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Rethinking natural, extensive systems for tertiary treatment purposes: The high-rate algae pond as an example

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ABSTRACT

The central element of the 60 m^3/d wastewater treatment plant (WWTP) of the campus of the Hassan II Institute of Agronomy and Veterinary Sciences (IAV) in Rabat is a high-rate algae pond (HRAP). This unit functions behind a two-step upflow anaerobic reactor (pre-treatment) and is followed by one maturation pond (MP) for polishing. The system totalizes a hydraulic retention time (HRT) of 9 d with a removal efficiency of the pre-treatment alone exceeding 80% of COD and 90% of TSS. Used in this configuration, the HRAP looses its BOD removal activity and becomes a strictly tertiary treatment unit increasing therefore its nutrients and pathogens removal capabilities. As such, the HRAP removes 85% of total N and 63% of total P. The filtered effluent has 35, 8.3 and 2.7 mg/L respectively for BOD$_5$, TKN, and total P. Removal of N is due to algae uptake (46%) and ammonia stripping (54%). Data analysis indicates that dinitrification only plays an insignificant or even no role at all. P removal is due to algae uptake and to phosphorus salts precipitation (around 50% each). Fecal coliforms (FC), removal in the HRAP is 1.23 log units with no helminthes eggs found in the effluent. Cumulated FC removal in the whole treatment line (pre-treatment/HRAP/maturation pond) could reach 4 log units in the hot season and often lies between 2 and 3 in the cold season.

Keywords: Two-step upflow anaerobic reactor (TSUAR); High-rate algae pond; Nutrients; Fecal coliforms; Ammonia stripping; Phosphate precipitation

1. Introduction

Water is closely related to sanitation and to food production. Water scarcity could lead to hunger, which is a salient feature of poverty. Hunger and poverty alleviation are among the main targets of the Millennium Development Goals [1]. Whenever community sanitation is affordable, treated wastewater must be considered for reuse, principally for food production. Now, if tertiary treatment could be provided within acceptable cost to produce microbiologically and chemically acceptable water qualities, then water reuse would be safer and environmentally acceptable.

Natural tertiary treatment is meant here as the reduction of nitrogen and phosphorus contents to acceptable levels while "natural disinfection" could mean the ability of the treatment to achieve fecal coliforms (FC) removal efficiencies of 3–4 log units and of 100% for helminthes eggs within reasonable retention times.

Few natural, extensive systems are able to achieve tertiary treatment and disinfection to the expected levels. Waste stabilization ponds (WSP) are the most suitable for disinfection. However, to reach nitrogen concentration in the range of 10–12 mg/L, a retention time of 100 d is required [2–4], while phosphorus removal efficiencies do not exceed 30–50% [5]. Sub-surface horizontal flow constructed wetlands (CW) also have limited performance for nitrogen, phosphorus and fecal coliforms removal [6,7]. To overcome these limitations, vertical flow with recycling [8] and hybrid (vertical and

Presented at the 2nd International Congress, SMALLWAT '07, Wastewater Treatment in Small Communities, 11–15 November 2007, Seville, Spain horizontal) systems were implemented [9,10]. Moreover, a two-stage vertical flow system developed in southern France showed good performance for nitrification but could not achieve dinitrification [11].

This paper explains how the initial basic concept of the high-rate algae pond (HRAP) proposed by Oswald in the late fifties as an alternative to waste stabilisation pond system is modified to improve its tertiary treatment capabilities. The paper reports the experience of the Institute of Agronomy and Veterinary sciences where a wastewater treatment plant (WTP) based on the HRAP has been built at the campus and monitored since 1997.

2. Materials and methods

2.1. Geographical data

Rabat is located in the north-west of Morocco (latitude 34°02′ N, longitude 6°48′ W) at 73 m above sea level. Average temperature in the site is 14°C in the cold season and 24°C in the hot season. The facility at the IAV campus receives wastewater mainly from the students' residence and restaurant.

