | 120 ± 71 | 56 | 120 ± 67 | - | 71 |
| $BOD_5$ ($mgO_2$/l) | 390 ± 139 | 200 ± 88 | 49 | 150 ± 75 | 25 | 120 ± 67 | 20 | 69 |
| SS (mg/l) | 330 ± 85 | 300 ± 120 | 9 | 280 ± 117 | 7 | 230 ± 102 | 18 | 30 |
| VSS (mg/l) | 190 ± 57 | 150 ± 51 | 21 | 160 ± 41 | -7 | 105 ± 41 | 34 | 45 |

(1) RR in % is calculated as follows (CODt-CODst)*100/CODt ; CODs: soluble COD.

Recorded specific biogas production in the TSUAR was 0.25 $m^3$ $kg^{-1}$ of COD removed. Methane represented 77%; nitrogen, 14%; carbon dioxide, 2% and $H_2S$ was only found in traces. The noticeable N content might be due to an uncommon anaerobic denitrification process, most likely the ANAMMOX process described by Mulder *et al.* (1995).

Table 3. Physicochemical characteristics of importance for anaerobic treatment in the TSUR.

| Parameter | Influent | Reactor $_1$ | Reactor $_2$ | Settler |
|---|---|---|---|---|
| pH | 6.9 ± 0.29 | 6.6 ± 0.2 | 6.8 ± 0.12 | 6.8 ± 0.15 |
| Temperature (°C) | 19.5 ± 3.1 | 20 ± 3.3 | 21.5 ± 3.6 | 21 ± 3.3 |
| EC (µS/cm) | 1290 ± 260 | 1400 ± 116 | 1415 ± 121 | 1420 ± 108 |
| VFA (mg/l) | 120 ± 56 | 170 ± 44 | 70 ± 35 | - |
| Alkalinity (mg $CaCO_3$/l) | 120 ± 42 | 164 ± 63 | 204 ± 42 | - |

VFA: volatile fatty acids

Figure 3 shows that $R_2$ achieved similar CODs removals as $R_1$ did. However, $R_2$ load was 2/3 of that of $R_{1,}$ indicating that CODs removal rate in $R_2$ was 1.5 times higher than in $R_1$. We concluded from this and from pH and volatile fatty acids concentrations analysis (table 3) that reactor $R_1$ might function as a trap for particulate COD (CODp) and as a digester in which, the acidogenesis process and the hydrogenotrophic methanogenic bacteria could dominante. On the other hand, reactor $R_2$ might function as a digester with a domination of acetotrophic methanogenic bacteria.

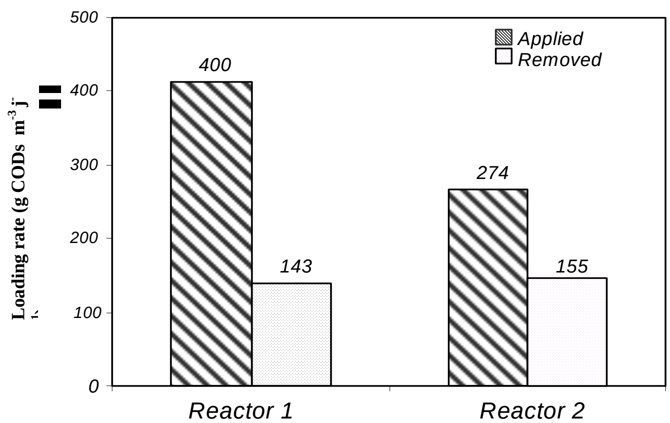



Figure 3. Applied and removed CODs for reactors $R_1$ and $R_2$

**Post treatment, high-rate algal pond unit**

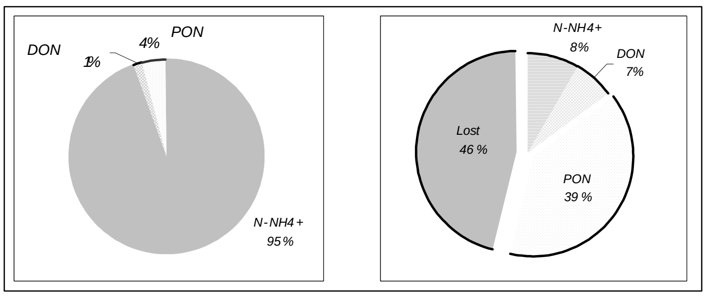
Under configuration II, organic matter removal rate was almost nil in the HRAP while those of N, P and pathogens were improved (table 4). Nitrogen was removed at 86% among which 39% was removed by algae uptake and 46% was lost by ammonia stripping (figure 4). Phosphorus was removed at 66% for which algae uptake and P precipitation under the effect of high pH values each accounted for 50%. Residual concentrations of N and P were 8.3 and 2.7 mg/l respectively. These figures are to be compared with those previously reported by El Hafiane *et al.*, (2003) for configuration I.

First-order reaction rate constant, $k_{20°C}$ for CODt removal, calculated following the method published earlier (El Ouarghi *et al.*, 2000 ; El Hamouri *et al.*, 2003) decreased from +0.038 in configuration I to the negative value of –0.250 $d^{-1}$ in configuration II. This indicates that no more organic matter was degraded in the HRAP under configuration II. At the same time, $k_{20°C}$ for N and P removals were multiplied by 2.3 and 1.6 respectively (table 5). Faecal coliforms removal rate also improved under configuration II; an average residual concentration of 2.4 $10^3$ unit/100 ml was recorded on MP1 (result not shown) leading to an overall removal of 3.92 log unit.

