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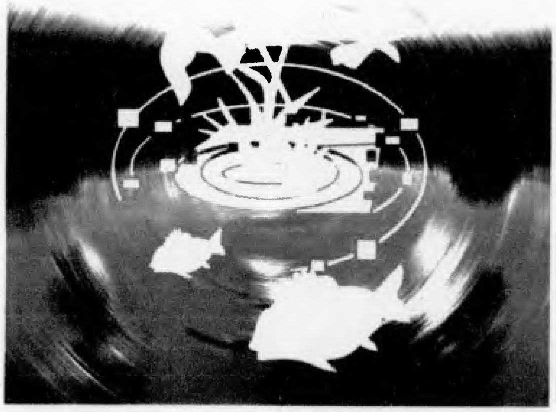

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Vermifiltration as a stage in reuse of swine wastewater: Monitoring methodology on an experimental farm

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ABSTRACT

Vermifiltration is a new technology using earthworms to process organically polluted water. A pilot associated with a swine facility (piggery) with 66 swine was developed to treat diluted manure, produce earthworms and vermicompost, and reduce air pollution. The aim of the experiment reported here was to devise an integrated method – biological, chemical and physical – for further research and development of vermifiltration in diluted swine manure, and provide some preliminary results. The earthworm population increased by 30% in 4 weeks, indicating the acclimation of the earthworms. A reduction in ammonia emission was observed of about 50% for the whole system. Higher water (+100%), carbon (+70%), and total nitrogen (+80%) gaseous losses were observed compared to conventional breeding on a slatted floor. This methodology can be used for further studies to develop vermifiltration for earthworm and vermicompost production from diluted animal manure, without pollution transfer.

1. Introduction

Animal farms use huge amounts of water and produce effluents that are generally spread on soils in Europe or directly released into rivers in some countries. Recycling of water is an essential factor in their economic and environmental improvement. Vermifiltration (or lumbrifiltration) is a new technology to process organically polluted water using earthworms. It was first advocated by the late Prof. Jose Toha at the University of Chile in 1992 (Aguilera, 2003; Bouché and Qiu, 1998). Worms and vermicompost can be sold to compensate for the cost of water treatment and reduce the amounts of manure spread on farm fields.

The benefits of earthworms in recycling liquid or solid organic residues have already been highlighted (for instance: White, 1996; Hertle et al., 2002; Sinha et al., 2002; Bajsa et al., 2003; Taylor et al., 2003; Bouché and Soto, 2004; Hughes et al., 2007). Vermicompost is the final product of organic wastes processed by earthworms. It improves the physical, chemical, and microbial properties of container media or

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soil, and stimulates plant growth (Kale et al., 1992; Sinha, 1997; Riggle, 1998; Szczech, 1999). Eastman et al. (2001) and Eastman (1996) observed that vermicompost could greatly reduce human pathogens in domestic wastewater sludge. Similar benefits may be expected when wastewater is filtered through a medium containing large numbers of earthworms. Earthworms were also regarded as bioindicators in ecotoxicity studies (Ferrière et al., 1981; Callahan, 1988; Bouché and Qiu, 1998).

Previous studies on vermifiltration only investigated the treatment's efficacy on water quality. However information on the population dynamics is also important to maximize the treatment capacity of the system. Moreover, the development of a new technology in agriculture should not increase the environmental impact. The control of gaseous emissions is therefore also important, since livestock production is a significant source of ammonia and greenhouse gases on the global scale.

However few, if any, studies of vermifiltration have been made with animal manure. In most regions with intensive livestock production, excessive releases of liquid and solid manure lead to water, soil, and air pollution. Therefore, a vermifiltration project was set up to process the wastewater from a swine facility (piggery), recycle the treated water to remove the manure by flushing, and improve the management of biosolids. Empirical development led to a design allowing continuous operation throughout the year.

The aim of the work reported in this paper is to describe an integrated method to study this vermifiltration system on two time scales: short-term changes for management purposes (earthworm population, gas emission), and long-term changes for environmental evaluation (mass balance of C, N, H_2O).

Fig. 1 – Photograph of the vermifilter.

