Design of an integrated piggery system with recycled water, biomass production and water purification by vermiculture, macrophyte ponds and constructed wetlands

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Abstract Since 2001 the swine experimental station of Guernévez has studied biological treatment plants for nutrient recovery and water recycling, suited to the fresh liquid manure coming out of flushing systems. An integrated system with continuous recycling was set up in 2007, associated with a piggery of 30 pregnant sows. It includes a screen, a vermifilter, and macrophyte ponds alternating with constructed wetlands. The screen and the vermifilter had a lower removal efficiency than in previous studies on finishing pigs. A settling tank was then added between the vermifilter and the first lagoon to collect the worm casts. A second vermifilter was added to recover this particulate organic matter. A storage lagoon was added to compensate for evaporative losses and complete pollution abatement, with goldfish as a bioindicator of water quality. The removal efficiency of the whole system was over 90% for COD and nitrogen, over 70% for phosphorus and potassium, and more than 4 logarithmic units for pathogens (*E. Coli*, enterococci, *C Perfringens*). Plant production was about 20 T DM ha^{-1} y^{-1}. Floating macrophytes (*Azolla caroliniana*, *Eichhornia Crassipes*, *Hydrocotyle vulgaris*) were more concentrated in nutrients than helophytes (*Phragmites australis*, *Glyceria aquatica*,…). *Azolla caroliniana* was successfully added to feed finishing pigs.

Keywords Horizontal subsurface flow constructed wetland; lagooning; macrophytes ponds; pig manure; reuse; vermifiltration.

INTRODUCTION

Water, soil and air pollution, related to the carbon and nitrogen cycles, affect climate, health, biodiversity and the safeguarding of resources (Galloway et al., 2003). Just for the example of swine production in France, 21 million m^3 of liquid manure are produced each year, while with 24 million pigs raised per year, France is far behind China, the main world producer, with nearly 500 million animals. In Brittany (France), the area used for manure spreading is mostly required to avoid harming ecosystems: the eutrophication of coastal waters and the resultant algal blooms are a concrete example of such regional water contamination (Charlier et al., 2007). On the other hand, the increase in crop and animal production following population increase on a global scale should increase the use of fertilizers in the regions with the highest potential yields (Mosier, 2002).

Farming systems should therefore reduce pollutant release and improve their efficiency of resource use, especially for water and nutrients. This can be achieved by means of complementary animal and crop production, designed to maximize short distance recycling of byproducts. System designs should integrate the specific know-how and technologies, sufficiently well understood to be controlled, available in the different regions of the world. For example in France, pig production and effluent management (flushing systems, compost production and use), might be associated with extensive water treatment systems (vermifilters, macrophyte ponds) in agro-environmental ecosystems, which allow maximum vegetative growth per hectare by reducing limiting factors and minimizing uncontrolled release to the surrounding natural ecosystem.

The storage of liquid manure below the pigs in animal houses is not conducive to animal health, and results in gaseous losses of around 25% of the excreted nitrogen in the form of reactive nitrogenous molecules (ammonia, nitrous oxide). Agro-environmental ecosystems should minimize pollution transfer and attempt to improve health and meat quality.

It thus became necessary to find alternative solutions to storage beneath the pigs and spreading for the elimination of the liquid manure. The liquid manure from the piggery can be removed as soon as possible by scraping or flushing. The first technique leads to a fresh liquid manure often treated by intensive processes. The second leads to a diluted fresh liquid manure which requires extensive treatment.

The flushing system is much used in Australia, but without effective treatment of the diluted fresh liquid manure, so resulting in malodorous gas emissions from anaerobic lagoons (FSA Environmental, 2000). **V**arious systems combining water treatment and production of biomass have been described in the literature; vermiculture (Stopped and Soto, 2004), macrophyte ponds (Reddy and Smith, 1987; Costa et al, 2003) and helophyte filters (Ennabili et al., 1998). It thus seemed worthwhile to devise a way of treating the diluted fresh liquid manure with a dual aim: to obtain purified water, and to maximizing various forms of production, starting from the elements contained in the effluent.