2.2. Experimental setup

The WTP occupies 1,200 m^2 and receives a daily flow of 60 m^3. After screening and grit removal, wastewater is pre-treated in a two-step upflow anaerobic reactor (TSUAR) [12], which includes a settler and a gravel filter behind the reactors with an overall hydraulic retention time (HRT) of 2.15 d. The next treatment step is the post-treatment, which includes the HRAP followed by one maturation pond (MP) (Fig. 1). All the construction components are made of reinforced concrete.

The HRAP has an area of 790 m^2 and a depth of 0.30 m. A tracer study, using Rhodamine WT, was performed on this unit in 1998 [13] and concluded that the hydraulic pattern was a plug flow with recirculation and small amount of dispersion with a mean HRT of 126 h (5.25 d). The maturation pond has dimensions of 17 m × 7 m and a depth of 1 m leading to a HRT of 1.4 d.

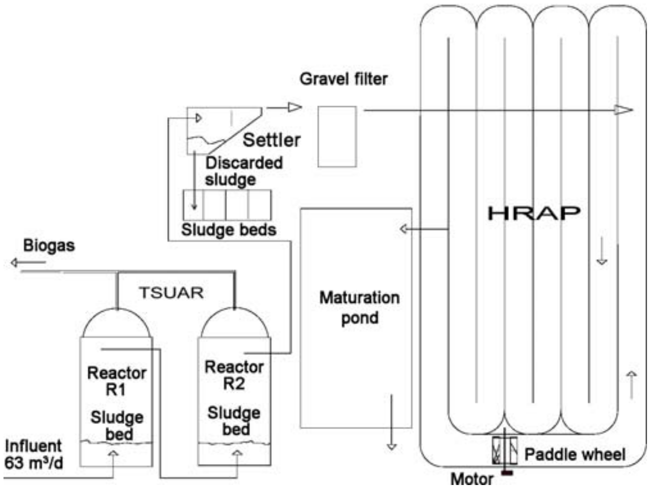

Fig. 1. Layout of the IAV treatment plant.

2.3. Sample collection and handling

Twenty four-hour composite samples were taken biweekly for main chemical characteristic analysis following Standard Methods [14] while daily *in situ* recording of temperature, pH, electrical conductivity (EC) and dissolved oxygen (DO) were carried out, which did not settle down in 30 min in a 2-L cylinder. Chlorophyll-a (Chl-a) was analysed following the method described by Pearson et al. [15]. Faecal coliforms (FC) were counted on grab samples using the MPN method [14] and helminth eggs were counted on composite samples following the flotation method described by Arther et al. [16].

3. Results and discussion

3.1. The HRAP operated as a secondary/tertiary treatment unit

The HRAP is a photosynthetic reactor, in which microscopic, photosynthetic algae are living together with heterotrophic bacteria. It is a carrousel-shaped, shallow (35–50 cm) pond which is continuously mixed by a paddle wheel [1,7–18]. The HRAP has a high capacity for solar energy capture that forces algae cells to evolve a maximum of oxygen for waste degradation by aerobic bacteria. In return, nitrogen, phosphorus and CO$_2$ resulting from the accelerated waste degradation are taken up by algae to sustain their growth in the pond. Such a cohabitation represented the central point of Oswald's concept using the HRAP, as a combined secondary/tertiary system, for sewage treatment (Fig. 2).

However, we have learned from our own experience, working on HRAPs in Morocco that this unit only works within limits. The adoption of a reliable pre-treatment unit to reduce sewage BOD and mainly TSS content before feeding the HRAP is a fundamental condition for sustainability of the HRAP "ecosystem". In the absence of a pre-treatment, "Oswald's symbiosis" often collapses as high concentrations of biodegradable organic matter favor bacterial growth at the expense of algae. On the other hand, algae must not take over and dominate the bacteria. The basic principle of the HRAP for sewage treatment is to collect sufficient solar energy in the form of algal biomass to oxygenate the waste, but not to grow more algae than is required for oxygen production [19]. Yet, the only efficient way to control algae content in the HRAP is cell harvesting at a regular basis as this is performed in *Chlorella* farms, where the Oswald's-like HRAPs are used for algae production (high-added value food) on fresh water. In these units, nutrients and CO$_2$ are supplied and algae are harvested at regular intervals. Such an approach is unconceivable in sewage treatment as the harvested algae would not be used for feeding

