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DUCKWEED - TILAPIA SYSTEM : A POSSIBLE WAY OF ECOLOGICAL SANITATION FOR DEVELOPING COUNTRIES

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SUMMARY

We have studied the possibility of wastewater treatment in a system of urban agriculture based on stabilization ponds and duckweed producing ponds for fish breeding. The goal of the study was double : a check up of the treatment potential of duckweed under African conditions and an estimation of the possibilities of nutrient valorisation in a duckweed – Tilapia agro-sanitary system.

We used a small pilot system at the university of Niamey (Niger), composed of 3 ponds with microphytes and 3 ponds covered with duckweed. The duckweed was harvested 3 times a week and fed to Tilapia in adjacent pond. The ponds were fed with 3.5 m³/day of wastewater, corresponding to a global charge of 1.1 kg-BOD⁵/day or 130 kg/ha/day. The first results give a relatively good efficiency for standard parameters like DCO and DBO : (about 70 %) and for nutrients N and P (about 80 %). Excellent pathogen removal of 4 log units (>99.95%) satisfied the discharge norms for agricultural reuse. Mean duckweed productivity was about 25 000 kg/ha/month depending on the nutrient charge. The first results of Tilapia farming predict a good production : 475 kg_{w.w.}/ha/month. The global benefits of such a system for 5000 inhabitant equivalents might be about 1000 € /month.

RÉSUMÉ

Le potentiel pour agriculture urbaine a été étudié dans un système de traitement des eaux usées par lagunage à macrophytes, dans lequel les lentilles d'eau produite sont réutilisées à de fin piscicoles. L'objectif de l'étude était double, il s'agissait d'une part de vérifier la capacité épuratoire de la lentille d'eau et d'autre part d'estimer les possibilités de valorisation des nutriments dans un système composé de lentilles d'eau et de Tilapia dans des conditions climatiques africaines.

Le traitement a été étudié dans un système de lagunage expérimental de l'université de Niamey avec 6 bassins en série, 3 bassins avec microphytes et 3 bassins couverts avec lentilles d'eau. Les lentilles ont été récoltées 3 fois par semaine pour alimenter des Tilapia dans un bassin annexe. La filière était alimentée avec 3.5 m³/jour et une charge globale de 1.1 kg-DBO⁵/jour ou 130 kg DBO⁵/ha/jour. Les premiers résultats montrent une bonne élimination de la charge polluante 70% pour la DBO et la DCO et 80% pour l'azote et le phosphore. L'abattement des pathogènes était souvent supérieur à 4 unités logarithmiques et a permis d'atteindre la norme pour la réutilisation des effluents en agriculture. La production des Lemnacées, de l'ordre de 25 000 kg/ha/mois du poids frais, a permis une production de Tilapia d'environ 475 kg/ha/mois. Les revenus potentiels par la vente de Tilapia, ou des lentilles pourront atteindre 1000 €/mois pour un système desservant 5000 habitants.

Keywords :

duckweed, stabilisation ponds, reuse, ecological sanitation, wastewater treatment, macrophytes, urban agriculture, Africa

1 INTRODUCTION

The African cities are, on one hand submitted to demographic expansion and, on the other hand to the consequences of the rural exodus. These factors increase the water consumption and the needs for management of wastewaters.

Because of the demographic pressure on the land, the elimination of solid and liquid wastes by mean of individual sanitation becomes less and less feasible. Urban environment and receiving waters become more and more fragile and ask for better protection against pollution.

The difficult economical conditions in West Africa make not very probable a quick set up of the public equipment such as collective sanitation. The national policies of decentralisation give the responsibility of wastewater treatment to the local government. Knowing that the latter have generally little financial income, the possibilities of mobilization of financial resources become once again more difficult. The wastewater treatment by means of stabilization ponds is, compared to other techniques, relatively simple and inexpensive (Sperling 1996). Its economical yield may be improved by means use of the vegetal biomass production, and can constitute a credible alternative for the treatment of wastewater waters in periurban areas of West Africa.

