

# Nitrification, denitrification and biological phosphorus removal in piggery wastewater using a sequencing batch reactor

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## Abstract

Nutrients in piggery wastewater with high organic matter, nitrogen (N) and phosphorus (P) content were biologically removed in a sequencing batch reactor (SBR) with anaerobic, aerobic and anoxic stages.

The SBR was operated with 3 cycles/day, temperature 30 °C, sludge retention time (SRT) 1 day and hydraulic retention time (HRT) 11 days. With a wastewater containing 1500 mg/l ammonium and 144 mg/l phosphate, a removal efficiency of 99.7% for nitrogen and 97.3% for phosphate was obtained.

Experiments set up to evaluate the effect of temperature on the process showed that it should be run at temperatures higher than 16 °C to obtain good removals (>95%).

Batch tests (ammonia utilization rate, nitrogen utilization rate and oxygen utilization rate) proved to be good tools to evaluate heterotrophic and autotrophic biomass activity.

The SBR proved to be a very flexible tool, and was particularly suitable for the treatment of piggery wastewater, characterized by high nutrient content and by frequent changes in composition and therefore affecting process conditions.

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## 1. Introduction

In many areas of Europe, the disposal of piggery wastewater poses a considerable problem for farmers (Oleszkiewicz and Sparling, 1987). This is basically due to the high concentration of pigs in a very limited area.

Pig manure has considerable amounts of non-stabilized organic matter and high concentrations of ammonia which can reach values around 8000 mg NH<sub>4</sub><sup>+</sup>-N, depending on the characteristics of the farm (Bernet et al., 1996; Coillard, 1999). The presence of nitrogen in wastewater discharge is undesirable for several reasons (Sedlak, 1991). Free ammonia is toxic to fish and many other aquatic organisms; moreover, both ammonium ion and ammonia are oxygen-consuming compounds which de-

plete the dissolved oxygen in receiving water. In addition, all forms of nitrogen can be made available to aquatic plants and can consequently contribute to eutrophication. Furthermore, the presence of nitrite and nitrate ions in drinking water is a potential public health hazard.

Thus removal of all forms of nitrogen is required. This can be achieved economically in biological treatment systems. Many studies have been carried out on the biological removal of carbon, nitrogen and phosphorus; however, few have addressed wastewaters with high concentrations of these compounds, such as piggery wastes (Bortone et al., 1992; Ra et al., 2000). The carbon content of pig manure can be initially treated with anaerobic digestion. However, the effluent of the anaerobic digester contains high amounts of nitrogen, most in the form of ammonia, and also some phosphorus. The most common and efficient method used to remove ammonia from wastewater is the biological nitrification–denitrification process (Cooper et al., 1994). Biological phosphorus removal involves the design or operational modification of conventional treatment

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systems that results in the growth of a biological population with a high cellular phosphorus content. Such systems incorporate an anaerobic operating phase, and the overall phosphorus content of waste sludge is typically in a relatively high range of 3–6% of total solids (TS). Therefore more phosphorus is diverted to waste solids and lower effluent phosphorus concentrations are attained (Sedlak, 1991).

To remove nutrients in one stage, a sequencing batch reactor (SBR) can be used either to treat the liquid fraction of pig manure or the effluent of anaerobic digesters (Tilche et al., 1999). The SBR performs well with respect to standard wastewater criteria for the removal of organic carbon, nitrogen and phosphate. In this kind of system, microbial population composition is sensitive to operational control of the batch sequence (Bortone et al., 1992; Irvine et al., 1997).

The basic aim of the study presented here was to evaluate the possibilities of a SBR to treat anaerobically digested piggery wastewater containing high  $\text{NH}_4^+\text{-N}$  concentration and to establish the removal limits of the system. Once these limits were established, the second objective was to study the effect of temperature on the nutrient removal yields. Presumably, low temperatures can be the bottleneck for practical application of this kind of treatment.

Up to now, the main experiments found in literature with piggery wastewaters have been studied at relatively low concentrations of  $\text{NH}_4^+\text{-N}$ . In any case, these concentrations do not reach values as high as the one studied in this paper (Bortone et al., 1992; Baozhem et al., 1996; Brustia et al., 1996; Kantawanichkul et al., 1999; Tilche et al., 1999; Bernet et al., 2000; Edgerton et al., 2000; Kalyuzhnyi et al., 2000; Ra et al., 2000; Westerman et al., 2000). This is of special relevance because nitrification at very large  $\text{NH}_4^+\text{-N}$  concentrations can be critical as toxicity problems may appear.

Another objective was to provide indirect data on microbial population through the ammonia utilization rate (AUR), nitrogen utilization rate (NUR) and oxygen utilization rate (OUR) parameters and to assess their effectiveness as monitoring parameters of the process.

