Microphyte and macrophyte-based lagooning in tropical regions

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Abstract A 720 m^2 plant made of 8 ponds in series, set in Yaounde (Cameroon), was successively operated as a macrophyte-based system (type M) from November 1997 to October 98, a microphyte-based system (type m) from October 1999 to September 2000 and a combination of macrophyte and microphyte ponds (type M + m) from May to July 2001. Average applied loads varied over the years; from 420 kg. BOD_5 ha^{-1} d^{-1} on the year 1997/98, the loads reached 510 kg BOD_5 ha^{-1} d^{-1} in 1999/2000 and 500 in 2001. Though the system became more and more overloaded and sludge accumulated rapidly in the first ponds, it provided average removals of SS, BOD_5 and COD that were always higher than 90% whatever the type of lagooning. Performances in the removal of SS, organic matter and the abatement of N-NH_4^+ and PO_4^{3-} did not significantly differ according to the type of lagooning and the applied load. Macrophyte lagooning did not show any definitive superiority as to nutrient removal when compared to microphyte lagooning. Microphyte lagooning was the most effective process in faecal indicators removal.

Keywords Cameroon; macrophyte; microphyte; removal; waste stabilisation ponds

Introduction

Natural systems, such as stabilisation ponds and constructed wetlands are nowadays recognised as suitable and cost-effective methods of wastewater treatment in developing countries, particularly those of sub-Saharan Africa which lack capital and qualified manpower (Denny, 1997; Mashauri *et al.*, 2000; Kivaisi, 2001). Indeed, construction and maintenance costs of conventional sewage treatment plants require large amounts of money that countries facing structural and financial adjustment cannot afford. Most of the conventional systems (especially activated sludge systems) present in the Sub-Sahara Africa lack maintenance, are overloaded or simply out of order (SOGREAH, 1993; Agendia, 1995).

Although land may be a limiting factor in densely populated areas, waste stabilisation ponds (WSPs) generally are an effective decentralised wastewater treatment technique for small communities where municipal land is not in short supply. Most significant advantages of WSP technology are: easy construction and operation, low operational costs, and a capability to withstand both organic and hydraulic shock loadings. Furthermore, most developing countries have warm tropical and subtropical climates that favour a year-round high biological activity and productivity, hence better efficiency of natural systems.

Among the natural systems present in Africa, WSPs, based on either microphytes or macrophytes, are gaining importance. In Cameroon for instance, all the towns planning sewerage programmes advocate their use for sewage treatment since almost all the activated sludge plants built after independence are out of function. The topography of the town of Yaounde, with many small watersheds allowing a gravitational flow of wastewater to inhabited lowlands should favour the adoption of decentralised WSP systems (SOGREAH, 1993). However, there is a growing controversy about the efficiency and possible reuse of by-products of the various types of WSP, particularly a confrontation between microphyte and macrophyte-based systems.

Several studies have shown the ability of both types to remove nutrients and pathogens from raw sewage (Reddy and Smith, 1987; Agendia, 1995; Verhoeven and Meuleman, 1999; Amahmid *et al.*, 2002), but very few have compared the treatment efficiency of both systems in the same operation and environmental conditions (Mandi *et al.*, 1993; Ouazzani *et al.*, 1995). Most of the works dealing with this comparison and reported in the literature have been carried out in Europe and America, the inlet wastewater often being primary or secondary effluents with a relatively low pollution concentration (Reddy and Smith, 1987; Vyzamal *et al.*, 1998). To the best of our knowledge, no such comparative investigation has been carried out in Western Africa, probably because of the slow expansion of this eco-technology in the region. Furthermore, the performance of these plants when receiving highly concentrated influents, as is the case in most African cities, has been little documented.