After several years of study on small units (a pilot vermifilter and macrophyte plant), a prototype was built. It includes a piggery of 30 pregnant sows and an experimental plant with a vibrating screen, a vermifilter, a settling tank and a combined system of macrophyte ponds and artificial wetland. Its design and the performance obtained are presented here.

MATERIALS AND METHODS

Equipment

All equipment was controlled automatically with float level switches and a clock.

Livestock building. This was a building of about 12 m x 5 m for 30 pregnant sows on a slatted floor. Flushing was effected 5 to 6 times per day by the swinging of 2 stainless troughs of 400 liters each (i.e. between 130 and 160 $l.d^{-1}.sow^{-1}$). The effluent flowed under the slatted floor and was collected in a concrete tank and then pumped to the screen.

Screen. This was a vibrating screen with a mesh of 600 µm, made out of stainless steel (Guillerm, Finistere). The liquid effluent fell into a concrete tank containing a pump to transfer it to the vermifilter.

Vermifilter. This consisted of a layer of coarse wood chips, about 0.5 m thick, resting on a stainless slatted floor with 5 mm slits, between two concrete walls on either side of a sloping floor (96 m^2). A slow-moving crane was used both to sprinkle the wood chips and to stir them weekly by means of a rotating fork (lombrimat ®, Cadiou, Finistère). The part receiving the fresh manure occupied approximately half of the area. The second half received the old vermifilter material moved by the fork, and the sludge collected in the settling tank. The liquids ran out by gravity towards the settling tank through a grid which retained the wood chips.

Settling tank. This consisted of a concrete tank 2.5m x 1m x 2m. The water flowed out from the top of the tank, on the opposite side from the supply pipe, into a PVC tank, from which it was pumped to the first pond.

Macrophyte treatment. This was carried out in five basins terraced at successive levels. Macrophyte ponds (P1 and P3 corresponding to levels 1 and 3) alternated with constructed wetlands (CW) with horizontal subsurface flow (P2 and P4 corresponding to levels 2 and 4). A pilot was run for two years to check various parameters, after which it was connected to the full scale treatment plant. The latter was built using results obtained with the pilot, with the same hydraulic retention time (HRT) of 5 days for the first basin and 4 for the others. Basins P1 to P4 had areas of 50, 95, 45 and 160 m^2 and maximum depths of 1.5, 0.6, 0.6 and 0.45 m respectively, *i.e.* water volumes of about 25 or 20 m^3. The basins were lined to ensure that they were waterproof. The support for the CW was made of 6-10 mm grade gravel. Water flowed by gravity between the basins. Filters P2 and P4 were planted with reeds (*Phragmites australis*) and a mixture of *Glyceria aquatica, Iris pseudoacarus and Carex* spp. respectively. During the experiment, P1 was covered with water hyacinth (*Eicchornia crassipes*) and P3 with water ferns (*Azolla caroliniana*).

The storage lagoon (P5) covered a maximum of 180 m^2. Its volume of 250 m^3 was chosen to compensate for the evaporative needs during the dry months. It received both full scale plant and pilot outflows. A submersible pump raised the water to the level of the piggery. Its hydraulic residence time of approximately 50 d when full after rainfall, decreased with evaporation. It was covered with water ferns or water hyacinth depending on the season. Microphytes settled or disappeared depending on the covering with macrophytes. 100 young goldfish were used as bioindicators of the water quality and to improve the stability of the aquatic ecosystem.

Sampling and analysis methods

Water samples were taken 2 twice monthly for chemical analysis. The analytical parameters assessed in this study were total solids (TS), suspended solids (SS), chemical oxygen demand (COD), total nitrogen (TN), ammonium nitrogen (NH_4^+-N), nitrite (NO_2^--N), nitrate (NO_3^--N), total phosphorus (TP) and potassium (K) according to the Standard Methods. pH and temperature were measured *in situ*. Plants were also sampled and sent to COOPAGRI-Bretagne laboratory to be analysed by standard methods in order to determine dry matter (DM), volatile solids (VS) and elemental composition.