A system that couples wastewater treatment and agricultural production meets the needs of sustainable water management. On one hand water is recycled and on other hand nutritious elements are recuperated and transformed in useful biomass. Such an agro-sanitary system makes a cheap treatment possible and may even become financially auto-sufficient. It's based on environment friendly technology, accessible to most of the developing countries. The advantages appear not only at the ecosystem level, but also in the social and economic sector as result of employment creation.

2. MATERIEL & METHODES

The main objective of the project is to test on small scale and under African conditions, the treatment of wastewater in a lagoon system using duckweed. The objective was double : to assess the treatment efficiency of a system producing biomass and to evaluate the direct reuse in fish farming.

This system was inspired by previous experiences of CENHICA in Guyaba (Santiago, 1997) the reports of Sandec (Iqbal 1999) and World Bank (Skillicorn 1993) on duckweed and aquaculture, following the guidelines given by Oron (1994), UNEP (1997) and Charbonnel (1989). As far as we know wastewater treatment by duckweed was not studied before in West African countries.

Physico-chemistry

The University of Niamey operates since 1998 a pilot plant for domestic wastewater treatment based on stabilisation ponds. This plant is composed of 3 lines of treatment, each composed of 6 trapezoid basins with an area of 14 m², a meter of depth and an approximate volume of 7 m³ (Idder et al 2000).

The duckweed treatment was studied from February to May 2002, in a serie of 6 basins. The first three basins used microphytes (B13 to B15 figure 1) and the last three were covered with duckweed (B16 to B18). The system (B13 to B18) received about 3.5 m³/day of wastewater from the university campus divided in 5 loadings (7h, 10h, 13h, 16h, 19h).

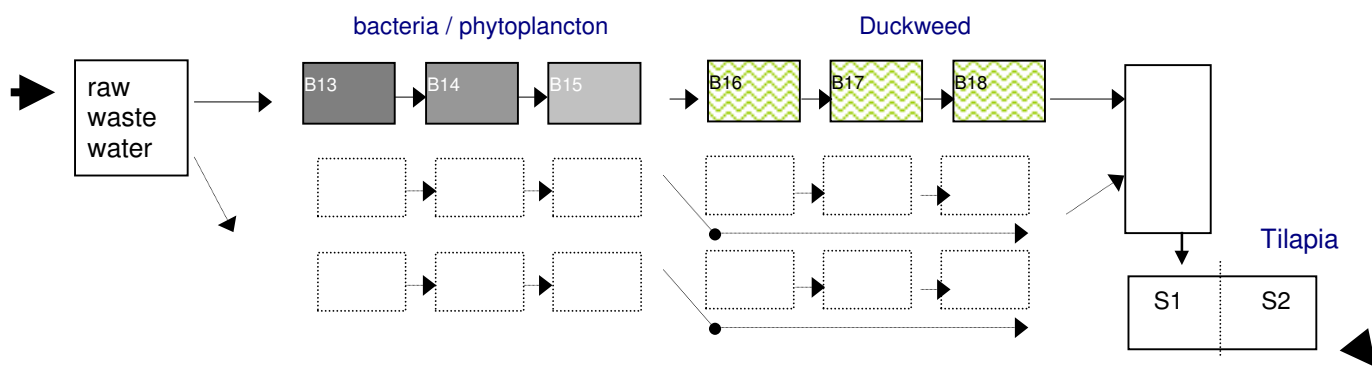


Figure 1: Outline of the pilot plant at the University of Niamey using the duckweed system. (B13 to B15 : microphytes, B16 to B18 : duckweed, P: collecting basin, S : Tilapia basin, dashed : other systems with daily flow of 4.5 m³)

To estimate the efficiency of the treatment, samples were collected each Friday at the entry of B13 and at the outlet of B15 and B18, about 10 minutes after the beginning of the flow during the whole experimentation. Classical parameters of water quality were estimated according to the French standards (AFNOR) and eventually the ISO standards.