2. Materials and methods

2.1. Experimental design and operation

Vermifilter design and management were developed empirically for 2 years before this experiment, using redox potential monitoring to avoid sprinkling with highly reduced water. All the details given below were found to be important for the continuous growth and reproduction of the earthworms throughout the year. The basic medium was a mixture of wood chips (one-third of total mass) and earthworm (*Eisenia andrei*) litter (two-thirds of total mass), the latter being the part containing most of the earthworms in the four vermifilters before this experiment. The wood chips and the litter contained 46 and 26% dry matter, 16 and 9.6% total carbon, 0.09 and 0.44% total nitrogen, 0 and 0.05% ammoniacal nitrogen, 0.01 and 0.19% total phosphorus, 0.05 and 0.14% total potassium, respectively. The litter was made of bark, wood chips, peat, straw, and vermicompost resulting from previous experiments to compare various materials and mixtures, and to calibrate the sprinkling schedule. Initial composition of the vermifilter is given in Table 1. The material was about 0.7 m high. It was supported by a slatted floor and a non-woven synthetic fabric (Fig. 1). Its surface was arranged into furrows and ridges so that the worms could inhabit the ridges when the water could not drain rapidly during sprinkling. Four vermifilters 5 m long × 2.5 m wide × 1 m high were placed in a room with natural ventilation.

The swine facility housed 66 growing-finishing swine with standard diet. It was mechanically ventilated and equipped with a flushing system under the slatted floor (Ramonet et al., 2007). It was flushed every 4 h using about 650 l from tank 4 (Fig. 2). Flushing removed the swine excreta. The diluted manure (wastewater = flushing liquid + excreta) was collected in tank 1. In this paper, 'excreta' means all outputs from swine metabolism and gut transit (e.g. urine or feces), while 'excretion' (or 'theoretical excretion' in Table 1) refers to ingestion minus swine growth and respiration (i.e. defecation, gas exhalation, and excretion *sensu stricto*).

Then, the diluted manure was put through a sieve to retain the coarsest suspended solids. After sieving, all the fresh liquid manure in tank 2 was sprinkled onto a vermifilter on 2 days per week to treat the wastewater and to feed the earthworms. The instantaneous and weekly sprinkling density were equivalent to 0.75 and 2.6 m^2 vermifilter/swine, respectively. In order to avoid water accumulation, the amount sprinkled was limited to 5 l m^{-2} per 10 min period. The amount sprinkled per vermifilter could not be adjusted exactly to the same value for all four vermifilters: it was about 20% higher for vf1 and vf2 than for vf3 and vf4. Maximum percolation rate

Table 1 – Total inputs and outputs of water, carbon, nitrogen, phosphorus, and potassium of the system during the whole experiment (all values are given in kg)

	Swine facility					Sieve				
	Swine		Food (+water)	Gas emission	Theoretical excretion	Solid refuse	% Excretion (solid refuse/ theoretical excretion)	Slurry	Water added to tank	% Excretion (slurry/ theoretical excretion)
	Initial	Final								
Weight	3939	6078	21717		7557	1520	20	9820	8542	17
Dry matter	2399	3495	5035	[a]	1335	233	17	254	0	19
Water	1540	2582	16682	12934	6222	1287	21	9566	8542	16
C	1199	1748	2445	1052	868	141	16	157	0[d]	18
N	99	153	134	11	80	8.2	10	31	0[d]	38
P	21	32	25	0[f]	14	1.8	13	6.3	0[d]	45
K	9	13	40	0[f]	36	3.0	8	13.7	0[d]	38

	Vermifilter + tank							Recovery (outputs as % inputs)
	Vermifilter		Added water	Tank after vermifilter	Gas emission (water)	Accumulation in vermifilter	% Excretion (loss or accumulation/ theoretical excretion)	
	Initial	Final						
Weight	20760	23846	7025	1769		−2171	[a]	[a]
Dry matter	7276	6559	0	16	[a]	−701	[a]	[a]
Water	13484	17287	7025	1753	2087	−1470	30[b]	100[c]
C	2698	2539	0[d]	7.9	103	−151	25[b]	91
N	57	53	0[d]	1.3	0.7[e]	−3	20[b]	89
P	21	22	0[d]	0.4	0[f]	2	12[g]	94
K	21	27	0[d]	1.4	0[f]	7	19[g]	83

[a] Gaseous emissions of dry matter are not estimated.

[b] Loss = (initial + 2/5 slurry − final − tank after vermifilter)/excretion; we assume that the losses of C and N from the tank after sieve (slurry) can be ignored (less than 10% of input).

[c] Recovery of water is 100% because the water deficit is used to calculate the C and N emissions from the vermifilter.