## 2. Methods

### 2.1. Substrate

Swine wastewater was obtained from a piggery located in Caldes de Montbui, 30 km from Barcelona. It had been treated in an industrial anaerobic digester, located on the farm. The effluent from the digester was centrifuged (centrifuge Beckman model J2-21) at 4000 rpm, for 15 min at 5 °C, to remove most of the suspended solids. The supernatant was used as substrate for the experiments. Previous to being fed in the reactor,

Table 1  
Characterisation of the piggery wastewater supernatant after centrifugation

Parameters	Average	No. of analyses
pH	8.4	–
TS (g/l)	11.21	5
VS (g/l)	5.35	5
TSS (g/l)	2.58	5
VSS (g/l)	1.96	5
BOD <sub>5</sub> (mg/l)	1730	4
COD (mg/l)	3969	8
Alkal <sub>7.74</sub> (mg/l)	1183	5
Alkal <sub>3.53</sub> (mg/l)	5226	5
Total N (mg/l)	1700	8
$\text{NH}_4^+\text{-N}$ (mg/l)	1650	6
$\text{NO}_3^-\text{-N}$ (mg/l)	0	6
$\text{NO}_2^-\text{-N}$ (mg/l)	0	6
$\text{PO}_4^{3-}\text{-P}$ (mg/l)	147	6
P (mg/l)	171	5
K (mg/l)	2130	5
Na (mg/l)	379	5
Ca (mg/l)	126	5
S (mg/l)	109	5
Zn (mg/l)	8.44	5
Mg (mg/l)	7.85	5
Fe (mg/l)	6.27	5
Cu (mg/l)	4.87	5
Mn (mg/l)	0.26	5
Ni (mg/l)	0.21	5
Cd (mg/l)	0.061	5
Pb (mg/l)	0.040	5
Cr (mg/l)	0.016	5
V (mg/l)	0.007	5

this supernatant was diluted with tap water to the desired concentration. Table 1 shows the characteristics of the supernatant.

### 2.2. Experimental device

The reactor was a cylindrical tank with a volume of 3 l; it was made of Pyrex glass and provided with mixing and air sparging systems (Fig. 1). It was complemented by two peristaltic pumps (Cole Parmer Instrument, Model number 7553-85, Chicago), one for feeding, the other for drawing off effluent and excess sludge. The SBR operation cycles were controlled by programmable timers.

A data acquisition system (model CRISON pHrocon 18, Barcelona) was used for the continuous recording of the mixed liquor temperature, pH and oxidation–reduction potential (ORP). Optimum pH was fixed at 8.1. A higher pH was corrected by mechanical addition of hydrochloric acid HCl (0.5 N).

### 2.3. Operational conditions

#### 2.3.1. Study of maximum $\text{NH}_4^+\text{-N}$ removal

Start-up of the reactor was carried out using activated sludge from a wastewater treatment plant and diluted 1:10 piggery-digester-effluent supernatant.

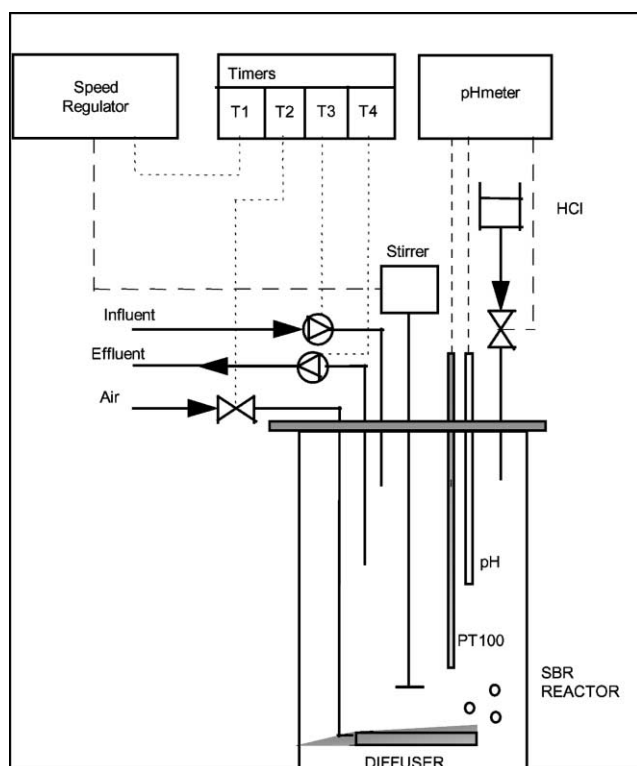


Fig. 1. Diagram of the SBR.

In order to study the maximum removal yield of  $\text{NH}_4^+\text{-N}$ , three experiments (P1, P2 and P3), each one with different concentrations of ammonia, were set up. A scheme of the SBR operation together with initial values for  $\text{NH}_4^+\text{-N}$  concentration and other parameters is presented in Fig. 2 and Table 2.