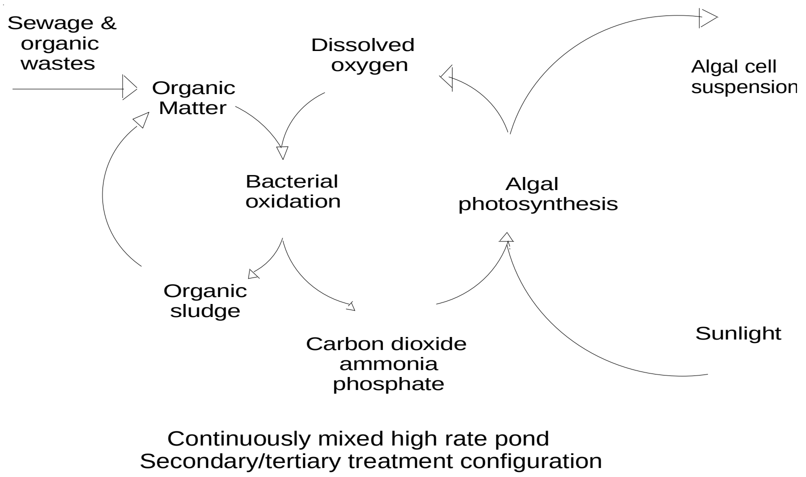

Fig. 2. Treatment principle in a HRAP conducted as a secondary tertiary treatment unit.

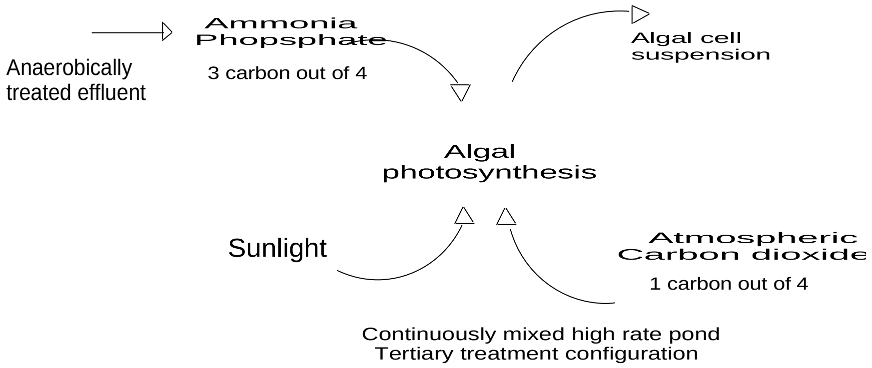

Fig. 3. Treatment principle in a HRAP conducted as a tertiary treatment unit.

animal and therefore the cost unsustainable although, some new opportunities are sticking out with biofuel production advent.

3.2. The HRAP operated as a tertiary treatment unit

At the IAV plant, the HRAP is used as a tertiary treatment unit (Fig. 3). The unit is placed behind a TSUAR that removes 80% of total COD (CODt) and 90% of TSS [12].

Table 1 summarizes the values of the operation parameters to conduct the HRAP as a tertiary unit. Comparison with the values used to conduct the HRAP as a secondary/tertiary unit shows that organic loading rate, the concentrations of chlorophyll-a and algal cells counts are roughly reduced by a factor of three.

Table 1
Operation parameters and constant of the first-order reaction rate, $k_{20°C}$ for secondary/tertiary and tertiary treatment modes

Parameter	Secondary/ tertiary unit	Tertiary unit
Organic loading rate, kg ha^{-1}d^{-1}	280	80
Hydraulic retention time, d	5.25	5.25
Depth, m	0.30	0.30
Chlorophyll-a, mg/L	2.0	0.6
Algae cell, 10^6/mL	3.0	0.8
$k_{20°C}$CODt removal, d^{-1}	0.038	–0.245
$k_{20°C}$ N removal, d^{-1}	0.282	0.653
$k_{20°C}$ P removal, d^{-1}	0.153	0.249