[d] Inputs of carbon, nitrogen, phosphorus, and potassium in the tap water are ignored.

[e] Of which around 10% was ammonia and 90% was nitrous oxide.

[f] Gaseous emissions of phosphorus and potassium are ignored.

[g] Accumulation = (final + tank after vermifilter − initial)/excretion.

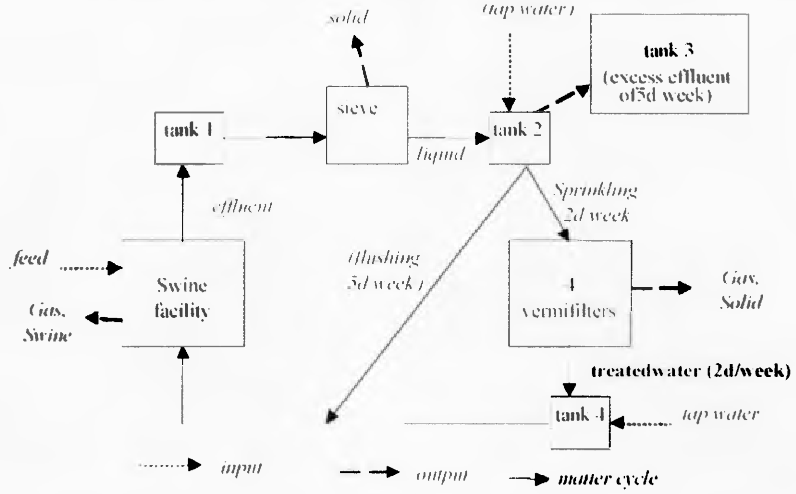

Fig. 2 – The structure and material recycling of the experimental system. The vermifilter was sprinkled 2 days per week and bypassed 5 days per week (italic characters = fluxes; normal characters = stocks).

was 0.4 l min^{-1} m^{-2}. The treated water was collected in tank 4 (Fig. 2) and then pumped to flush the swine facility so that the water was recycled. It was necessary to add tap water to tank 4 to have enough water for the flushing.

On the 5 days per week when the vermifilter was not sprinkled, the swine facility was flushed with the sieved effluent from tank 2. Tap water was added to tank 2 at the beginning of the 5 days period. This formed a cycle, bypassing the vermifilter. When tank 2 was full, the excess liquid flowed into a neighboring pit (tank 3). Before beginning the next 2 days' sprinkling of the vermifilter, tank 2 was emptied into tank 3 so that no old slurry could reach the vermifilter.

During the experiment, all the solids and liquids entering the system were stored. The food and water added in the swine soup (pigswill) were recorded by the food mixing system. All the tap water added manually in the tanks was recorded with a volumetric counter. The swine and the sieved solids were weighed each week.

The whole process was controlled automatically by a computer, and lasted 5 weeks.

2.2. *Solid and liquid sampling and analysis*

When filling the chambers with new materials and removing vermifilter material to the outside at the end of the experiment, wood pieces and litter with earthworms were randomly sampled. For each vermifilter, over 50 subsamples were taken to make one sample of *ca* 50 kg. These four vermifilter samples, gently mixed, were divided into small units for chemical analysis and dry matter measurements.

In addition, between the filling and emptying dates, vermifilters were sampled 1, 2 and 4 weeks after filling the four chambers. Each sampling was done at least 1 day after the end of sprinkling, using a stainless steel pipe sampler with a sharpened edge, allowing it to be pushed into the vermifilter materials manually. Its length was 1 m and its internal diameter 0.11 m, to limit damage to earthworms. We sampled 3 equidistant points in each ridge and each of the 4 inside furrows, totaling 27 samples per chamber, weighing around 40 kg. The sample depth was about 0.4 m. All the 27 samples were gently mixed and subdivided until small samples were obtained. This mixture was sampled again to fill six small plastic boxes and two bags, totaling about 6 kg. The remaining material was returned to the original chamber.

The material from one bag was chopped and used for chemical analysis, the other being stored in a deep freeze at −18 °C. Three small plastic boxes of samples were weighed and oven dried at 105 °C to measure the dry matter content. The other three boxes were weighed and used to count the earthworms (adults, sub-adults, juveniles and cocoons). All the worms taken out of each box were kept on moist paper towels at room temperature in the dark for 2 days to empty their gut content by defecation. Then the worms and cocoons were dried at 105 °C to measure their dry biomass.