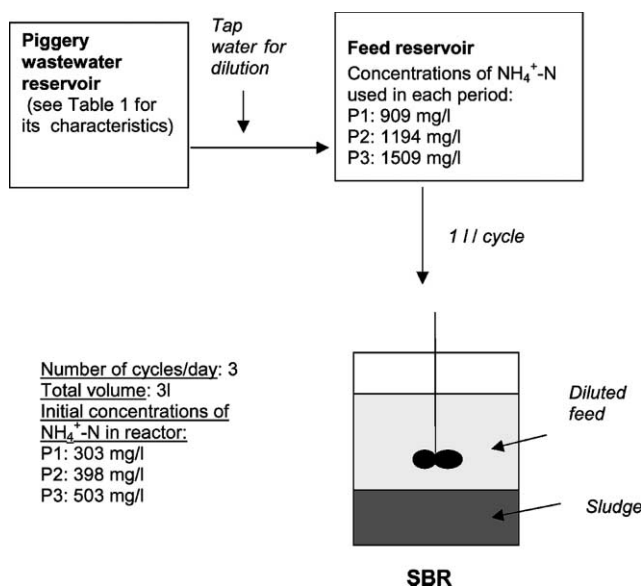


Fig. 2. Scheme of the SBR operation. Each cycle was fed with 1 l of diluted substrate after the removal of 1 l of reactor supernatant content. In each cycle the N was removed completely.

Table 2

Values of different parameters at the beginning of the cycle for the four experimental periods (analytical values represent the average of 10 analyses)

Experiments	P1	P2	P3	P4
<b>Parameters</b>				
<i>Feed reservoir concentration</i>				
$\text{NH}_4^+\text{-N}$ (mg/l)	909	1194	1509	1650
$\text{PO}_4^{3-}\text{-P}$ (mg/l)	88.7	117.3	144	150
COD (mg/l)	2255	2962	3744	3970
<i>Reactor initial values</i>				
$\text{NH}_4^+\text{-N}$ (mg/l)	303	400	502	550
$\text{PO}_4^{3-}\text{-P}$ (mg/l)	29.5	39.1	49.4	55.9
COD (mg/l)	767	1010	1260	1325
TS (g/l)	3.62	5.68	10.5	12.8
VS (g/l)	2.44	3.66	5.01	6.03
TSS (g/l)	2.16	3.39	2.42	3.65
VSS (g/l)	1.75	2.73	1.83	2.89
pH	8.15	8.24	8.32	8.35

Other parameters: the same for all the experiments; HRT: 1 day; SRT: 11 days; cycle/day: 3; temperature: 30 °C.

The experiments P1, P2 and P3 were carried out at 30 °C (estimated as the actual temperature of the digester effluent after centrifugation in a full-scale plant).

On the basis of results from a previous study (not shown) and those obtained by other authors (Tilche et al., 1999; Ra et al., 2000), SBR was operated (in all the experiments) by three 8-h-cycles per day. In the same way, hydraulic retention time (HRT) and sludge retention time (SRT) were fixed at 1 day and 11 days respectively, in accordance with Bortone et al. (1994).

The 8-h cycle began with an anaerobic stage of 2 h for phosphorus removal: the reactor was stirred but not aerated.

Between the second and the sixth hour of the cycle there was an aerobic stage for nitrification with stirring and aeration.

The sixth hour was anoxic (with stirring but no aeration, in order to allow denitrification). Denitrification needs an available and easily biodegradable C-source as an electron donor. Since the nitrified liquor remaining in the SBR at the sixth hour was deficient in organic carbon, an external organic carbon source (acetic acid) was provided. Concentrations of acetic acid added in each experiment were respectively 1275 mg/l (P1), 1700 mg/l (P2) and 2125 mg/l (P3) (stoichiometric values with respect to  $\text{NO}_x\text{-N}$  concentrations in each period).

After 7 h, the sludge was drawn, with stirring and aeration to assure an homogeneous purge over this step. In this way, SRT (or sludge age) was kept constant and equal to 11 days over all the experiments. The solids then settled and liquid was drawn (approximately 1/3 of the reactor supernatant in each cycle) in order to maintain an HRT of 1 day. Then a new cycle started.

### 2.3.2. Study of the temperature effect

Another set of experiments were carried out, using the same operational conditions of P3. The following temperatures were tested: 8, 10, 12, 14, 16, 18, 20, 22, 25 and 30 °C to determine the effect of this parameter on  $\text{NH}_4^+$ -N removal yield. Temperature was maintained at the desired level ( $\pm 0.05$ ) by means of a thermostatic RM6 Lauda.

### 2.4. Characterization of sludges

After achieving steady-state conditions in each experiment, the sludge remaining in the SBR was characterised by determining the specific utilization rates of ammonia (AUR), nitrate (NUR) and oxygen (OUR) (Kristensen et al., 1992).