A WSP facility was built in 1986 by local authorities to treat domestic sewage from approximately 650 inhabitants of a residential quarter of Yaounde (Cameroon). The plant received high organic concentration wastewater ($BOD_5 > 450\,kg\,ha^{-1}d^{-1}$). It offered the opportunity to document the controversy in the local context. This paper presents the results of a comparative analysis of the treatment efficiency of the plant operated in three ways: floating macrophytes (LM), microphytes (Lm) and a combination of macrophyte and microphyte ponds (LM + Lm).

Materials and methods

This work was carried out at the Biyem-Assi pilot plant constructed to treat approximately $45\,m^3d^{-1}$ of raw sewage from a quarter of the capital city Yaounde (latitude 3° 52 N, longitude 11° 32 E, altitude 760 m). The total surface of the plant is approximately 0.1 ha (Figure 1). The system is made up of eight ponds dug in lateritic soil and separated with dykes of compacted soil (Table 1). The first pond (B0) is designed as an anaerobic pond. The other ponds (B1–B7) are rectangular with a length to breadth ratio of 5, allowing the hydraulic pattern to resemble a piston-like flow and to minimize the dead zones; with a velocity generally very small in Yaounde the wind hardly contributes to mixing. Wastewater flows by gravity and the hydraulic retention time is between 9 and 16 days.

From November 1997 to October 1998, ponds B1–B7 were planted with floating macrophyte *Pistia stratiotes* (LM), water hyacinth being absent in Cameroon. Previous studies carried out in the same plant showed that *Pistia stratiotes* should be harvested between the 15th and the 25th day of cultivation; this duration takes the rapid turnover of the absorbed nutrients into account (Agendia, 1995). For the current studies, 2/5th of each pond were harvested every 25 days to minimize the harvesting stress.

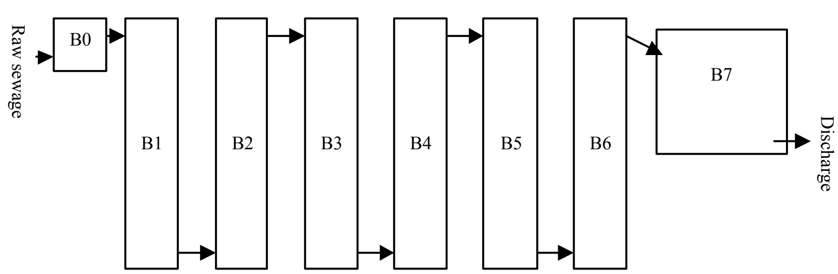

Figure 1 Layout of the Biyem-Assi waste stabilisation ponds (B0: anaerobic settling pond; B1–B7: lagoons)

Table 1 Characteristics of the Biyem-Assi sewage treatment plant

Pond	Length (m)	Breadth (m)	Depth (m)	Surface (m^2)	Volume (m^3)
B0	7.5	3.5	1.8	26.3	47.3
B1	22	4.4	0.7	97.0	67.9
B2	22	4.3	0.8	94.0	75.2
B3	22	4.4	0.9	96.0	86.5
B4	22	4.3	0.8	95.0	76.0
B5	22	4.3	0.9	95.0	85.5
B6	22	4.4	0.9	96.0	86.4
B7	18	6.6	0.5	119.0	59.5

After this first stage, the plant was allowed from October 1999 to September 2000 to function mainly with microphytes (Lm) by clearing ponds B2–B7, where micro algae could develop. Pond B1 was planted with a mixture of *Ipomoea aquatica and Enydra fluctuans* since these macrophytes help to reduce the emanation of foul odors.

Lastly, from May to July 2001, macrophyte and microphyte ponds were combined (LM + Lm). Pond B1 was left vegetated with *Enydra* and *Ipomoea*, the following three ponds, B2–B4, were planted with *Pistia stratiotes* and the rest (ponds B5–B7) remained without macrophytes.