Table 1 : Operational parameters of the duckweed system

Parameter	Specification
<u>Whole system</u>	
flow	3.5 m ³ /day (inlet) – 2.8 m ³ /day (outlet) → 80% restitution
evaporation	free surface : 8.4 mm/day – duckweed : 7.5 mm/day
mean residence time	12 – 15 day
capacity	25 equivalents based on 40 g-BOD/eq./day
treatment	3.4 m ² /equivalent
<u>Microphytes</u> :	
global load	1.1 kg BOD/day
anaerobic basin load	160 g/m ³ /j
facultative basin load	325 kg/ha/day
<u>Macrophytes</u> :	
density	230 g/m ² (mean for the 3 basins)
extraction	500 –1500 kg/ha/j
<u>Basin (6)</u>	
volume	7 m ³ (L*h = 5.6*2.6*1.0 m) a basin
surface	14.2 m ² a basin

Macrophytes

The macrophytes used belong to the family of Lemnaceae, habitually called duckweed and were collected from water ponds near the university where they grow naturally. The primary production was estimated 3 times a week, to optimise the production and to establish a financial balance for the system. The harvest of the duckweed was carried out manually on Tuesday, Thursday and Saturday, by harvesting between one third and one half of the surface of each basin. The remaining duckweed was spread homogeneously where after the new density was estimated by harvesting of 1 m². The harvested biomass was weighed to obtain the wet weight, a small part was used for the estimation of standard parameters and the rest for Tilapia feeding. The determination of N-content of duckweed was done after drying at 60°C by the ISO method for Kjeldahl nitrogen.

Tilapia

One of the direct valorisation forms of harvested macrophytes is fish breeding (Iqbal 1999, Alaerts 1996, Skillicorn 1993). The fish form a product with a more important added value than the macrophytes themselves. The pool S, with an area of about 30 m² and a depth of 50 cm was divided in two equal sections by a plastic grid and sown with minnows of *Tilapia nilotica* originating from the river Niger. The average size was in the order of 10 cm (12g) and the initial density about 5 to 6 individuals a square meter (70 g/m²).

In part S1, the fish were not fed, while in the part S2, the *Tilapia* were fed with a mixture of the Duckweed harvested on the basins B16 to B18. The nutrition, of about 500 grams of fresh duckweed a day per kilo of fish fresh weight (Skillicorn 1993), was consumed in few hours. In both compartments the Fishes could feed on naturally present invertebrates and plankton.

3. RESULTS

We have chosen to design a highly loaded system to evaluate the possibilities of treatment in a compact pond system. The surface needed for treatment (3.4 m² per inhabitant) is only one third of the surface used in France (11 m² per inhabitant). Despite the short residence time (15 days for the whole system, taking in account the evaporation) the obtained results indicate a fair treatment efficiency (picture 1).

Table 1 : Average treatment efficiency (R) for the microphytes basins (B13 to B15), the duckweed basins (B16 to B18) and the whole pilot during 4 months of functioning. If not stated the parameters concern the total fraction. "f" stands for filtered fraction. The filtered fraction of NTK is very similar to NH4 and as is therefore not shown.

Parameters	SS	DBO-f	DBO	DCO-f	DCO	NTK	NH4-f	PO4-f	pathogens /100ml	
	(mg/l)	(mg/l)					(mg-N/l)	(mg-P/l)	strepto	coli
Raw (B0)	238	171	312	239	645	62.9	45.7	3.91	2.5E+06	5.7 ^E +07
effluent B15	103	73.5	144	100	280	41.8	25.9	2.41	1.8E+04	8.3 ^E +04
effluent B18	99.6	43.6	98.9	97.7	233	21.9	12.8	0.7	1.1E+03	9.8 ^E +03
R – micro	57%	57%	54%	58%	55%	34%	43%	38%	99.28%	99.85%
R – duckweed	3%	41%	31%	2%	17%	48%	51%	71%	93.89%	88.19%
R – total	58%	75%	68%	59%	64%	65%	72%	82%	99.96%	99.98%