To determine the AUR, sludge from the SBR and tap water were mixed in 250-ml-batch-reactors, so that the concentration of suspended solids in the mixed liquor ranged around 3–4 g/l. The liquor was kept in suspension by aeration through diffusers, which also provided the sludge with oxygen at a concentration of 6–8 mg  $\text{O}_2$ /l. Ammonia was added to an initial concentration of 100 mg N/l. Samples of 3 ml of mixed liquor were drawn off at 10-min intervals for 3 h. These samples were immediately filtered and analysed for ammonia nitrogen. The AUR was calculated from the slope of the resulting ammonium consumption curve.

The NUR was determined by the use of completely mixed 250-ml-batch-reactors in a closed atmosphere. Sludge from the SBR and tap water were mixed in the reactors to obtain a concentration of suspended solids in the range of 3–4 g/l. Nitrate was added to reach a concentration of 50 mg/l. Samples of 3 ml were drawn off every 10 min for 3 h. During this operation, nitrogen gas was added in order to prevent oxygen from entering the reactors. Samples were pre-treated as in the AUR determination and nitrate plus nitrite nitrogen was determined. The NUR was calculated from the slope of the resulting nitrate plus nitrite utilisation curve.

To determine OUR, sludge from the SBR and tap water were mixed to a concentration of suspended solids of around 2–3 g/l in a 250-ml-batch-reactor. Acetate was added at a concentration of 200 mg/l as COD. Nitrification was inhibited by the addition of 12 mg/l of allylthiourea. The batch was aerated to have an initial concentration of around 8 mg  $\text{O}_2$ /l. Oxygen utilisation was measured by introducing an oxygen probe into the flask. The OUR was calculated from the slope of the resulting oxygen utilisation curve.

### 2.5. Analytical methods

Analyses of chemical oxygen demand (COD), biochemical oxygen demand ( $\text{BOD}_5$ ), alkalinity, total nitrogen and solids (total suspended solids (TSS), volatile

suspended solids (VSS), total solids (TS) and volatile solids (VS)) were performed following standard methods (APHA, 1992).

Nitrogen compounds, nitrates, nitrites and phosphates were analysed with an ionic chromatograph (KONIK model KNK-500-A Series, column Waters IC. Pak) under the following conditions: automatic injector (Kontron model HPLC autosampler 465), volume sample 80  $\mu\text{l}$ , conductivity detector (Wescan) for concentrations between 2 and 50 mg/l and UV detector (Kontron HPLC 332), for low concentrations (0.1–2 mg/l).

Ammonium was determined by an ammonia specific electrode (Crison, model pH 2002, Barcelona).

Acetic acid was analysed by gas chromatography (HP 5890 Series II, flame ionisation detector) under the following conditions: column from 120 to 170 °C, injector at 280 °C, detector at 300 °C and volume sample 1  $\mu\text{l}$ . Helium was employed as carrier gas.

Total organic carbon (TOC) concentration was determined by analysing centrifuged samples (10,000 g, 10 min) in a TOC analyser (Dohrman model DC 190 ASM, Santa Clara).

Oxygen was measured by an oxygen meter YSI model 51B Series 5696 equipped with an oxygen probe.

Metals were analysed by ICP-MS (inductively coupled plasma-mass spectrometry) (two units were used: model Elan-6000 and model Optima 3200-RL, both from Perkin Elmer).

Samples were centrifuged at 10,000 rpm for 10 min and filtered through 0.45  $\mu\text{m}$  paper filters to remove suspended solids prior to being fed to the chromatographic columns and to the TOC analyzer.

## 3. Results and discussion

### 3.1. SBR experiments to determine the maximum $\text{NH}_4^+$ -N load

In order to establish the maximum  $\text{NH}_4^+$ -N concentration that could be removed in a SBR, a initial series of three experiments were carried out at the conditions shown in Table 2.

Figs. 3–5 show the profiles of the most important parameters during the complete cycle in the experiments P1, P2 and P3, respectively. Figs. 3(A), 4(A) and 5(A) show the trend of nitrogen compounds in these three periods which were quite similar: in the anaerobic stage (first 2 h), there was almost no change in the concentrations of nitrogen compounds. Afterwards, nitrification of  $\text{NH}_4^+$  to  $\text{NO}_3^-$  (temporarily to  $\text{NO}_2^-$  as intermediary metabolite) occurred for 4 h, in which nitrate increased constantly. After this aerobic stage, nearly all ammonium was nitrified to nitrate (final  $\text{NH}_4^+$ -N concentration <5 mg/l). Table 3 shows the