Organic load (COD, BOD_5, SS), nutrients ($N\text{-}NH_4^+$, PO_4^{3-}) and bacterial indicators of fecal contamination (fecal coliforms and fecal streptococci) were monitored during the experiments two to five times per month. Water was sampled at the exit of each pond except for fecal indicators which were collected only at the entry and exit of the plant during the first stage. Analyses were performed using a Hach manometric apparatus for BOD and Hach DR 2010 for the rest of physico-chemical parameters (Hach, 1992). Fecal coliforms and fecal bacteria determination were done by MPN or membrane filtration technique using appropriate media (APHA, 1992). Rainfall and mean daily temperature are given in Figure 2.

Results

Despite some variations, the average quality of inlet wastewater did not change dramatically over the investigation period (Table 2). However, high standard deviation values showed a significant variability in the short term. As often observed in developing countries where access to water is limited either by its cost or by a short supply, suspended solids and organic matter concentrations were two to three times higher than those generally observed in European domestic wastewater. Studies generally assume that approximately 50–70 L are rejected per inhabitant per day against 160–200 L in developed countries (Nduka Okafor, 1985; Eckenfelder, 1982). High pollution content could also be explained by womens' extra activities such as traditional cassava processing and meal cooking. Furthermore, it also suggests poor maintenance of the wastewater collection network.

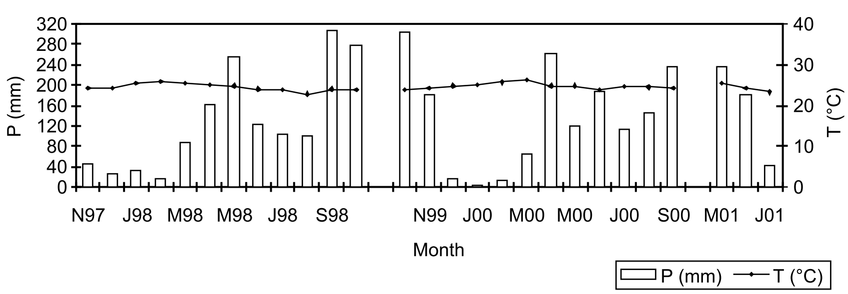

Figure 2 Rainfall and temperature in Yaounde

Table 2 Inlet and outlet water quality

	LM		Lm		LM + Lm	
	Inlet	Outlet	Inlet	Outlet	Inlet	Outlet
SS (mg/L)	835 ± 572	30 ± 19	880 ± 389	87 ± 32	865 ± 325	145 ± 90
BOD_5 (mg/L)	687 ± 138	103 ± 68	756 ± 136	148 ± 76	803 ± 200	128 ± 63
COD (mg/L)	1630 ± 726	140 ± 72	2367 ± 914	229 ± 131	1946 ± 812	250 ± 117
PO_4^{3-} (mg/L)	32 ± 39	12 ± 8	52 ± 20	16 ± 7	46 ± 10	13 ± 4
N-NH_4^+ (mg/L)	121 ± 45	52 ± 24	144 ± 55	52 ± 16	114 ± 34	39 ± 20
Fecal coliforms (nb/100 ml) $\times 10^6$	39 ± 50	0.19 ± 0.14	85	0.015	79 ± 81	0.46 ± 0.3
Fecal streptococci (nb/100 ml) $\times 10^6$	30 ± 39	0.067 ± 0.12	13	0.006	40 ± 78	0.03 ± 0.04

