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SIMULTANEOUS NITRIFICATION–DENITRIFICATION PROCESSES IN ACTIVATED SLUDGE PLANTS: PERFORMANCE AND APPLICABILITY

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ABSTRACT

This paper deals with the development of technologies aimed to upgrade existing waste water treatment plants, paying attention to high process efficiencies and low costs. We established conditions for good N removal efficiencies in extended aeration activated sludge plants which are not equipped with specific denitrification steps. The experimental process is based on establishing conditions in the biological reactor which allow simultaneous nitrification and denitrification without alternating (in time or in space) anoxic and aerobic phases; the aeration system is controlled by means of dissolved oxygen and/or redox potential measurements. The research was carried out on two real plants (design size: 2,500 p.e. and 440,000 p.e. respectively). The main advantages of this process (even if some aspects are still under investigation) are: total N removal efficiencies similar to a pre-denitrification process, without the need for an anoxic basin and decrease of operating costs (savings in electric energy consumption in particular) due to the low oxygen concentration required in the biological reactor. © 1999 Published by Elsevier Science Ltd on behalf of the IAWQ. All rights reserved

KEYWORDS

Biological nitrogen removal; extended aeration plants; full-scale plants; ORP-DO control; simultaneous nitrification-denitrification; upgrading

INTRODUCTION

In Italy, due to the introduction of stricter effluent standards (in part as a consequence of the E.C. Directive 91/271), in particular for nutrients, many existing wastewater treatment plants will be upgraded.

As far as nitrogen removal is concerned, there is no alternative for the biological nitrification-denitrification process. Upgrading of plants with conventional processes requires the extension of tank volumes and the construction of new reactors. Many researchers in the world are developing innovative processes which satisfy the following requirements: high removal efficiencies, upgrading with minimal interference with the existing facilities (low investments) and simple technologies (low operating costs). Simultaneous nitrification-denitrification process, applied to extended aeration activated sludge plants, is one of the possible options.

In this paper, recent results following earlier reports (Collivignarelli *et al.*, 1993; Bertanza, 1997; Bertanza *et al.*, 1997a, b) are presented. In particular, the aim of this work is the evaluation of the process performance and its applicability under different conditions.

The process was applied to a small plant (design size: 2,500 p.e.) and to a large plant (design size: 440,000 p.e.). Both plants consist of parallel sections, one of which was equipped with the simultaneous nitrification-denitrification process. The other sections continued to work according to the conventional pre-denitrification scheme. Besides, some small scale tests were carried out in order to establish the optimal operating conditions for the process in the specific situations, and microbiological analyses characterised the biomass. An economic evaluation was also carried out in order to verify possible savings in the application of the non conventional process.

THE SIMULTANEOUS NITRIFICATION-DENITRIFICATION PROCESS

Conventional activated sludge treatments for nitrogen removal include several phases with different oxygen concentrations or only one reactor in which alternating aerobic and anoxic phases are achieved in time or space. In "non-conventional" processes, the oxygen concentration is controlled in order to obtain the simultaneous (in time and in space, that is with constant conditions and in the same reactor) activity of denitrifying and nitrifying bacteria. It was shown, in fact, that denitrification reactions take place also under aerobic conditions and that nitrification is possible at low levels of dissolved oxygen (Robertson and Kuenen, 1984; Ritmann and Langeland, 1985; Andreottola *et al.*, 1990; Osada *et al.*, 1991; Suwa *et al.*, 1992). As far as denitrification under aerobic conditions is concerned, "aerobic denitrification" and "microzones denitrification" can be defined; in the former, micro-organisms utilise nitrate and oxygen simultaneously as terminal electron acceptors; in the latter, denitrification occurs in the anoxic microzones within a biological floc. This last phenomenon was supposed to occur in the tested process due to the particular aeration conditions (very low dissolved oxygen [DO] concentrations). One problem related to low levels of dissolved oxygen can be nitrite accumulation due to incomplete nitrification (Hanaki *et al.*, 1990): this phenomenon was observed in some cases also during our experiences (but at negligible concentrations).