For microbial analysis, 10 g of each sample taken on September 19th was transferred into 90 mL of peptone water and then 10-fold diluted. *E. coli* were counted using 3M™ Petrifilm *E. coli* (incubated 24 h at 44°C). Enterococci were counted on selective Slanetz–Bartley agar (Biokar, France), incubated 48 h at 37°C, with subsequent confirmation on Bile Esculin Agar (Biokar, France) incubated 4 h at 44°C. Spores of *Clostridium perfringens* were counted after a thermal shock at 80°C for 20 min, according to the protocol described by Sartory *et al.* (2006). Tests were performed in triplicate. All results were expressed as wet weight of sample.

Macrophyte use

As feed input represents a high cost in animal production, addition of floating plants to the feed was tested. *Azolla* was chosen because it can be grown throughout the year and has already been used as a food supplement in Latin America and Asia. It has a high content in crude protein content (24%; FAO, 1997). A first trial was carried out for 45 days with two groups of 4 fattening pigs (treatment and control) fed with standard diet *ad libitum*. The treatment group received 0.5 $kg.d^{-1}.pig^{-1}$ (wet weight) for one week, then 1 $kg.d^{-1}.pig^{-1}$ until slaughter. *Azolla* came from P3. It was harvested daily, and spread directly on the floor.

RESULTS AND DISCUSSION

Design of the system

After one year of continuous recycling of the water, the experimental treatment plant designed for a piggery of 30 pregnant sows gave satisfactory results. It allowed worm and goldfish growth and reproduction, and plant production. The ammonia in the ambient air of the piggery fell from 25 (the median value often found in this type of piggery) to around 8 ppm.

To obtain these results, adjustments were necessary. Only 20% of the phosphorus was retained by the screen while 80% was expected (Landrain, 2007). The nitrogen and potassium removal during screening was negligible. Only the COD and SS removal were acceptable (about 50%) but not optimal. The vermifilter gave lower removal efficiency of COD and nitrogen, compared to pilot scale results (Li et al., 2008): around 20 and 40% respectively, against 85 and 65% previously achieved. The phosphorus removal was similar, around 22%. This difference can be explained by a higher porosity of the second vermifilter, that had to be maintained for continuous water recycling. Porosity maintenance was achieved by particulate organic matter removal (worm casts carried away by the water) and weekly declogging and vermifilter moving with the rotating fork. The high release of particulate organic matter from the vermifilter made it necessary to install a settling tank between the vermifilter and the first macrophyte pond, with regular sludge removal, to avoid the saturation of the pond by sludge. Therefore, a second vermifilter for sludge retention was added to the design. It was not necessary to place it on a slatted floor because the water input during one sludge removal was limited to the free air space of the vermifilter. The pilot macrophyte plant was integrated into the full scale treatment plant using part of the settling tank effluent, which contributed to approximately 7% of the total removal efficiency.

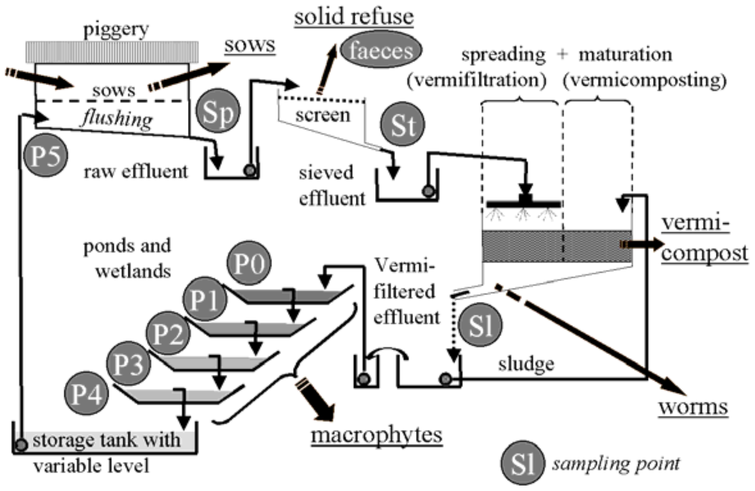

Figure 1. General scheme of the prototype of clean piggery built at Guernévez, with indication of the sampling points mentioned in figures 3 to 6.