The results of table 1 show that the treatment efficiency of our pilot depends primary on the action of bacteria and microphytes in the first three basins. In less than one week more than 50% of pollutant load were removed. The duckweed has no effect on COD removal, a slight effect on BOD but very significant action on N, P removal. Seven day of residence in the duckweed section may not be enough to eliminate particulate BOD coming principally as phytoplankton from the basin B15. On the other hand harvesting can introduce or reintroduce some suspended solids in the water body. The ratio BOD/COD, an indicator for biodegradability of the organic matter, doesn't change for the particulate fraction between inlet and outlet, but decreases from 74% to 45% for the dissolved fraction between B15 and B18, indicating that the abatement of organic pollution in the duckweed section is major for the dissolved fraction. The nutrients N and P in the duckweed section are principally eliminated by the biomass extraction. Their evolution in time can be illustrated by filtered NTK as shown in Figure 2A Nitrogen is present mostly in dissolved form and its proportion is not significantly changing between the inlet and the outlet (Figure 3).

As we can see in figure 2B the average efficiency of pathogen removal is satisfactory during the whole period and the effluent content of streptococci is meeting the WHO norm of 1000 a 100 ml. The principal remove of pathogens occurs as affect of sun radiation in the microphyte section. The diminution of pathogen in the duckweed ponds is only partially due to the extraction of pathogens during duckweed

harvesting. The mean production of the duckweed in our pilot was about 0.8 kg/ha*day or 3.5 kilo fresh weight a day. With a mean concentration of $2.2 \cdot 10^7$ Coli per kilogramme, this means a decrease of $2.7 \cdot 10^3$ /100 ml in the effluent, which is only a fraction of the removal observed (table 2). Streptococcus show comparable results. This suggest another mechanism for pathogen removal in the duckweed ponds.

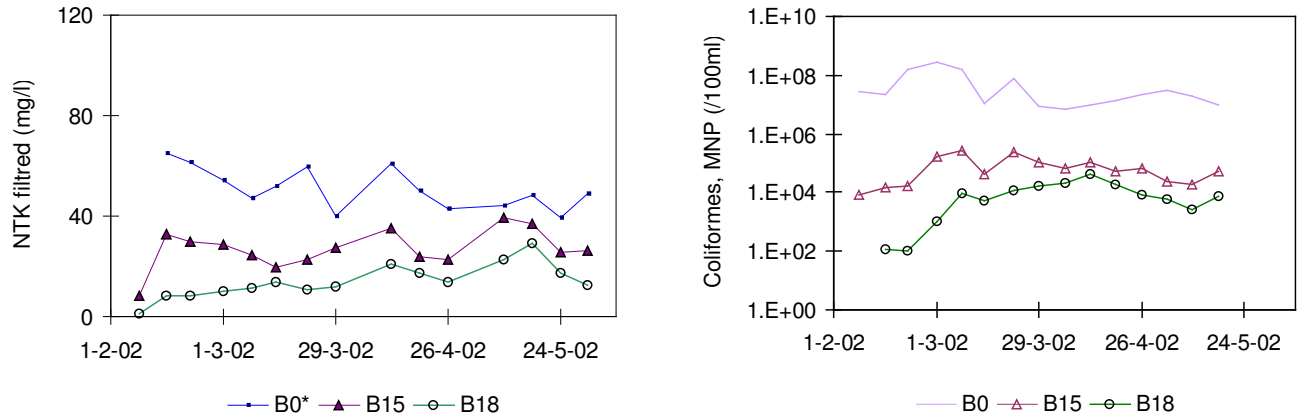


Figure 2A, B : Evolution of nutrients (total nitrogen) and pathogens (Coliforms) in the pilot.