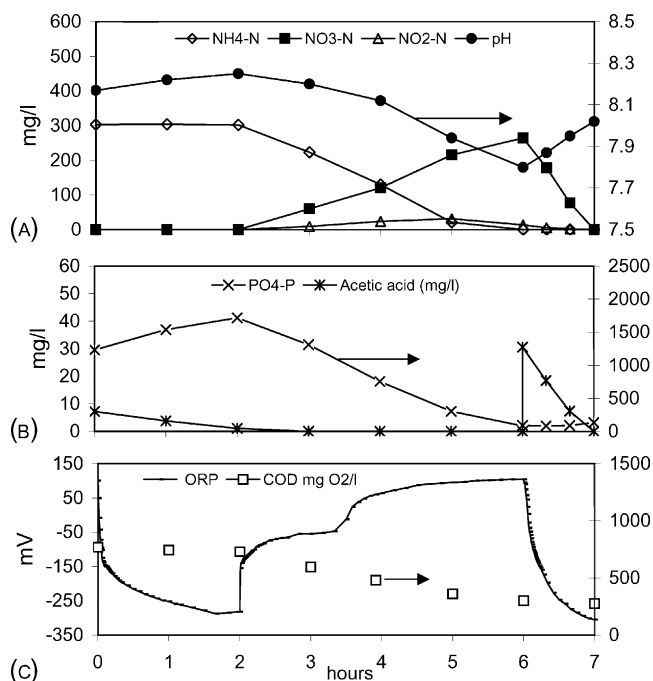


Fig. 3. Profiles of different parameters in a single cycle of the SBR operation during experiment P1.

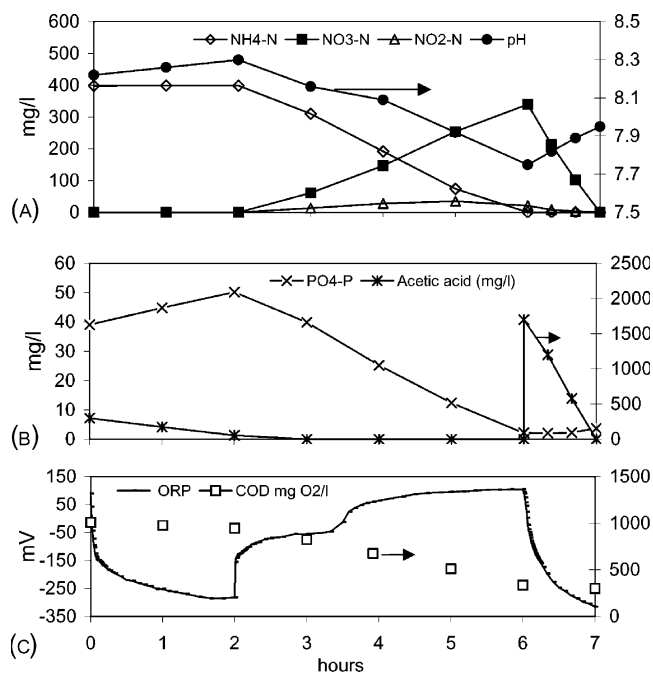


Fig. 4. Profiles of different parameters in a single cycle of the SBR operation during experiment P2.

average ammonium removal rates achieved for the three experiments P1, P2 and P3. In the following denitrifying anoxic stage of the three periods, nitrate was reduced to nitrogen gas. Table 3 also shows the average denitrification rates.

Operational conditions in experiment P3 point out the limit capacity of the SBR operated with this se-

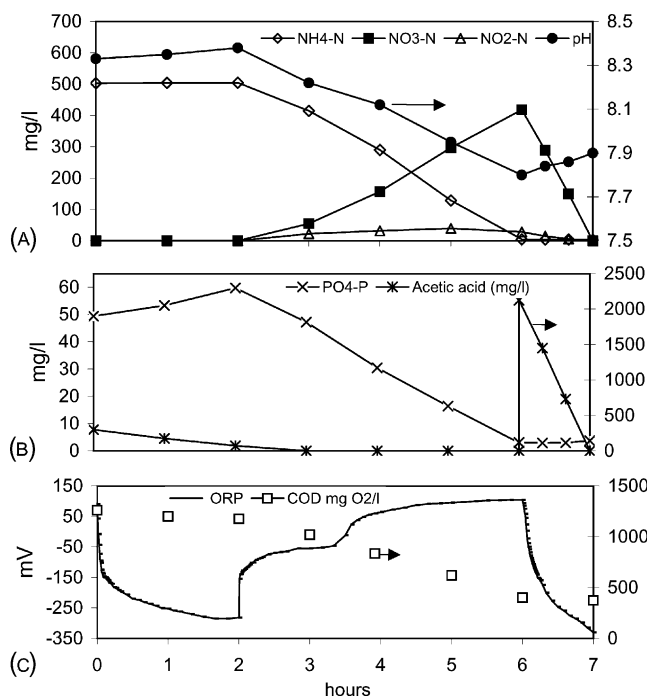


Fig. 5. Profiles of different parameters in a single cycle of the SBR operation during experiment P3.