Low oxygen concentrations can be maintained by direct DO control (Ritmann and Langeland, 1985; Osada *et al.*, 1991; Suwa *et al.*, 1992) or indirect DO control, that is measuring other process parameters, like ORP (Moriyama *et al.*, 1990; Moriyama *et al.*, 1993) or NADH fluorescence (Helmo, 1993). The present authors' experience deals with aeration control systems coupled with ORP and/or DO measurement. ORP measurement allows to achieve better process conditions than DO measurement only; in fact ORP takes into account the dissolved oxygen level and other parameters which determine suitable conditions for simultaneous nitrification - denitrification: ORP value is determined by O_2/OH^- equilibrium, but also by NO_3^-/NH_4^+ (generally prevailing), NO_2^-/NH_4^+, etc. (Comolli, 1994).

PLANTS AND EXPERIMENTAL CONDITIONS

The first plant (design size: 2,500 p.e.)

Description. This plant treats domestic wastewater (about 250 m^3/d) and industrial wastewater from a tannery (about 750 m^3/d). The plant consists of a mechanical pre-treatment section (screening and grit and oil removal) and by two parallel biological sections, realised in different periods: the older one consists of a combined aeration-sedimentation basin (volume of the aeration tank = 162 m^3); the second has a pre-denitrification step (V = 100 m^3), an oxidation-nitrification basin (V = 196 m^3) and is equipped with a separate settling tank. The influent flow is divided as follows: about 40% to the older section, about 60% to the second. In the older oxidation basin, which was designed as an extended aeration process, a low DO level was imposed by means of direct measurement (aeration system consists of air diffusers). In this way it was possible to compare the results of the non conventional nitrification-denitrification process and the conventional pre-denitrification process.

Experimental conditions. The experiments were carried out during 1996 and 1997: eleven periods have been characterised by different operating conditions, as reported in Table 1.

Table 1. First plant: operating conditions (average values)

Parameter	Plant Section	Period										
		I	II	III	IV	V	VI	VII	VIII	IX	X	XI
HRT (h)	A	11	11	13	12	6.9	6.3	4.0	4.1	7.6	14	9.1
	B*	8.2	10	9.7	8.2	7.3	5.0	3.4	3.7	5.7	10	6.5
F/M (kgBOD/kgSS/d)	A	0.08	0.03	0.05	0.07	0.13	0.12	-	0.08	0.06	0.05	0.15
	B	0.06	0.03	0.07	0.06	0.10	0.09	-	0.15	0.16	0.14	0.35
DO (mg/L)	A	0.3	1.2	0.6	0.6	0.2	0.1	0.4	1.0	0.3	0.2	2.9
	B*	1.7	5.4	2.6	2.3	1.0	0.5	2.4	5.2	4.6	0.2	3.3
ORP (mV)	A	+130	+196	+131	+160	+116	+110	-	-	-	-	-
T (°C)		15	15	20	23	23	19	18	12	16	18	21
COD_{in} (mg/L)		820	450	600	400	420	330	230	100	200	180	270
$N_{tot\,in}$ (mg/L)		196	48	41	39	45	34	-	27	29	51	29
NH_4^+-N_{in} (mg/L)		13	11	15	14	14	10	10	5	7	10	10
BOD_5/TKN_{in}		1.4	1.8	4.3	2.8	4.3	3.1	3.1	0.6	4.1	3.9	5.9
$COD/BOD_{5\,in}$		5.8	7.6	3.3	4.0	2.5	3.6	3.2	2.2	2.1	1.4	1.6

A: older section (with low imposed DO level)   B: new section (with pre-denitrification step)
* In the aerobic reactor
Period I: 8/2/96 to 29/2/96   Period II: 7/3/96 to 28/3/96   Period III: 11/4/96 to 7/5/96
Period IV: 14/5/96 to 11/6/96   Period V: 13/6/96 to 25/7/96   Period VI: 15/9/96 to 22/10/96
Period VII: 11/11/96 to 29/11/96   Period VIII: 5/12/96 to 9/1/97   Period IX: 17/1/97 to 20/2/97
Period X: 20/3/97 to 16/4/97   Period XI: 16/5/97 to 26/6/97

The second plant (design size: 440,000 p.e.)