The initial volume was not measured because negligible volume decrease during the experiment was initially expected. After the first week, before sampling, the volume of the vermifilter was estimated by measuring the level of each furrow and ridge at 5 places, totaling 45 points.

The liquids in the system were sampled at the beginning and end of the second sprinkling period to estimate the partitioning of the elements throughout the system: treated water before flushing (tank 4), diluted swine manure (tank 1), sieved effluent before flushing (tank 2), and treated water just out of vermifilter before tank 4. On these liquids, dry matter content was measured and chemical analysis was carried out. After 5 weeks, the volume of treated water was measured in tank 4 and the slurry in tank 3 was weighed. Both liquids were carefully sampled and stored in the deep freeze at −18 °C before analyzing.

The solid and liquid samples were analyzed for total nitrogen (TN, Kjeldahl method, NF EN 25 663), total phosphorus (TP, colorimetric assay after acid extraction of the ash, NF V18-106), total carbon (TC, CO_2 emission after acid treatment of the

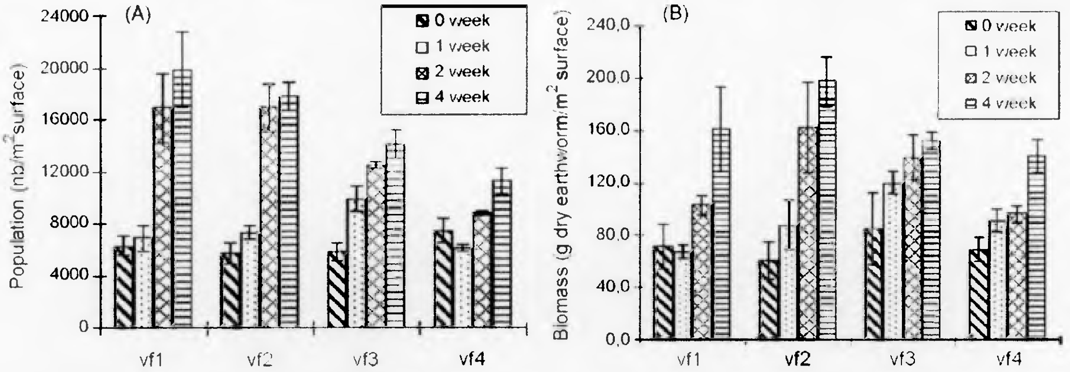

Fig. 3 – Earthworm abundance (A) and biomass (dry weight, B) in each vermifilter during the 4-week experiment. Values are means, bars are S.E., $n = 3$. The legends show sampling times. Each value at the beginning was significantly different from the value at 4 weeks in the same vermifilter ($p < 0.05$).

wet sample, NF ISO 10 693), total organic carbon (TOC, Anne method by chemical oxidation and spectrometry, NF ISO 14 235), total potassium (TK, atomic absorption after extraction of the ash, NF V18-106), ammoniacal nitrogen (NH_4-N, distillation after MgO addition to the wet sample). The composition of the swine food, as indicated by the manufacturer, is given in Table 1.

2.3. Air measurements

NH_3 and CO_2 were measured in the swine facility, vermifilter and outside air, using colorimetric tubes (Draeger™). Temperature and humidity were measured manually with a thermohygrometer (Testo). Nine days' measurements were used to characterize the 5-week experiment. N_2O was measured continuously in the swine facility and the vermifilter atmospheres with a photoacoustic spectrometer (Innova, 3426) during the last 3 weeks. The minimum concentration observed (0.33 ppm N_2O) was taken as the outside concentration to calculate the concentration gradient.

2.4. Data processing

Swine excretion was calculated as the difference between the food input and the gaseous outputs and swine live weight (Dourmad et al., 2002; CORPEN, 2003). The gaseous outputs were assumed to be only CO_2 and water vapor. CO_2 production was deduced from the total heat production, with a simple equation using the swine live weight (CIGR, 1984). Water vapor produced by the swine respiration was deduced from total heat production and a latent heat ratio of 45%. The metabolic water production was calculated from heat production, assuming 1 mol of water produced for 1 mol of CO_2.

The emission from the swine facility was calculated from concentration gradients and ventilation estimates (Phillips et al., 1998). The concentration gradient was deduced from the concentration measurements described above and the air density calculated from temperature and humidity measurements. The ventilation was calculated from the total heat produced by the swine and the enthalpy difference between inside and outside air. The sensible heat lost through the walls was calculated using $0.9\,W\,K^{-1}$ per swine as insulation coefficient of the building.