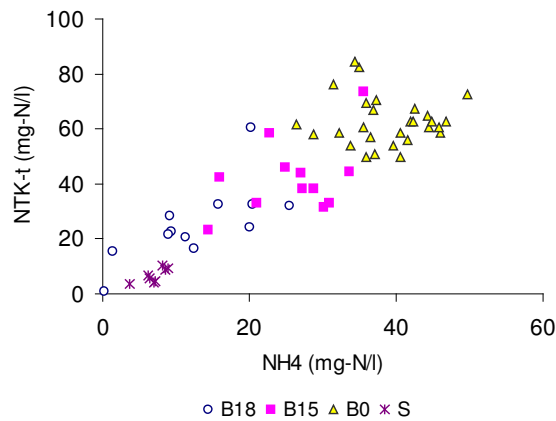


Figure 3 : Evolution of organic nitrogen through the pilot

During the test period from February to May the maximum temperature of water during the day rose gradually from 25°C to 35°C. This increase was followed by increasing NH₄ concentration in the duckweed ponds (from 20 to 30 mg/l of NH₄-N). Combination of both factors altered and finally stopped the duckweed growth at the end of the experimentation. The optimum temperature for duckweed growth is about 30 to 32°C depending on the specie (Iqbal 1999) and further rise inhibits its growth. A comparable action was established for ammonium by Caicedo et al (2000) suggesting 20 mg/l of NH₄-N as maximum.

The mean duckweed productivity was slightly higher in the first basin than in the two last. The difference between the basin B17 and B18 was not significant. As mentioned in the literature (Iqbal 2001, Santiago 1997) the protein or the nitrogen content is depending on the dissolved nitrogen concentration in the solution (table2).

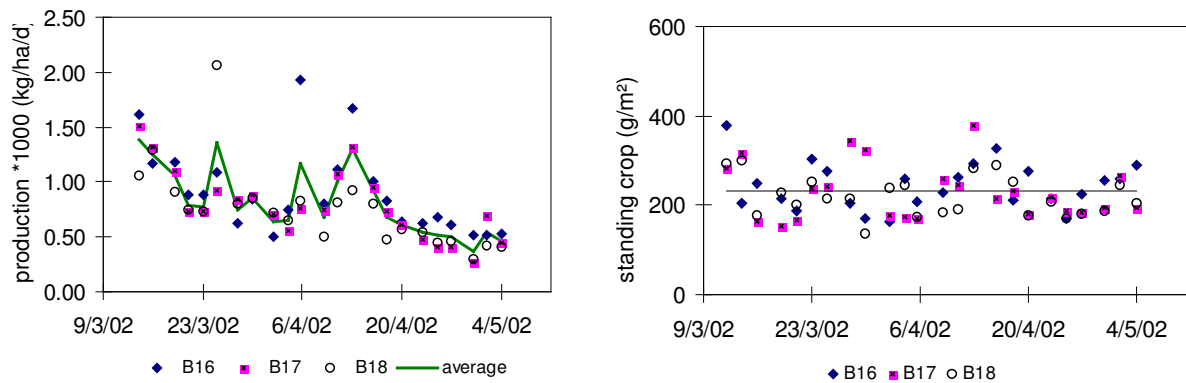


Figure 4 A, B: Evolution of the biomass in the duckweed ponds. The average production was 820 kg/ha/day decreasing from 1390 to 360. - The average standing crop was 0.23 kg/m²

Table 2: Characteristics of the harvested duckweed.