The first order reaction rate constant for CODt, total N and total P removals were worked out from Rhodamine WT tracer studies [13]. The results shows that the shift from secondary/tertiary to tertiary mode of operation is accompanied by a dramatic decrease in the value of $k_{20°C}$ for CODt removal and an increase of $k_{20°C}$ values for N and P removals. This means that the HRAP does not degrade any organic mater. Instead and in order to utilize available N and P (mineralised in the pre-treatment unit), the HRAP is importing CO_2 from the atmosphere explaining the occurrence of a negative $k_{20°C}$ value for CODt (Table 1).

Operated as a tertiary unit, the HRAP removes high amounts of N and P. Part of these elements is taken up and immobilised as new algae material. Now and because the availability of CO_2 is limited, the idea here is to use the slow atmospheric carbon fixation as a tool to limit the growth of algae preventing them from impairing the treatment performance. At least twice a year the HRAP ecosystem collapses due to excessive algae growth when the HRAP is operated as a secondary/tertiary treatment unit (Fig. 4) [13;20].

The positive effects of the changing the HRAP from a secondary/tertiary to a tertiary unit are shown in Fig. 5. A three-day continuous recording of dissolved oxygen (DO) during the coldest period of year 2005 shows that the HRAP did not become anoxic even in the night [21]. This is to be compared with the recording obtained on the same HRAP used as a secondary/tertiary unit during the year 2000, where the anoxic conditions prevail for almost 10 h at night.

Also, the maximum values for DO increases from 17 to 25 mg/L and those of the pH from 8 to 8.9 when the operation mode is changed from the secondary/tertiary to the tertiary operation. This corresponds to a difference of 8 mg/L for DO and almost one pH unit (see also Table 2).

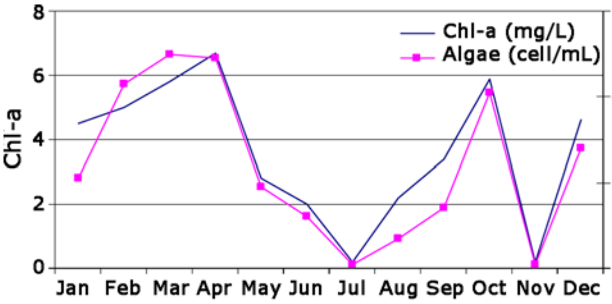

Fig. 4. Algae content and chlorophyll-a concentration during a year in a HRAP conducted as a secondary/tertiary treatment unit.

3.3. Nutrients removal

The HRAP removes almost 86% TKN, (assumed here as total N, because of the low nitrate and nitrite content), and 66% of total P with respective residual concentrations of 8.3 and 2.7 mg/L (Table 2). At the same time, the VSS content, which is made up, for more than 95% of algal cells, is multiplied by a factor of 17. Nutrient re-