The emissions of CO_2, NH_3, and N_2O from the vermifilter were calculated assuming that all of the water deficit was due to evaporation by the vermifilter. In fact, water deficit corresponds to the difference between inputs (initial water + water additions), and outputs (final water in tanks + water in the swine and solid effluents + water vapor output of the swine facility). Then the ratios of the mean concentration gradients (inside – outside) of CO_2, NH_3, or N_2O to water were used to estimate the gas emissions. The concentration increase during the sprinkling periods was negligible when compared to the air humidity increase, so these periods were neglected.

All the values of chemical analysis and gas emission were used to calculate the deficit of the mass balance in the whole system and to evaluate the treatment efficiency of the vermifilter to the wastewater processing facility.

Microsoft Excel 2000 was used to carry out statistical analyses and to draw figures. The results were expressed as mean ± standard error and were analyzed by Student's t-test at a significance level of $P < 0.05$.

3. Results and discussion

3.1. Temperature and humidity in the vermifilter

The measured relative humidity in the sampled materials was 60–80%, considered ideal for earthworms. The air temperature varied between 16 and 30 °C above the vermifilter, between 23 and 30 °C inside the swine facility, and between 13 and 30 °C outside. We noticed that the vermifilter was warmer than the sprinkled water, suggesting that active composting occurred inside it. The rather high porosity of the material also allowed diffusion of gases, especially ingress of oxygen and release of carbon dioxide. The exothermic biotransformation inside the vermifilters induced a temperature increase, while sprinkling ensured moist conditions throughout the period and helped to prevent over-heating.

3.2. *Increase in earthworm population and biomass*

There was no accumulation of mud in the vermifilter material during the experiment, but dense small holes and numerous earthworm casts on the surface indicated intense earthworm activity. During sprinkling, earthworms can die within a few hours if either too much water or too much organic matter or anoxic liquid is added to the vermifilter. This was not observed. It shows that both the water and the organic matter inputs were neither excessive nor toxic during sprinkling, since earthworms have been used in standard tests of ecotoxicity (Ferrière et al., 1981; Callahan, 1988; Bouché and Qiu, 1998). Between the sprinkling periods, the living conditions were also suitable as indicated by the growth of the population and the biomass, and the numbers of cocoons and juveniles (Figs. 3 and 4).

Most of the studies on vermicompost or vermiculture have investigated the chemical changes in the substrate and the growth of individual earthworms under laboratory conditions, and few of them have recorded the dynamics of the earthworm population (Gunadi et al., 2003; Garg et al., 2005). On a pilot scale, working densities for particular vermicomposting systems have been reported to be between 1 and 4 kg earthworms (wet weight) per m^2 of bed (Frederickson and Ross-Smith, 2003).

The maximum number of earthworms at the end of our experiment was 11–20 $\times$ 10^3 worms m^{-2}, i.e. similar to the density in commercial breeding sites (Aguilera, 2003). The differences between two consecutive values were not always significant, but all the initial values were significantly different from the values at 4 weeks in the same vermifilter. The observed increase in earthworm population indicated that living conditions were suitable, and enough nutrients were supplied to the vermifilter.

The maximum wet weight at the end of the experiment was between 1 and 1.5 kg m^{-2}, and the corresponding dry weight was between 140 and 197 g m^{-2}. This showed indirectly that the earthworms did not escape from the sampling area to the sides or bottom of the vermifilters. The increase in biomass ranged from 79% in vf3 to 225% in vf2 after 4 weeks and the average value for the 4 vermifilters was 130%. This increase of 1.3-fold within 1 month was in the same range as in previous studies (Frederickson and Ross-Smith, 2003).

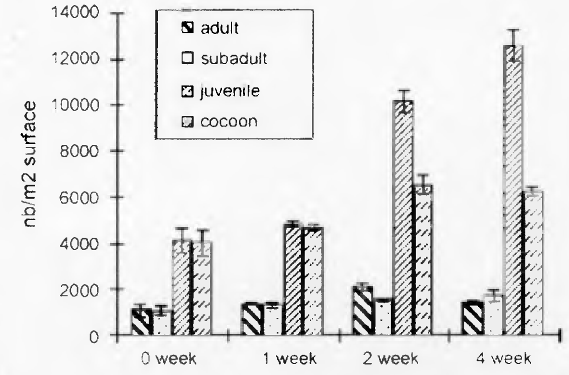

Fig. 4 – Average abundance of adults, sub-adults, juveniles and cocoons for the four vermifilters during the 4-week experiment. Values are means, bars are S.E., *n* = 4. The legends show earthworms at different life stages.