Description. The plant is designed for a loading of 440,000 p.e. and it treats mainly domestic wastewater. The average influent flowrate is 70,000 m^3/d. The treatment includes mechanical pretreatments (bar racks and lifting, screening, grit and oil removal), primary sedimentation in 3 circular basins (volume = 3,405 m^3 each), biological activated sludge process in 5 parallel circular reactors (global volume = 24,850 m^3) equipped with air diffusers and submerged mixers, final sedimentation in 8 circular basins (volume = 2,200 m^3 each). In four biological basins (volume = 4,737 m^3 each), the pre-denitrification process is carried out (without mixed-liquor recirculation in winter; the primary aim is to achieve complete nitrification, so the aerobic zone volume is increased reducing the anoxic zone; in order to achieve only partial denitrification, mixed-liquor recirculation is not required). The fifth biological reactor (volume = 5898 m^3) was used to test the simultaneous nitrification-denitrification process, keeping a low dissolved oxygen concentration (by means of direct measurement) in a partial volume of the basin, as described below. This plant is also equipped with a pre-treatment station (activated sludge biological treatment with pure oxygen) for industrial wastewaters (among which landfill leachates and wastewaters from septic tanks are also included).

Experimental conditions. The experimentats were carried out between 1997 and 1998 and were divided in two parts, characterised by different conditions as reported in Table 2. In particular, during the first period, about 37% of the reactor volume was operated at low DO concentration (this is possible because the basin has a "channel" configuration, and the air flowrate can be reduced in the first part of the reactor). This "microaerated" zone was extended to 50% of the basin volume during the second period. Previous pilot scale tests had shown the optimal values of operating parameters (ORP around 110 mV, DO around 0.6 mg/L, F/M ratio around 0.1 kgBOD/kgSS/d) and expected nitrogen removal efficiency (50-60%). Hydrodynamic tests had shown that good mixing could be achieved even if low oxygen concentrations were maintained. In order to compare the "non conventional" process with "conventional" predenitrification, one of the other four sections of the plant was monitored during the same periods.

Table 2. Second plant: operating conditions (average values)

	Period I (24/6/97 to 1/8/97)		**Period II (16/12/97 to 29/1/98)**	
Parameter	**Simult. nit.-den.**	**Predenitrification**	**Simult. nit.-den.**	**Predenitrification**
HRT_{tot} (h)	6.6	8.9	7.2	9.4
$HRT°_{anox}$ (h)	2.5	2.2	3.6	2.9
F/M (kgCOD/kgSS/d)	0.23 (0.14*)	0.17 (0.13*)	0.15 (0.08*)	0.15 (0.10*)
F/M (kgBOD/kgSS/d)	0.15	0.11	0.09	0.09
SRT (d)	13.8	21.1	19.1	17.6
$DO°_{anox}$ (mg/L)	0.5	0.2	0.7	0.2
DO_{ox} (mg/L)	4.6	4.0	8.6	7.5
$ORP°_{anox}$ (mV)	81	-	177	-
ORP_{ox} (mV)	114	-	180	-
T (°C)	21.0		11.4	
COD_{in} (mg/L)	150		200	
$N_{tot\ in}$ (mg/L)	20.9		19.8	
NH_4^+-N_{in} (mg/L)	14.5		11.6	
BOD_5/TKN_{in}	5.0		6.5	
$COD/BOD_{5\ in}$	1.6		1.7	

* Calculated on the aerobic zone

° "Microaerated" zone in the simultaneous nitrification-denitrification process; anoxic zone in the pre-denitrification process

RESULTS AND DISCUSSION

The first plant

In Figures 1 and 2 the removal efficiency of nitrogen and COD, respectively, is reported for both the conventional and non conventional process.