All design adjustments were finished in July 2008, resulting in mean removal efficiencies ranging between 71% and 96% for various parameters (figure 2), observed between August and October 2008. Ammonia and pathogen removal are the main challenges for water recycling in present swine production systems. Furthermore, avoiding natural ecosystem contamination and producing biomass are necessary for the development of sustainable farming systems.

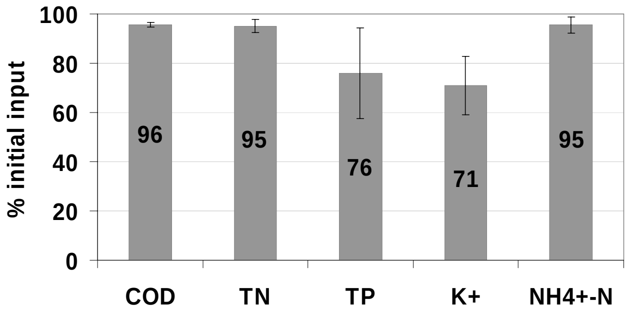

Figure 2. Percentage reductions in various parameters from August 6th to October 7th, 2008, Guernévez experimental plant.

Ammonia removal

Ammoniacal nitrogen is generated by organic nitrogen mineralization and leads to ammonia emissions. Its concentration can be limited by dilution or by assimilation by macro and microorganisms. Its concentration decreased throughout the system, the reduction factor being 95 % (figure 3). This high removal efficiency, despite an initial dilution to around 30 times less than slurry concentrations, can be explained by the transformations in the successive ecosystems.

The concentrations of NO_2^--N and NO_3^--N throughout the process are characteristic of the system's operation. In the vermifilter, the alternate sprinkling and drying phases caused considerable nitrification, as shown by the maximum nitrate concentrations (figure 3). In the settling tank, there was rapid denitrification as shown by the big decrease in nitrate concentration despite the smallest HRT of the system. The sludge can bring it about because it consists of worm casts, known to be rich in denitrifying bacteria (A. Brauman, pers. comm.), and because the water is rich in dissolved carbon. The effect of the vermifilter on nitrogen transformation (abatement of ammoniacal nitrogen and nitrification) is similar to that of a vertical filter (see e.g. Molle et al., 2008).

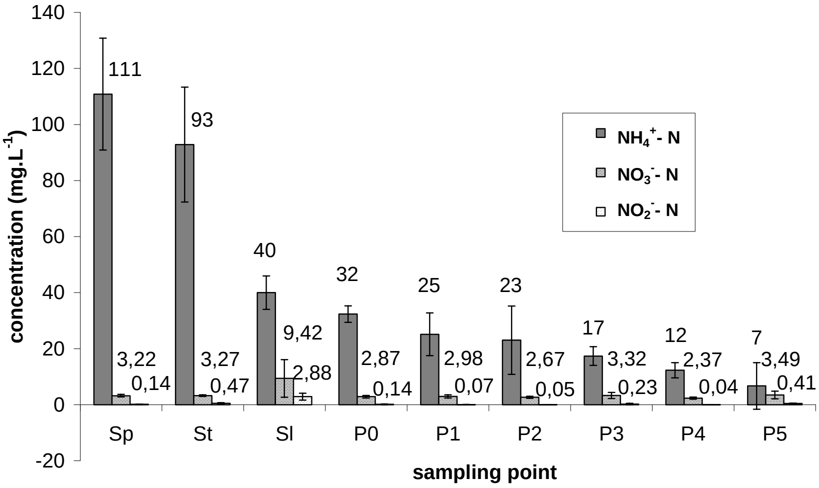

Figure 3. NH_4^+-N, NO_3^--N and NO_2^--N concentrations along the treatment plant. Sampling points refer to figure 1. The values are the averages of 5 samplings; bars give the standard deviation.