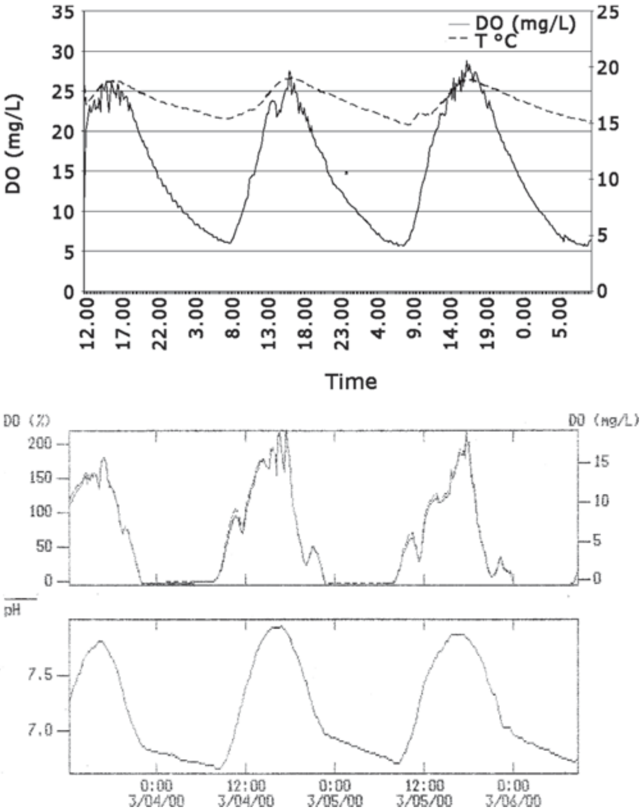

Fig. 5. Continuous recording of DO and temperature in a HRAP used as a tertiary unit (year 2005) (above) and of DO and pH in a HRAP used as a secondary tertiary unit (below).

Table 2
Treatment performance of the HRAP operated as tertiary unit

Parameter	Influent	Effluent	Removal efficiency (%)	Increase (%)
pH	7.2	8.9		
CODt, mg/L	110	250		66
BOD_5 , mg/L	45	35	22	
TSS , mg/L	15	115		95
VSS , mg/L	5	85		98
TKN , mg/L	60	8.3	86	
Total P, mg/L	7.45	2.7	66	
FC, $\log_{10}$/100 mL	4.6 E5	2.7 E4	1.23*	

moval and algae growth are then positively correlated. Algae cells uptake nutrients using solar energy to produce new cell material whose composition and behavior are, of course, different from those of the sewage TSS.

Nitrogen mass balance approach is used to determine the fate of nitrogen in the unit. Obtained data show that ammonia accounts for 95% of total N (Fig. 5). Such high ammonia concentration is normal as active mineralisation of organic nitrogen and phosphorus takes place in the TSUAR. At the effluent side, soluble nitrogen (ammonia and dissolved organic nitrogen (DON)) is reduced to 15% while 39% of the nitrogen mass is immobilised as new algae material (PON) and 46% are lost. Nitrification could take place in the HRAP due to the abundant DO. However, analyses of nitrate always give low concentrations. An explanation could be that nitrate is produced but immediately taken up by the algal cells. In the absence of evidences of such a hypothesis, the nitrate question in the HRAP remains unsolved. However, we could state that, the absence of anoxic conditions on a 24-h cycle basis is a good indication that, at least, denitrification could not take place in a HRAP operated as a tertiary treatment (Fig. 5). Therefore, the only possible way to loose nitrogen is by ammonia stripping.

Nitrogen stripping takes place when ammonia (NH_3) is the dominating form in water. The transformation from NH_4^+ to NH_3 is governed by both pH and temperature in the pond. The species NH_4^+ is dominant at pH values lower than 8 while almost all nitrogen is transformed into NH_3 at pH 11 [22–24]. The dependence of this process on temperature and on pH is shown by Eq. (1), which indicates that the NH_3 concentration is multiplied by 10 for one unit pH increase and by 2 for an increase in temperature of 10°C. Based on this equation, the HRAP operated as a tertiary treatment unit allows ten times more ammonia stripping than a secondary/tertiary unit. The follow up of the pH in the HRAP showed that samples did have NH_3/NH_4^+ values between 0.5 and 1 explaining therefore the nitrogen mass loss observed in Fig. 6.

$$NH_3/\,NH_4^+ = 10^{(10\,-\,pH\,-\,0.03\,T)} \tag{1}$$

The result of the mass balance worked out for phosphorus is shown in Fig. 8. It indicates that $P\text{-}PO_4^{3-}$ concentration decreases from 90% in the influent to 37% in the effluent. Removal efficiency of P in the HRAP is much lower than for N. The data also show that 25% of total P are taken up by algae while 23% of are lost by precipitation of phosphate salts under the effect of high pH values (Fig. 8). Phosphorus precipitation in the HRAP has been reported by many authors [24–26]. Summarizing the fate of phosphorus in the HRAP operated as a tertiary unit, one may conclude that roughly 25% of the admitted phosphorus mass is lost by precipitation and 25% is assimilated by algae.