The biomass and abundance increases were higher in vermifilter vf1 and vf2 than in vf3 and vf4. This could be related to the control of the amount of sprinkled slurry, which was about 20% higher for vf1 and vf2. It indicated that more liquid manure could be applied. These increases not only strengthen the capacity of vermifilter to treat the organic pollutant in the effluent and to produce earthworms and vermicompost, but also is an integrated bioindicator to monitor experimental conditions. Therefore the system design, the effluent quality, the sprinkling program, the earthworm abundance, and the vermifilter material in this study were adequate.

3.3. *Cocoon and juvenile production*

The main group contributing to the population increase was the juveniles. Significant differences between juvenile abundance at 1, 2, and 4 weeks (Fig. 4) did not induce similar differences in adult populations because it takes more than a month for a juvenile hatched from a cocoon to become adult. The adult can produce 1 cocoon between 1.5 and 5.5 days and 1 cocoon can hatch into 4–5 juveniles between 14 and 28 days (Fayolle, 1982), depending on local abiotic conditions.

The data for cocoons were not as regular as for general worm abundance and biomass (Figs. 3 and 4). The average cocoon abundance during the whole experiment was 4.7, 4.7, 6.5, and 6.1 $\times$ 10^3 individuals m^{-2} for vermifilters 1–4, respectively. The highest mean number of cocoons produced per earthworm was 8.1 $\pm$ 2.8, and the overall mean value for the four vermifilters was about 3.7 $\pm$ 1.2. Previous studies indicated from 1.9 to 2.9, in cattle and swine manure solids (Gunadi et al., 2003), or 6.8–12.4 cocoons/earthworm between the 3rd and 11th week of vermicomposting of solid textile mill sludge mixed with farm manure (Kaushik and Garg, 2004). The values of cocoon numbers per earthworm in the present study were similar to those previous results, suggesting that the microclimate in the material was suitable for cocoon production, and the fecundity of the earthworms was not reduced.

There was no significant change in the four vermifilters, except in vf2 after 1 week and in vf3 after 4 weeks. These less regular results for cocoons than for earthworms may be explained by the immobility of cocoons and a higher spatial heterogeneity of cocoon deposition compared to the distribution of mobile life stages.

In the present study, the biomass (wet weight) should continue to increase because the new cohorts of juveniles will grow until the adult stage, while lifespans of up to 216 weeks have been observed for *E. andrei* in favorable conditions (Cluzeau, 1992). High earthworm densities would limit earthworm multiplication (Frederickson and Ross-Smith, 2003).

3.4. *Effect of water reuse on pollutant concentrations*

When the liquids passed the vermifilter, organic matter and minerals were retained by the vermifilter materials. The observed decreases in the concentrations were roughly: dry matter, 40%; organic matter, 50%; NH_4-N, 60%; total nitrogen, 50%; total phosphorus, 30%; organic carbon, 50%; inorganic carbon, 60%. Potassium concentration was almost unchanged.

Table 2 – The pollutants in input and output water of the vermifilter

	C total ($kg\,m^{-3}$)	Organic matter (%)	NH_4-N ($kg\,m^{-3}$)	N organic ($kg\,m^{-3}$)	N total ($kg\,m^{-3}$)	P ($kg\,m^{-3}$)	K ($kg\,m^{-3}$)
Effluent after sieving[a]	5.6	68	0.52	0.40	0.82	0.21	0.79
Water in tank after vermifilter at the end	3.2	52	0.08	0.06	0.14	0.08	0.36

[a] Average of two values during the second week.

These reductions were smaller than in previous results (Bouché and Soto, 2004).

Despite the reuse of the wastewater and the collection of swine excreta, the concentration of pollutant in the water in the tank after vermifiltering at the end of the experiment remained lower than that of the liquid after sieving (Table 2).

Ammonia was removed from the liquid through rapid adsorption on organic matter after sprinkling, and progressive organization by the biomass. This removal of ammonia was no doubt the cause of the significant decrease (around 50%) in the ammonia emission from the building. The odor in the effluent was removed as it passed through the vermifilter.