quence mode. Indeed, when the initial reactor concentration of ammonium was higher than 500 mg/l, it was not removed completely. This was confirmed by an additional experiment P4 in which the initial reactor concentration of NH<sub>4</sub><sup>+</sup>-N was around 550 mg/l using an undiluted supernatant (see Table 2). At this initial concentration, the effluent NH<sub>4</sub><sup>+</sup>-N concentration was 50 mg/l at the end of the cycle (Fig. 6). Thus, in this period P4, although the percentage of nitrogen and phosphate removed was high, 96% and 95.8%, respectively, and was similar to the removal rates observed in previous periods, NH<sub>4</sub><sup>+</sup>-N was not completely eliminated (see Table 3). It should be added that the alkalinity in the reactor was high enough for nitrification (the alkalinity of the piggery wastewater in reservoir was 1590 mg/l, higher than the stoichiometric value). Nitrification may have been inhibited in this experiment because of the presence of ammonia or nitrous acid, since in the unionised form, these compounds are toxic. When the pH decreases (oxidation of ammonium) the concentration of free nitrous acid increases and with an initial NH<sub>4</sub><sup>+</sup>-N concentration greater than 500 mg/l, inhibition of *Nitrosomonas* and *Nitrobacter* may occur (Anthonisen et al., 1976; Ford, 1980; Brond and Sund, 1994). Nitrification could also have been inhibited by metals dissolved in the wastewater, but this was not the case because of the low concentrations of metals in this piggery wastewater (Table 1).

In the denitrification stage, an external organic carbon source is needed to remove all the NO<sub>x</sub>-N present in

Table 3

Average nutrient removal rates, values of AUR, NUR and OUR, and percentage of nutrient removals obtained during the four experiments

Parameters	Units	P1	P2	P3	P4
Ammonium removal rate	mg NH <sub>4</sub> <sup>+</sup> -N g VSS <sup>-1</sup> h <sup>-1</sup>	24.3	36.9	43.1	42.8
	mg NH <sub>4</sub> <sup>+</sup> -N l <sup>-1</sup> h <sup>-1</sup>	75.5	99.5	124.7	123.4
Nitrate removal rate	mg NO <sub>3</sub> <sup>-</sup> -N g VSS <sup>-1</sup> h <sup>-1</sup>	105.6	125.9	144.1	145.1
	mg NO <sub>3</sub> <sup>-</sup> -N l <sup>-1</sup> h <sup>-1</sup>	264.2	345.0	418.0	420.0
Phosphate removal rate	mg PO <sub>4</sub> <sup>3-</sup> -P g VSS <sup>-1</sup> h <sup>-1</sup>	3.9	4.4	4.9	5.1
	mg PO <sub>4</sub> <sup>3-</sup> -P l <sup>-1</sup> h <sup>-1</sup>	9.8	12.0	14.2	15.3
AUR	mg NH <sub>4</sub> <sup>+</sup> -N g VSS <sup>-1</sup> h <sup>-1</sup>	27.5	28.4	30.2	30.1
NUR	mg NO <sub>3</sub> <sup>-</sup> -N g VSS <sup>-1</sup> h <sup>-1</sup>	31.1	34.2	37.4	37.7
OUR	mg O <sub>2</sub> g VSS <sup>-1</sup> min <sup>-1</sup>	1.7	2.8	3.5	3.6
Ammonium removal	%	99.7	98.7	99.7	96.9
Nitrate removal	%	99.9	99.8	99.9	99.9
Phosphate removal	%	97.8	97.5	97.3	94.8
COD removal	%	64.1	70.3	70.2	69.1

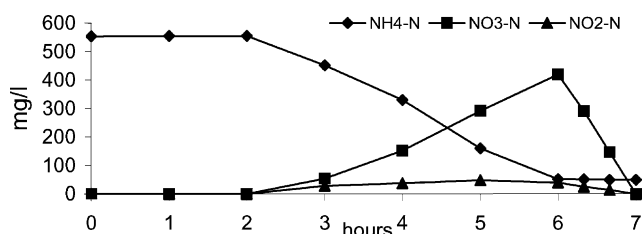


Fig. 6. Profiles of different parameters in a single cycle of the SBR operation during experiment P4.

the reactor after nitrification. Thus, acetic acid was added after the sixth hour because of the lack of available organic carbon in the feed for proper denitrification (see profiles in Figs. 3(B), 4(B) and 5(B)). The ratio of biodegradable carbon/nitrogen (C/N) is a key value for this process. In P1, P2 and P3, complete denitrification was obtained when this ratio was higher than 1.7 (C-acetic (g/l)/NO<sub>x</sub>-N (g/l)), which is in agreement with the values used by Bernet et al. (1996) and also with the basic stoichiometry of the denitrification reaction (Sedlak, 1991).

Figs. 3(B), 4(B) and 5(B) also show the concentrations of phosphate during one reaction cycle. The increase of soluble phosphorus concentration during the anaerobic stage of the three experiments was the result of phosphate release by species of *Acinetobacter* type. These bacteria utilise low molecular weight intermediates (particularly acetate) as carbon energy source (Fush and Chen, 1975). The amount of phosphate released in the anaerobic stage is proportional to the amount of VFA available.