Table 4. Treatment performance of the HRAP under configuration II

| | Influent | Effluent | Removal rate (%) |
|---|---|---|---|
| CODt (mg $O_2$/l) | 110 | 250 | - |
| $BOD_5$ (mg $O_2$/l) | 45 | 35 | 22 |
| SS (mg/l) | 15 | 115 | - |
| VSS (mg/l) | 5 | 85 | - |
| TKN* (mg/l) | 61 | 8.3 | 86 |
| N-$NH_4^+$ (mg/l) | 49 | 7 | 86 |
| Pt* (mg/l) | 8 | 2.7 | 66 |
| P-$PO_4^{3-}$ (mg/l) | 5.8 | 2.4 | 59 |
| Faecal coliforms (U/100 ml) | 4.6E5 | 2.7E4 | 1.23** |

*Filtered effluent; **Reduction in Log Unit.




(DON, PON stand for dissolved and particulate organic N)

Figure 4. Nitrogen mass balance in the HRAP in config. II

The significance of the negative $k_{20°C}$ CODt, found under configuration II, is that the HRAP did add organic material instead of removing it from the effluent. We believe the HRAP was forced to do so because the carbon concentration left by the TSUAR system in the effluent was not enough to support the algae production that could be supported by the available N and P concentrations in the HRAP. Carbon was then imported from the atmosphere and used for that purpose. This means that the HRAP shifted from a combined secondary/tertiary treatment unit, observed under configuration I (see also El Ouarghi *et al.*, 2000), to a strictly tertiary unit under configuration II. With this configuration the HRAP operated in a way similar to that used in Chlorella farms, where $CO_2$ and nutrients are supplied to produce algae biomass on clean waters (Oswald, 1988).

Table 5. First-order reaction rate constants for CODt, N and P removals in the HRAP.

| | Configuration I | Configuration II |
|---|---|---|
| $k_{20°C}$ N ($d^{-1}$) | 0.282 | 0.653 |
| $k_{20°C}$ P ($d^{-1}$) | 0.153 | 0.249 |
| $k_{20°C}$ DCOt ($d^{-1}$) | 0.038 | -0.245 |

One of the main consequences of such a fundamental change in the way to operate the HRAP was that the algae concentration in the HRAP was more stable and that the treatment process (N, P and pathogen removal) was sustainable. Algae cell concentrations were kept within optimal limits values (table 6) when compared with the succession of high and low concentrations observed in configuration I, where the HRAP was operated as a secondary/tertiary unit. Average DO concentrations recorded during 7 ays in the HRAP during the coldest period of the year 2004 is shown on figure 5. The typical diurnal DO profile shown is different from that reported earlier on

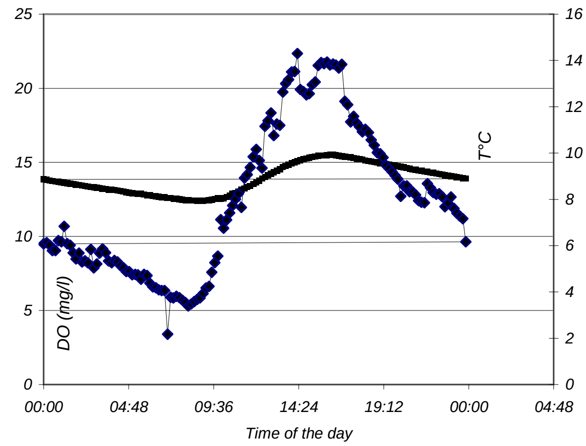


**Figure 5 One-week continuous recording of diurnal water temperature and dissolved oxygen in the HRAP during the coldest days of the year.**

the same HRAP operated under configuration I (El Ouarghi *et al.*, 2000). The anoxic period recorded in the night, which extended for approximately 4 h was absent under configuration II.

Table 6. Changes in HRAP operation parameters upon the switch from configuration I to II.

| | Configuration I | Configuration II |
|---|---|---|
| Organic loading rate (kg CODt $ha^{-1}d^{-1}$) | 233 | 83 |
| HRT (d) | 5.2 | 3 |
| Water depth (m) | 0.35 | 0.35 |
| Chlorophyll-a (mg/l) | 2.0 | 0.6 |
| Algae cell counts($10^6$/ml) | 3.0 | 0.8 |

## CONCLUSION

The two-step up flow anaerobic reactor (TSUAR) presented in this paper showed an excellent behaviour and operation simplicity. Not only were the performances high when compared to open anaerobic ponds, but the troublesome task of removing sludge from the pond every four to five years is no longer necessary. Also, the absence of any contact between wastewater being treated inside the reactors and the atmosphere prevents offensive odour release, which is a significant drawback of open anaerobic ponds. On another hand, the paper demonstrates that the combination of a TSUAR and an HRAP, as a post-treatment unit, is attractive. The organic matter degradation occurs in the TSUAR, while the HRAP, operated as a tertiary treatment unit, removes N and P, and helps to reduce FC survival. The advantages of such a combination are numerous: the effluent is of good quality, the land area requirements are low (1.0 $m^2$/capita for a complete treatment following configuration II conditions), odour problems are tackled and sludge management is simplified.

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