As a comparison, averages removal efficiency of total nitrogen is 70% under secondary/tertiary mode and 86% under tertiary mode while, total phosphorus average removal efficiency is 40 and 60% respectively; i.e., the transition from secondary/tertiary to tertiary treatment allows 23 and 50% improvement respectively for N and P removals. Nutrients removals of such an importance must be highlighted especially because the system relies on solar energy, is cheap to construct and easy to operate and maintain.

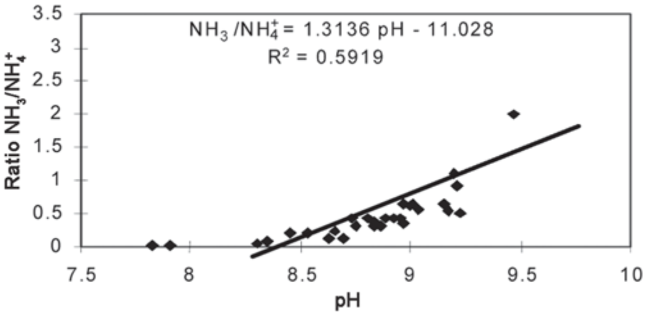

Fig. 7. NH_3/NH_4^+ ratio for pH values recorded on the IAV HRAP operated as a tertiary unit (data of the year 2003).

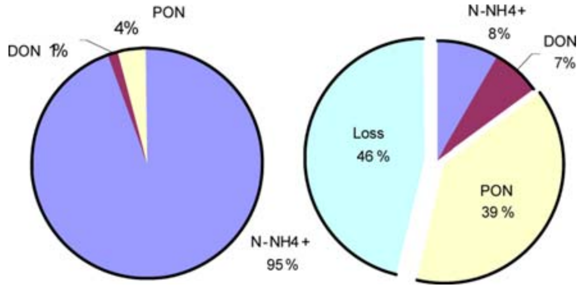

Fig. 6. Nitrogen mass balance in the HRAP (DON and PON stand for dissolved and particulate organic nitrogen respectively).

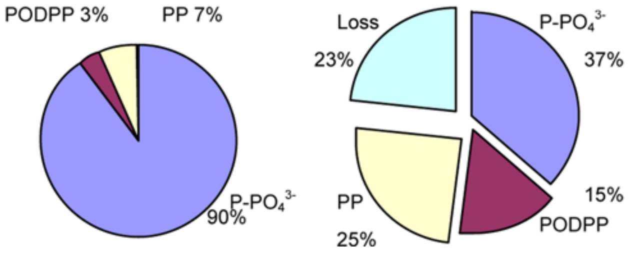

Fig. 8. Phosphorus mass balance in the HRAP operated as a tertiary unit. (PP: particulate P; PODPP: dissolved organic P and polyphosphates).

Table 3
Role and performance of the maturation pond

Parameter	Influent	Effluent	Removal efficiency (%)
CODt, mg/L	250	170	32
BOD_5 , mg/L	35	25	28.5
SS , mg/L	115	115	
TKN , mg/L	8.3	6.0	28
Total P, mg/L	2.7	2.4	10
FC, $\log_{10}$/100 mL	2.7E+04	2.4E+03	1.05

3.4. *Adding a maturation pond to a HRAP conducted as a tertiary unit?*

Table 3 shows that a maturation pond placed behind a HRAP plays an important role in the tertiary treatment. This pond acts as a polishing step in which almost 30% of BOD_5, CODt and total nitrogen are removed. Settling of algae at this stage of the treatment seems to be the main mechanism of such a polishing effect.

3.5. *Does the presence of algal cells impair the effluent quality?*

The presence of relatively high concentrations of TSS (made of algae) does not impair the HRAP effluent quality (Table 2). BOD_5 concentration decreases in the effluent of the HRAP while unfiltered or CODt doubled. The discrepancy between BOD and COD occurs because algae are oxidized in the COD test while they have no effect on the BOD_5 test. The presence of reasonable concentrations of algae in the effluent has no negative impact on receiving media. In the contrary and upontheir disposal, algae will operate as immediate oxygen suppliers in the receiving water body and as source of food for the protozoa and algae consuming fish. This is why CODt measurements are meaningless in the case of WSP and HRAP systems. Soluble or filtered COD better describes the situation. In Europe, algae contribution is subtracted from TSS before checking compliance with disposal standards for WSP plants effluents. If the effluent is to be used for irrigation then this biological material constitutes a humus source to improve the soil characteristics and texture as well as a progressive N and P releasing source. If the effluent is to be used in advanced irrigation systems, our experience at the IAV shows that placing a sand filter and a screen behind the pressure pump is sufficient to allow sprinklers operate without major problems.