During the aerobic second stage (4 h), soluble phosphorus was taken up and was stored as polyphosphates. A net removal of PO<sub>4</sub><sup>3-</sup>-P resulted considering both stages (anaerobic and aerobic), as can be seen in Figs. 3(B), 4(B) and 5(B).

The initial ratio P/VFA measured at the beginning of the cycle was 0.045 (PO<sub>4</sub><sup>3-</sup>-P (g/l)/acetic (g/l)). This

value is in accordance with the results obtained by Fukase et al. (1985) and Stante et al. (1997), who found ratios of 0.046 and 0.044, respectively.

The average phosphate removal rate was very similar in the three experiments (Table 3), so that no limitations seemed to exist at these operational conditions. Nutrient removal can also be monitored by the ORP values. This parameter of control followed faithfully the evolution of the process (Figs. 3(C), 4(C) and 5(C)). Thus, at the beginning, the ORP profile exhibited a sharp decrease in anaerobic conditions and then a sharp increase due to the appearance of dissolved oxygen coming from the aerator. During the aeration phase, a second, smoother, increase was noted when the ammonia concentration decreased to low levels and nitrite began to appear. This second inflexion showed the end of the nitrification stage.

ORP is a very sensitive parameter to follow-up the stages of a SBR system: the distinct phases of the cycle (anaerobic, aerobic and anoxic) can be very well distinguished by means of the ORP profile. This had been previously observed by several authors (Koch and Oldham, 1985; Peddie et al., 1988; Charpentier et al., 1989; Nakanishi et al., 1990; Wareham et al., 1993, 1994; Lo et al., 1994; Saune et al., 1996; Ra et al., 2000).

Finally, it is important to point out that a good organic matter removal was obtained after completing the aerobic step (see Figs. 3(C), 4(C) and 5(C)). Probably, the remaining COD corresponded to refractory compounds.

### 3.2. Batch experiments

In each experiment, the biomass was characterised by determining the AUR, NUR and OUR. These tests allow the estimation of the activity level of nitrifiers, denitrifiers, and heterotrophic micro-organisms. The

AUR test can also be used to identify possible inhibitory effects of wastewater.

The values of AUR, NUR and OUR during the three periods studied are reported in Table 3. Fig. 7(A) shows the  $\text{NH}_4^+\text{-N}$  and  $\text{NO}_x^-\text{-N}$  profiles obtained during the experiment P3. These profiles were used to estimate AUR and NUR respectively. Fig. 7(B) presents the profile of  $\text{O}_2$  consumption obtained and used for OUR calculation. Similar profiles were obtained in experiments P1 and P2. Higher values of AUR, NUR and OUR were obtained during the third experiment, because of the higher activity of the viable biomass used at higher substrate concentration (Table 3). Values for AUR, NUR and OUR increase with substrate concentration. This shows how active were these sludges, adapting to the conditions of the medium and how they grew in accordance with substrate concentration.

It is also relevant to note the clear correlation between average nutrient removal rates observed during SBR operation and the values of AUR and NUR within the three experiments studied (Table 3). As a consequence, AUR and NUR can be used to evaluate the activity of a nitrifying–denitrifying sludge, without the

need of performing longer experiments to calculate the percentage of nutrient removal.

Values of OUR were high and agreed with the good COD removal percentages obtained during the SBR cycle, taking into account the refractory character of the remaining COD after anaerobic digestion.

### 3.3. Effect of temperature

Temperature often imposes some limitations for nitrification to proceed at rates acceptable for practical purposes. To establish the temperature limits of this step in the operation of a SBR, a series of experiments were carried out using the same operational conditions as in experiment P3, but using nine different temperatures, ranging from 8 to 25 °C. Table 4 summarises the results obtained and includes those obtained at 30 °C (experiment P3) for comparative purposes. At the lower temperatures tested, there was a substantial reduction in both the removal percentage and the rate of removal measured through the AUR tests. This decrease was specially noticeable below 16 °C. Temperatures lower than 16 °C offer ammonium removal yields that can become unacceptable in most of the practical situations. Denitrification is not so affected by temperature, as can be seen in Table 4. Effectively, the decrease in the yield of the process, measured as the nitrate removal percentage, did not occur until 8–10 °C.

On the other hand, Fig. 8 shows the percentage of decrease in both AUR and NUR, taking as a basis (100) the values of these parameters at 30 °C. Here, the biomass activity for both nitrification and denitrification was maintained at rather constant level until 18 °C; a temperature at which a noticeable decrease in AUR and NUR was produced. Although the removal percentage of nitrate was high even at the lowest temperatures tested, the removal rates were affected by low temperatures.

As a conclusion it can be said that SBR operation, at operational conditions of experiment P3, can be carried out without any special concern at temperatures higher than 16 °C.