Average applied loads varied over the years, mainly because of inflow variation. From respectively 520, 420, 1000 and 19 kg ha^{-1} d^{-1} SS, BOD_5, COD and PO_4^{3-} on the year 1997/98, the loads reached 590, 510, 1600 and 35 kg ha^{-1} d^{-1} SS, BOD_5, COD and PO_4^{3-} in 1999/2000 and then decreased to 540, 500, 1200, and 29 kg ha^{-1} d^{-1} SS, BOD_5, COD and PO_4^{3-} when the ponds were operated as a combined macrophyte–microphyte system (Table 3). Mean ammonia load was about 75 kg N-NH4^{+}ha^{-1}d^{-1} not to mention organic nitrogen which could not be analyzed. Fecal indicator concentrations in the influent were generally above 10^7 bacteria/100 ml. Compared to the European standards of microphyte ponds, the Biyem-Assi facility would be appraised as being 4 to 5 times smaller than required. Fortunately, the climate of Yaounde is tropical with small seasonal variations. Mean water temperatures were between 22.9 and 25.9 °C, with a range of temperature less than 1.5 °C. However, the organic load, higher than 420 kg BOD_5 ha^{-1}d^{-1}, is almost two times higher that the maximum generally recommended for these plants (Mara, 1976). Despite a real under sizing, all types of WSP provided high pollutant removal.

Pollution patterns along the plant showed fair similarity whatever the type of WSP (Figure 3). A great reduction of the pollutants was observed mainly in the first three ponds (B0–B2), followed by a relatively slight decrease of pollutant contents in the following ponds (B3–B7). Reduction of SS and organic matter in the first ponds accounted for approximately 60–70% of the total pollution removed. As total phosphorus and Kjeldahl nitrogen could not be measured, assessing nutrient removal requires some caution; nevertheless, as organic P and N are likely to be mineralized in the first ponds, it is not inappropriate to think that the first three ponds also play a very important part in the removal of N and P. Though concentrations decreased slowly in ponds B3–B7, their role must not be underestimated. Indeed, thanks to evaporation and possible infiltration, mean water flow rate decreased steadily from 44, 48 and 45 m^{3}d^{-1} at the inlet of the plant to respectively 15, 25 and 17 m^{3}d^{-1} at the outlet of pond B7. Therefore, mass flow diminished more than is shown through concentration values.

The rapid decrease of pollution in the first three ponds (B0–B2) highlights the predominance of physical processes in the removal of pollutants as reported by Kadlec (1997). The partitioning of the plant into a series of ponds led to sedimentation and important sludge accumulation in the first ponds. A 25 cm/year deposition of sludge was noted in pond B1, causing a rapid filling of the ponds. Therefore water residence time was smaller during Lm and Lm + LM experiments in this pond, leading to a lack of efficiency in BOD and P abatement (Figure 3). Analysing pond malfunction in France, Racault (1993) suggested an increase of the surface and the depth of the first ponds to limit the frequencies of cleaning-out.

Despite the high concentration of the influent, the treatment efficiency of the plant remained relatively high. Some little differences were nevertheless observed amongst the

Table 3 Applied loads and pollution removal

	LM		Lm		LM + Lm	
	Load (kgha^{-1}d^{-1})	Removal (% or log units)	Load (kgha^{-1}d^{-1})	Removal (% or log units)	Load (kgha^{-1}d^{-1})	Removal (% or log units)
SS	513	94 ± 4	592	94 ± 3	542	92 ± 7
BOD_5	422	95 ± 3	508	89 ± 7	503	93 ± 5
COD	1020	97 ± 2	1590	95 ± 4	1220	94 ± 4
PO_4^{3-}	19	81 ± 15	35	81 ± 4	29	89 ± 4
$N\text{-}NH_4^+$	76	84 ± 9	97	79 ± 7	72	87 ± 8
Fecal coli.		2.0		3.8		2.8
Fecal strept.		3.0		3.3		2.2