3.6. *Helminthes egg removal*

Helminthes eggs are mostly removed in the pre-treatment stage. However, in the TSUAR, the average sludge retention time of 30 d and the prevailing anaerobic conditions, might be indications that the loss of helminth eggs viability is likely to occur. In the particular example of the IAV treatment plant where the pre-treatment consisted of a TSUAR, followed by a settler and a gravel filter, helminthes eggs are not detected in the effluent of the pre-treatment. Now, the geometry and the design of the HRAP also contribute in helminthes eggs removal just in the case some viable eggs escape from the pre treatment unit. If the HRT in the HRAP is 5.25 d (Table 1) with a travelling distance of 380 m and a recirculation time of 78 min, then a drop runs an average of 37 km before living the HRAP giving little chance to any eggs to leave the pond.

3.7. *Fecal coliforms removal*

In a HRAP operated as a tertiary unit, the removal efficiency could reach 1.23 log units. This performance is obtained in 5.25 d, a relatively short HRT for a natural, extensive system. Now, in the IAV experiment, the HRAP is preceded by a TSUAR (2 d HRT) that achieves a removal of 1.7 log units and followed by a maturation pond (1.4 HRT) that removes 1.05 log units. The cumulated removal efficiency is almost 4 log units achieved in less than 9 d overall HRT. It is of importance to highlight the salient performance of the maturation pond placed behind the HRAP operated as a tertiary unit. This pond removes 1 log unit while the FC loading is much lower than those applied to the TSUAR and to the HRAP indicating that the maturation pond plays a key role in the disinfection phenomenon taking place in the IAV experimental plant.

The settling and trapping (adsorption, flocculation, etc.) of bacterial cells or flocs explain most FC die-off in the TSUAR. In the HRAP, the main mechanisms at the origin of FC die-off are governed by algal photosynthesis. Indeed, strong variations of pH and DO concentrations between extreme values, being high during the day and low at night (Fig. 5) take place in the HRAP as a consequence of the algal photosynthesis. These sharp variations play a key-role in FC die-off. Similar mechanisms are also observed in facultative and maturation ponds but at much less extents [28–31].

4. Conclusion

The change in the principle governing wastewater treatment in a HRAP from a secondary/tertiary to a tertiary system is easy to implement: the HRAP must be placed behind a pre-treatment unit, which is capable of removing at least 80% of CODt and 90% of TSS. Operated under these conditions, the HRAP could achieve removals efficiencies of 86% for total N and 63% for total P. Algae uptake and ammonia stripping for N and algae uptake and precipitation for P are the main mechanisms of N and P removals.

Regarding the “natural disinfection” capabilities, the HRAP removes alone 1.23 log unit of FC with the whole treatment line (TSUAR/HRAP/MP) achieving almost 4 log in a HRT of 9 d. Such a short retention time has great economical consequences in term of capital, operation and maintenance costs. It points out the HRAP as an excellent tertiary treatment unit for effluent reuse in agriculture and landscaping in small communities of the southern Mediterranean area.

Placing a maturation pond (HRT of 1.4 d) behind the HRAP also plays an important role in the tertiary treatment. This pond acts as a polishing step in which almost 30% of BOD_5, CODt and total N admitted in the MP are removed. Settling of algae at this stage of the treatment seems to be the main mechanism of such a polishing effect.

Dedication

This work is dedicated to Prof. William J. Oswald, who died December 8, 2005. I am grateful to him for his pioneering work on the high rate algae ponds, which was the starting point for many among us working on this system throughout the world.

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