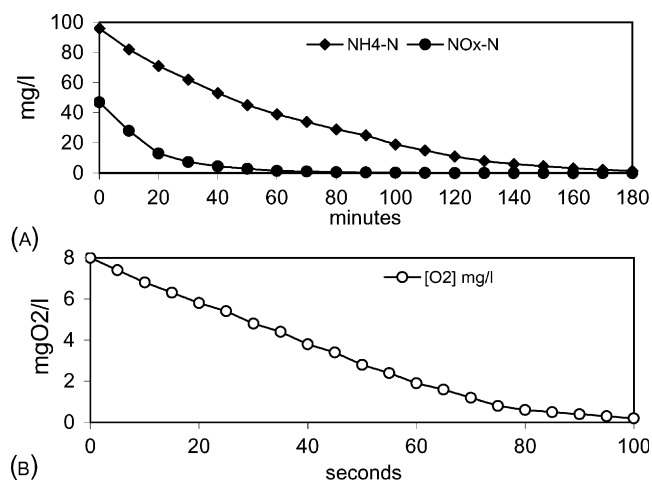


Fig. 7. (A) Profiles of  $\text{NH}_4^+\text{-N}$  and  $\text{NO}_x^-\text{-N}$  used to assess AUR and NUR values during experiment P3. (B) Profile of  $\text{O}_2$  used to determine OUR values during experiment P3.

Table 4  
Temperature influence on nutrient removal

Temperature (°C)	30	25	22	20	18	16	14	12	10	8
AUR mg N g VSS <sup>-1</sup> h <sup>-1</sup>	30.2	27.2	26.9	26.7	26.0	24.5	21.0	15.6	11.9	1.4
% $\text{NH}_4^+\text{-N}$ removal	99.8	99.2	99.0	98.3	97.4	96.3	84.4	74.8	52.6	11.5
Cumulative decrease in % $\text{NH}_4^+\text{-N}$ removal		0.6	0.8	1.5	2.4	3.5	<b>15.4</b>	25.0	47.2	88.3
NUR mg N g VSS <sup>-1</sup> h <sup>-1</sup>	37.4	30.9	30.3	30.0	29.5	26.2	23.3	18.0	14.0	5.8
% $\text{NO}_x^-\text{-N}$ removal	99.9	99.9	99.9	99.8	99.7	99.6	99.4	99.0	90.0	70.0
Cumulative decrease in % $\text{NO}_x^-\text{-N}$ removal		0	0	0.1	0.2	0.3	0.5	0.9	9.9	<b>29.9</b>
OUR mg O <sub>2</sub> /g VSS min	2.2	1.9	1.7	1.7	1.6	1.5	1.2	0.9	0.7	0.4

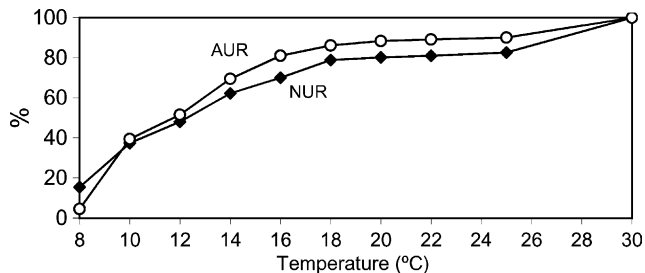


Fig. 8. Percentage of AUR and NUR increase at different temperatures.

#### 4. Conclusions

In this study, a SBR was used to carry out nitrification, denitrification, and phosphorus removal of the supernatant of digested piggery waste. A removal efficiency of 99.7% for nitrogen and 97.3% for phosphate was attained, working with initial concentrations of 1500 mg/l  $\text{NH}_4^+\text{-N}$  and 144 mg/l  $\text{PO}_4^{3-}\text{-P}$ , that is, practically without dilution. This  $\text{NH}_4^+\text{-N}$  concentration represents an upper limit for total N removal, with 3 cycles of 8 h and with an initial reactor concentration of around 500 mg/l  $\text{NH}_4^+\text{-N}$  in each cycle.

The ratio C/N must be higher than 1.7 to obtain complete denitrification to molecular nitrogen during the denitrification stage.

The SBR can also remove high concentrations of  $\text{NH}_4^+\text{-N}$  even at temperatures as low as 16 °C.

In any case, a proper design of the time cycle is necessary, together with optimisation of the duration of the single phases for each particular case.

Even with the recalcitrant character of the substrate COD (it came from the effluent of an anaerobic digestion), a further reduction of the COD of around 70.2% was observed.

The variation in operating conditions, including temperature, demonstrated that the SBR is a very flexible tool, and is particularly suitable for the treatment of piggery wastewater that presents frequent changes in composition and, therefore, in process conditions.

As the distinct phases of the cycle can be very well distinguished using the ORP, this parameter can be used as a monitoring parameter to manage biological nitrogen removal in SBR systems. The regulation of ORP allows N of the effluents to be controlled by constantly adapting aeration to the amount of reducing matter present in the sludge.

AUR, NUR and OUR tests are efficient tools for characterising biomass in sludge in SBR systems. Routine performance of the AUR and NUR tests can be a useful tool for forecasting any problem arising from the process (for instance, low temperatures).

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