Micro-organism removal

Figure 4 summarizes the behavior of three types of micro-organism used to indicate pathogen removal throughout the system. Regardless of the type of bacteria, a progressive decline of bacterial numbers was observed, confirming observations in the literature (Bastos et al., 2006). At the end, the microbiological quality was satisfactory for water to be reused (less than 10 bacteria / mL) within the piggery. The *E. coli* counts were reduced in each of the five basins, with the greatest contribution at the CW stages. The succession of basins resulted in a large decrease in the bacterial counts (over 4 log. units, i.e. 10,000-fold). Compared to other biological manure treatments which reduce the numbers of *E. coli* by two logarithmic units (100-fold) (Chinivasagam et al., 2005; Vanotti et al., 2005), the system appeared more effective.

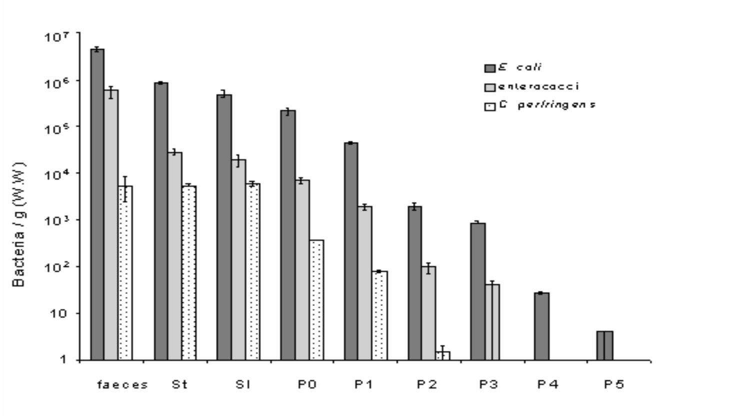

Figure 4. Concentrations of *E. coli*, enterococci and *C. perfringens* along the treatment plant. Sampling points refer to figure 1; the feces replace the output of the piggery (Sp). Bars indicated minimum and maximum values.

TS, SS and COD removal

TS, SS and COD removal efficiencies of the overall experimental plant were 72, 98 and 96% respectively (figures 2 and 5). The settling tank was efficient (SS removal (64%) and COD (69%) calculated from its input to its output). The nature of the COD, initially mostly composed of reactive organic matter, is modified by the vermifilter into more stable compounds produced by the metabolism of macrofauna, bacteria and fungi, and is rich in worm casts, which facilitate aggregation and settling. The removals for the whole vermifilter/settling tank were thus 82 and 80%. The first CW (P2) also had a noticeable contribution to the COD removal (43%).

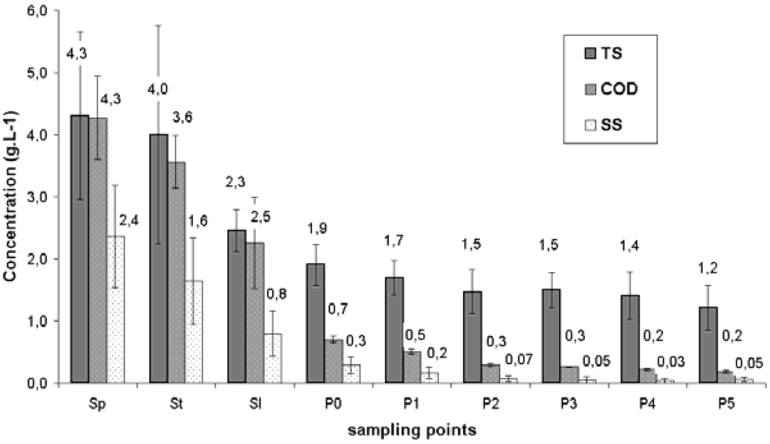

Figure 5. TS, COD and SS concentrations along the treatment plant. Sampling points refer to figure 1. The values are the averages of 5 samplings; bars give the standard deviation.