Removal is a percentage of the applied load

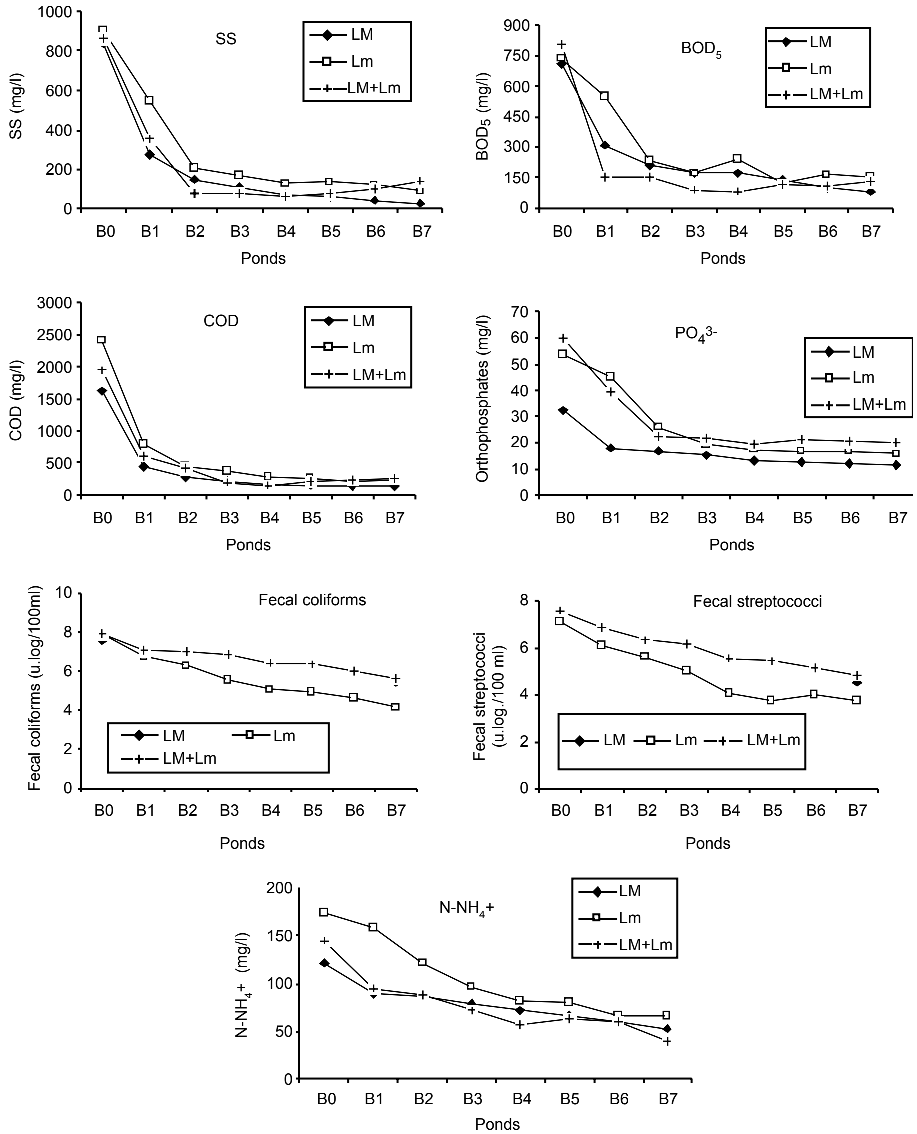

Figure 3 Pollutant patterns along the plant (LM: ponds with macrophytes; Lm: ponds with microphytes; LM + Lm: ponds with macophytes and microphytes)

types of treatment (Table 3). The macrophyte-based treatment system (LM) appeared to be the best system in the removal of organic load (mean COD removal: 97%, mean BOD_5 removal: 95%), followed by the combined LM + Lm system (mean COD removal: 94%, mean BOD_5 removal: 93%) and the microphyte-based one (Lm) with a rough average removal of 95% and 89% for respectively, COD and BOD_5. Removal of SS was very effective in LM, with a very low outlet content of $30\,mgL^{-1}$. Though the outlet content was higher in Lm, mean SS removal was 94% in both cases due to differences in hydraulic flow rates. The relative high efficiency of the macrophyte based-system to remove organic load and suspended matters could be due the presence of roots which filter the water by trapping the organic particles and enhance their sedimentation speed by reducing the flow velocity of the water (Brix, 1997). Furthermore, there was a greater development of algae in the last ponds when they were operated without macrophytes.