Compared to the customary output from water treatment systems, the concentrations in the recycled water were high, but they are acceptable for recycling the water inside the swine facility because odors and ammonia are strongly reduced, and because we observed no health impact during 4 years' trials. To improve the wastewater quality, a further treatment with macrophyte lagooning was added after the vermifilter (Morand et al., 2005; Hamon et al., 2006). It was designed to increase not only nutrient reduction and biomass production (Gumbricht, 1993; Greenway, 2005; Bojcevska and Tonderski, 2007), but also retention time (Tashiro et al., 2003; Kreuzinger et al., 2004), and to accumulate rainwater to compensate for the evaporation of the vermifilter and the swine facility.

3.5. *Mass balance shows further abatement between sprinkling events*

The mass balance of the vermifilters results from biological, physical and chemical reactions, including the adsorption of molecules and ions, oxidation–reduction of organic matter, the behavior of earthworms and their synergetic effects with microorganisms (Bouché and Soto, 2004).

The calculated mass balance of all the substances put into and taken out of the experimental system gives rise to a loss of matter which is greater than the input through sprinkling (Table 1).

The recovery of C, N, P, K ranged from 83 to 91%, which validates the integrated method to sample solids and liquids, as well as the methods to measure the gas emissions.

The volumes of material fell clearly in all four vermifilters by 13–16% (Fig. 5). This is the result of active composting inside the vermifilter.

The losses of C, N, and dry matter were far above the error level of 5%. The minimum inputs to the vermifilter can be estimated as 2/5 of the mass found in the slurry (2 days sprinkling the vermifilter; 5 days output to slurry tank 3). Therefore, they can be estimated at about 100, 60, 10, 3, 5 kg for dry matter, C, N, P, and K, respectively. With these values, the mass balance of P and K in the vermifilter is within 5% of its theoretical value. It shows that the possible error, due to sampling and analyzing the solids, is acceptable for using this methodology on a farm scale.

3.6. *Increased water, carbon, and nitrogen volatilization*

The amount of water evaporated by the system was large in relation to the inputs (90% of the water added with the food). This can be related to the flushing system used and the vermifilter. Most of the evaporation occurred in the swine facility. Compared to a conventional slatted-floor system, evaporation increased by around 50% of the water in excreta. Only 13% of the water added with the food was evaporated by the vermifilter, corresponding to 30% of the water in excreta.

The mass of C lost from the vermifilter can be estimated from the C measured in the solids and from the CO_2 measured in the air. This second estimate is around 100 kg (Table 1). It confirms that the loss is higher than the theoretical input, but it is half of that estimated from the solid analysis (around 200 kg). This difference can be explained by the experiment's short duration: the inputs and outputs of the pilot are close to the initial and final stocks in the swine facility and in the vermifilter. The emissions from the vermifilter are low compared to its initial and final stocks, so an error of 5% in the estimated initial and final stocks can induce a large error in the mass deficit.

The ammonia emission of the system was less than that of a standard slatted-floor breeding system. French swine facilities are thought to emit around 20% of excreted nitrogen as ammonia (CORPEN, 2003). In the present pilot, the emission from the building was around 10% of excreted nitrogen, while emission from the vermifilter was less than 1%. Even if a high error on the emission is assumed (cf. C emission), the ammonia emission of the vermifilter is very low. The nitrous oxide emission from the vermifilter was higher than its ammonia emission but it was also less than 1% of the excreted nitro-

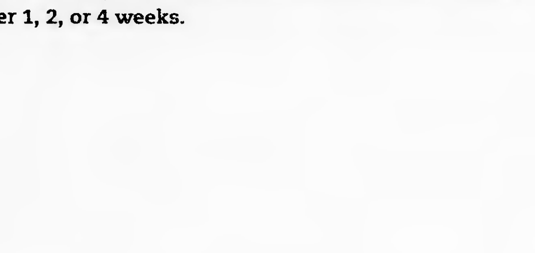

Fig. 5 – Changes of volume of materials in four vermifilters after 1, 2, or 4 weeks.

gen. This indicates that nitrification–denitrification occurred within the vermifilter.