	B16	B17	B18
average productivity (10 ³ kg/ha/year)	330	280	270
dry matter (%)	6.5 ±0.5%	5.8 ±1.0%	4.5 ±0.7%
nitrogen in dry matter (%)	6.5 ±0.2%	3.7 ±0.1%	2.3 ±0.1%
NH4 basins (mg-N/l)	18.9 ±5.0	13.9 ±4.5	10.2 ±2.0
Coliformes (10 ⁷ /kg fresh weight)	3.47 ±2.2	2.19 ±1.7	1.04 ±0.9
Streptococcus (10 ⁸ /kg fresh weight)	1.13 ±1.3	0.42 ±0.6	0.18 ±0.2

As can be observed in figure 5 the most important organisms in the nitrogen cycle are bacteria, followed by phytoplankton and macrophytes. At the beginning of April we can see an increase of nitrogen flow from the maturation pond to the duckweed section. This is most probably due to algal bloom. As the standing crop is almost constant we can estimate that the withdrawn quantity by duckweed harvesting is equal to that produced and thus the N-flux is equal to N-assimilation rate $2.2 \cdot 10^3$ kg-N/ha*year (1.1 to 3.8). During the production period the mean N-load of duckweed section was $14 \cdot 10^3$ kg-N/ha*year, while $6.7 \cdot 10^3$ kg-N/ha*year left by the overflow. Though the duckweed assimilation accounted for almost 30% of nitrogen removal in the macrophyte section. The remaining decrease is most probably the result of nitrification / denitrification processes.

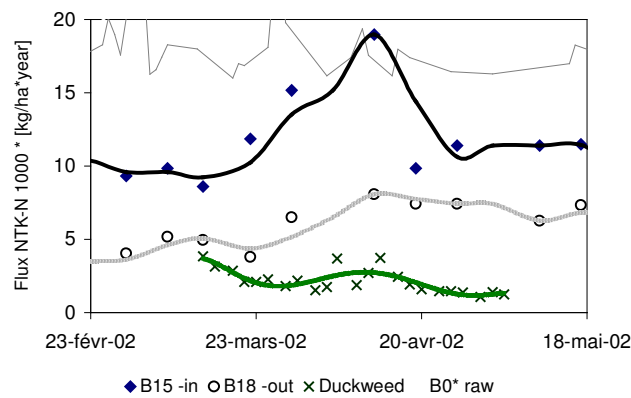


Figure 5: Estimation of the nitrogen fluxes in the phytoplankton and duckweed section

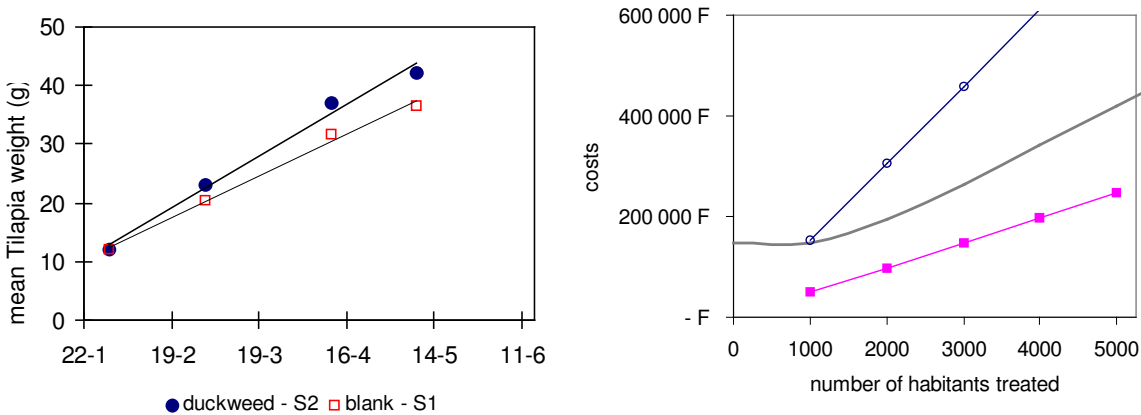


Figure 6A: Growth of Tilapia in basin fed with fresh duckweed (Lemna) and Tilapia grown in the same effluent without supplementary feeding (blank). The respective slopes are 0.32 and 0.26 g/day with $r^2 > 0.99$. Figure 6B : Cost analysis of duckweed system based on local evaluation : monthly benefits for Tilapia commercialisation for duckweed conversion of 1.5%(□) and 5%(○) compared to monthly maintenance costs (---). The operating costs are based on wastewater elevation (electricity + renewal of electromechanical device) and wages (1 person at 100€/month for 2000 equivalent), but no construction costs are included.