Regarding the nutrients, 87% of N-NH_4^+ and 89% of PO_4^{3-} were removed by the combination of macrophytes and microphytes (LM + Lm) against 79% and 81% respectively for Lm and 84% and 81% respectively for LM. These figures do not take organic N and P into account, therefore actual removals of N and P were likely to be higher than shown in Table 3. For the same reason, discussing and comparing P and N removals is not that easy. It was difficult to explain the best abatement of nutrients in LM + Lm. N-NH_4^+ removal looked slightly higher in LM than in Lm. Removal of PO_4^{3-} was about the same. Equivalent nutrient removal efficiency of the plant with and without macrophytes certainly clashes with the assertion presenting aquatic macrophytes as a key factor for the removal of nutrients in natural systems. Ouazzani *et al.* (1995) found similar results when comparing the efficiency of waste stabilisation ponds with and without plants in arid conditions. Indeed, they found that 60% and 62% of NH_4^+ and PO_4^{3-} respectively were removed in microphyte-based waste stabilisation ponds against 50% and 26% respectively in water hyacinth ponds in Marrakesh (Morocco). The increase of phosphorus precipitation in response to pH fluctuations and a high volatilisation of ammonia or nitrification/denitrification in free water may certainly explain these observations.

The reduction of faecal indicators was considerably higher in Lm than Lm and LM + Lm. Indeed, fecal coliform removal was 3.8 log. units when the plant was vegetated with microphytes against 2 and 2.2 respectively for LM and LM + Lm. Fecal streptococci removal was approximately the same for LM and Lm (3.3 and 3 log. units respectively), but slightly higher than that of LM + Lm (2.8 log units). The higher fecal coliforms numbers in the effluent in the presence of floating macrophytes (LM) confirm their negative impact on die-off. The removal efficiencies obtained were in accordance with those mentioned in others studies (Mandi *et al.*, 1993; Ouazzani *et al.*, 1995; George *et al.*, 2002). The key factors generally pointed out are bactericidal effects of sunlight and high pH values (Mezrioui, 1987; Davies-Colley *et al.*, 1999).

Conclusions

Despite the low dimensioning of the plant with respect to the organic load, the high reduction of pollutants confirms the flexibility of the natural systems. Indeed, the pond surface of Biyem-Assi WSP is less than 1 m^2 per p.e, which is very low compared to the 2–5 m^2 $p.e^{-1}$ generally recommended in hot climates (Mara, 1976). The abatement is higher than 2 log. units for the fecal indicator organisms, more than 90% for the organic load and more than 80% for the nutrients. This system, when properly maintained, particularly with respect to desludging, would provide higher quality effluent whatever the type of WSP. However, with respect to European standards, pollution concentration remains relatively high in the effluent. If required by water uses in the receiving body, this situation might be improved by adding supplementary ponds to the Biyem-Assi facility. These data reinforce the place that such natural systems could take in the battle against pollution of the environment and for the improvement of the sanitary quality of water in the African context.

Slight differences were observed in the performance of the different types of WSP tested. The macrophyte-based treatment showed a small advantage over other WSP types in its ability to remove organic load, while the microphyte-based treatment was more able to reduce the fecal indicators and the combination of macro and microphytes to remove nutrients. These results revealed the high complexity of a cut-and-dried choice of a natural system to treat wastewater. This choice should therefore be done in accordance to the priority of the wastewater treatment in the area of concern. In Cameroon, as in many other African countries, the protection of populations against waterborne diseases is of primary concern. The microphyte-based treatment better responds to this requirement and should therefore be promoted. The respective management constraints must be considered; among which the regular harvesting of floating macrophites is the most exacting, not to mention the disposal and fate of the harvest. Moreover, environmental impacts must be taken into account, particularly mosquito breeding (Kengne *et al.*, 2005). However further investigations for a better dimensioning, cost-benefit analysis and environmental impact of the system need to be done.

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