N, P and K removal

Figure 6 presents the average concentrations of nutrients and K along the system**.** The treatment plant had a very high performance (95% overall removal for N, 76% for P, 71% for K). N is removed mainly by the vermifilter (49%) and the first macrophyte pond (54%); P, by the settling tank (33%) and the deep lagoons P1 (14%) and P5 (22%), where settling may occur. The residual concentration of N (19 mg l^{-1}) was low enough for flushing and is acceptable in the case of overflow after very high rainfall. Whereas K is difficult to remove by traditional treatment systems, the screen provided a 20% removal and the vermifilter removed a further 20%, as previously observed by Li et al. (2008). Adsorption on reactive organic particles can explain this removal. K was not retained in the sludge of the settling tank. It was further removed by absorption by the plants: removal by the macrophyte ponds ranged between 10% (P1) and 20% (P3 and P5). The constructed wetlands were less efficient for all these parameters. The difference is due to the high biomass production of the floating macrophytes in summer and their high nutrient concentration.

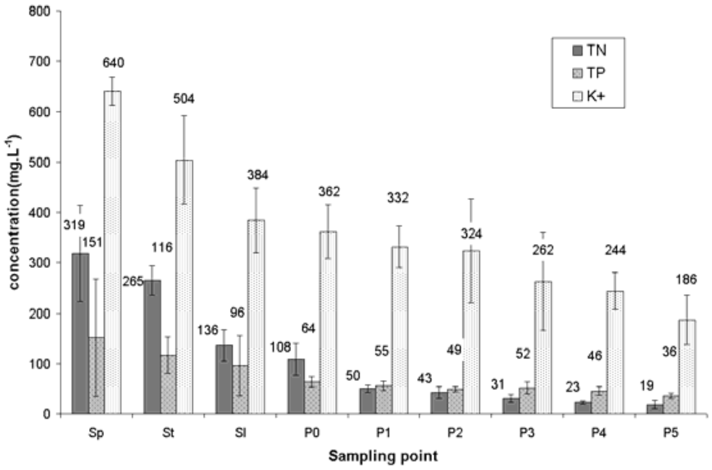

Figure 6. TN, TP and K^+ concentrations along the treatment plant. Sampling points refer to figure 1. The values are the averages of 5 samplings; bars give the standard deviation.

Biomass production and use

Production. The hydrophytes' doubling time ranged from 9 d to 16 d for the water hyacinths in P1, and from 9 d to 13 d for the ferns in P3. Weekly harvests were necessary to avoid overpopulation and growth decrease. Over the whole year, the harvested biomass of hydrophytes was 20 t DM ha^{-1}. The helophyte biomass harvest was of the same order of magnitude. The higher nutrient concentration of the hydrophytes compared to the helophytes explained their higher contribution to nutrient removal. It may be due to the fact that only the aerial parts of the helophytes are collected, whereas the whole of the floating plants is harvested, and the nutrient concentrations are higher in the roots than in the leaves or stems (e.g. Blake et al., 1987).

Use. The trial with *Azolla* as feed showed that it is very acceptable: the animals ate *Azolla* exclusively just after its distribution. No signs of indigestion were observed. The treatment group reduced their feed consumption from 340 kg DM (control) to 284 kg DM (treatment: weight including the *Azolla*) for 45 days. The growth of the treatment group was slower but the conversion ratio (feed/meat) was higher. Water hyacinths are also a traditional swine feed in tropical regions. Similar experiments have already been undertaken with water hyacinths from treatment plants, with quite positive results (Costa et al., 2000). Other uses of macrophytes are possible (insulation, supply of materials, energy). Moreover, worms and fish grew and reproduced.

CONCLUSIONS

The designed plant allowed continuous water recycling for more than a year, plant and earthworm growth and reproduction, pathogen and nutrient removal from the water, and organic matter production (fresh, as solid refuse from the diluted slurry, or mature, as vermicompost). Therefore it appears acceptable for further use and to be incorporated into new farming systems with improved nutrient efficiency.

Some nutrients such as K, Cu, and Zn were mostly assimilated by the plants and harvested, whereas others volatilized (C from respiration, N from nitrification/denitrification) or settled as sludge (P).

Further study of the use of organic matter production in agriculture or horticulture, and of the macrophytes (food or non-food uses) is still necessary to evaluate the economic feasibility of the development of such integrated systems beyond mere manure treatment and spreading.

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