During the study we have obtained a fish production of $5.6 \cdot 10^3$ kg/ha/year for the fed population and $4.3 \cdot 10^3$ kg/ha/year for the non-fed population. This order of magnitude agrees with data given by Iqbal (1999) which states a production of $7 \cdot 10^3$ kg/ha/year in mixed fish culture using duckweed as sole fish feed. The conversion ratio of duckweed of 4.5% for the fed Tilapia is rather low compared to 10% given in the literature (Skillicorn 1993). Compared to the natural fed population this ration or the gain obtained by duckweed feeding is only 1.5%. One of the explication can be find in the proportion of duckweed feed / natural feed, which was constant and did not evaluate with the increasing fish biomass. The aquaculture is one of the most simple application of duckweed. The plants do not need to be stored, transformed or transported. According to the WHO the fishes grown in this way do not present any inconveniences for the human consumption if, before the consumption, self-cleansing in clean water is allowed.

Thanks to high nutritional value, comparable to soybeans, duckweed represents a strong market value. It can be compared to another local plant the Bourgou (*Equinocloa stagnina*), which is used as animal feed. The market price of duckweed is most probably situated something lower than that of Bourgou commercialised at 25 CFA⁽¹⁾/kg. We estimate it at 100 CFA a bucket or between 10 and 30 CFA/kg. The usual price of the carp (Tilapia) is between 800 and 1200 CFA/kg. Taking 800 CFA/kg for Tilapia, a duckweed surface of 1.7 m²/habitant (table 2) and a productivity of $25 \cdot 10^3$ kg/ha/month a treatment capacity of 1000 equivalents can generate monthly 150 000 CFA (230 €) in fish production. This amount roughly equilibrates operating costs (figure 6B). Taking in account the difference between natural and fed population the difference in conversion should be at least 2.5% to make a conversion in Tilapia financially attractive, otherwise a commercialisation of duckweed as animal feeding at 20 CFA/kg should be preferable. Low duckweed prices and high conversion factors make the fish breeding an optimal solution.

4. CONCLUSIONS & DISCUSSION

Our results show the feasibility of the wastewater treatment in a urban agro-sanitary system. The stabilisation ponds used, attains removal efficiencies for BOD and COD comparable to other systems in the region, but with significantly better pathogen removal. Only 3.4 m² were needed to treat an equivalent of habitant. The effluent meets the WHO guidelines for reuse in agriculture. To obtain a lower

¹ CFA local currency in 12 countries of West Africa, 655 CFA = 1 Euro

concentrations of carbon and nitrogen in the effluent a lower load or a higher residence time can be applied. A more practical solution consists in the utilisation of settler/digester at the entrance of the treatment file. For an optimal duckweed production care should be taken to maintain the temperature and the ammonium below 30 mg-N/l and 30°C.

The macrophytes play an important role in the elimination of the nutrients as nitrogen and phosphorus. About 20% of the dissolved nitrogen entering the duckweed system was immobilised and extracted with the harvest. Nevertheless the bacterial action remains the most important factor in the N-balance. The duckweed production obtained is comparable to that described in the literature (Steen 1998, Vermaat 1998, Santiago 1997, Alaerts 1996, Edwards 1992) and represents about 300×10^3 kg/hectares/year of fresh weight.

The study showed that a Duckweed – Tilapia system is able to generate sufficient income for the maintenance and operating of treatment facilities starting already at 1000 habitant equivalents. Once the treatment facilities set up, the maintenance can be financed by means of urban agriculture. Such agro-sanitary systems can form a solid base for sustainable wastewater treatment in West Africa.

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