As nitrogen did not accumulate in the vermifilter (Table 1), and ammonia and nitrous oxide emissions remained low, most of nitrogen loss was assumed to be as N_2 and thus not transferred into other polluting phases (solid or gas). This result also implies that the sprinkled quantity of liquid manure in this study did not compensate for the nitrogen consumed by the earthworms and the microorganisms. Therefore, an increase in the organic load to the vermifilter is possible (between 1 and 2 m^2 vermifilter/finishing swine). The vermifilter can be further used to recycle the water in the swine facility without pollution transfer.

3.7. *Accumulation of P and K added with the diluted swine effluent*

P and K accumulated in the vermifilter by around 10–20%. This result was close to those of former studies involving P and using vermifilters to treat municipal wastewater (Aguilera, 2003; Bouché and Soto, 2004). The vermifilter can retain some P initially and thus decrease the P content of the effluent. When the P content in the vermifilter increases, so does the release of P, and the filtering efficiency for P reaches equilibrium. For P and K, this experiment was too short to observe saturation. The vermifilter material should be changed when the material is saturated, and the compost could be used as P and K fertilizer on the farm.

3.8. *Design and management of vermifiltration for diluted swine manure*

About 30% of the water, 25% of the C and 20% of the N from the excretion was lost as gases in the vermifilter for the whole experimental period (Table 1). The vermifilter removed about 85% of the C and 65% of the N in the swine excretion (related to 2 seventh of total excretion because of 2 days/week sprinkling). The losses would exceed the excretion with 0.4 swine m^{-2} vermifilter, based on 2 days' sprinkling per week with the sieved slurry. The C and N lost from the vermifilter corresponded to 116 g C m^{-2}, and 8 g N m^{-2}. Without the sieve, the treatment capacity would be about 0.30 swine m^{-2} on the basis of total C excreted, and about 0.25 swine m^{-2}, on the basis of total N excreted.

For practical use of vermifilters on swine farms, the sprinkling program and vermifilter surface area should be adapted to maintain a moderate temperature and humidity in the vermifilter material. Discontinuous sprinkling or omission of effluent sieving can be used to adjust to gaseous losses of C and N.

The design and management of the vermifilter can influence the water evaporation. If the frequency of sprinkling increases, then the relative duration of the evaporation periods will decrease. Alternatively, if the area of the vermifilter increases, the evaporation will increase. Increased evaporation reduces the cost of transporting the vermicompost.

The addition of wood chips contributed to the supply of C to the metabolism in the vermifilter and to maintain the porosity for water circulation and gas diffusion. The wood chips should be added before the cold season to improve temperature conditions inside the vermifilter.

The observation of dead or escaped earthworms is a simple bioindicator to manage the nutrient load of the system. Fewer worms will increase the risk of excessive organic input, which may lead to the death of worms by anaerobiosis in the vermifilter. If the nutrient supply is lower than the needs of the population, or if humidity is too low, some worms will escape and the population will not increase, reducing the efficacy of the system.

4. Conclusion

Vermifiltration can be used to treat diluted swine manure. The wastewater can be reused to flush the manure, inducing a reduction in ammonia emissions compared to rearing on a slatted floor with slurry accumulation. Vermifiltration also resulted in higher volatilization of water, carbon, and nitrogen, reducing transportation costs.

An integrated methodology was developed to study vermifiltration in a swine facility. It can be applied on a farm. It deals with water treatment and gas emissions in order to avoid the possibility of pollution transfer through treatment. It shows that when recycling the water, the treatment capacity cannot be evaluated simply from the difference between input and output. The integrated mass balance should also be used because of the progressive accumulation or loss of matter in the water tanks and vermifilter materials.

It was important to know the dynamics of the earthworm populations during the vermifiltration. These were not only related to the treatment capacity but also were a bioindicator of the experimental conditions and perhaps of pollutant input. The earthworm behavior and demographic parameters can be used as bioindicators to manage the nutrient input to the system and to maintain, for example, a low level of ammonia emissions.

Water is now an important factor in the management of swine manure, with frequent removal by flushing. In order to avoid excessive economic and ecological costs, the water excreted by the swine can be reused to flush the manure. The amount of water needed would decrease with continuous use of the vermifilter, because much of it is evaporated either due to the flushing system design or due to biological activity heating the vermifilter. Reuse of the water can include the construction of a water treatment plant using macrophytes for further nutrient exportation. The collected solids from the sieve and the vermifilter can be used as organic fertilizer or recomposted. Other outputs from another extensive treatment plant, like macrophyte lagooning, could bring added value to the system.

A longer experiment is needed to assess the limitations of the system before using it on a commercial farm.

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