The following observations can be made from the data analysis:

- the same efficiency has been achieved in both sections of the plant until period VII; the low nitrogen removal efficiency in the second period was due, in the non conventional process, to the high DO concentration (see Table 1);
- process efficiency decreased until the seventh period (in particular as far as nitrogen removal is concerned); after that, only the non conventional process increased again its performance.
-

This behaviour can be explained on the base of the following considerations:

- the lower nitrogen removal efficiency up to period VI observed in both plant sections may be due to a variation of influent characteristics, less suitable for nitrification (decreasing the COD/BOD ratio from 5.8 to about 3, increasing the BOD/TKN ratio from 1.4 to more than 4: Table 1); besides, in periods V and VI DO and ORP values were low and from the second period on the F/M ratio was increasing; finally, batch tests carried out with activated sludge (NUR: Nitrogen Uptake Rate) had shown bad characteristics of industrial wastewater;
- during period VIII the industrial wastewater was not fed to the plant; besides, in the following periods influent characteristics and operating conditions remained almost constant (even if not in the optimal range and not for period XI in which a too high DO concentration caused low denitrification efficiencies) and allowed the improvement of process performance at least for the conventional process; for the other section of the plant, several electromechanical failures (mixed-liquor recirculation pumps, submerged mixers, aerators) determined further decreasing of removal efficiency.

Further microbiological analyses (described in Bertanza *et al.*, 1997b) confirmed the importance of operating conditions and the effect of industrial wastewater.

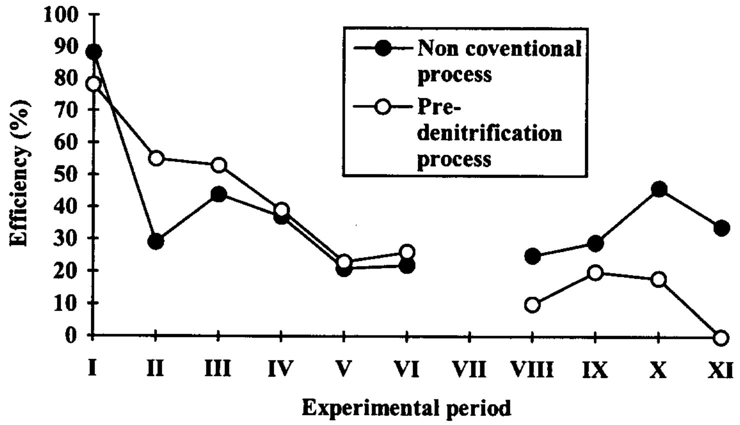

Figure 1. First plant: nitrogen removal efficiency.

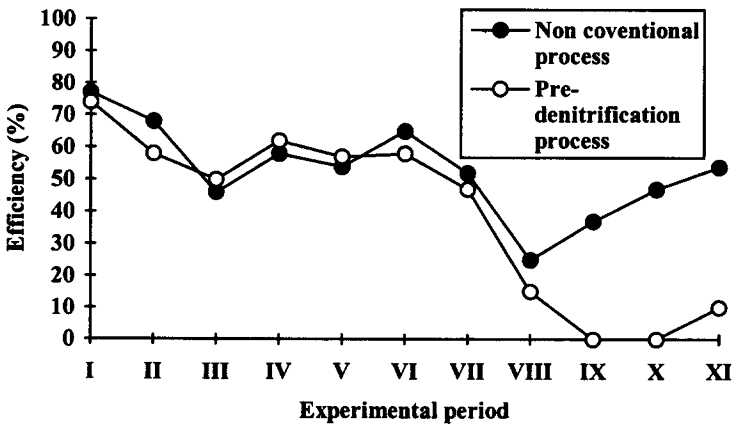

Figure 2. First plant: COD removal efficiency.

In summary, our experiments have shown the possibility to achieve the same COD and nitrogen removal efficiencies as conventional pre-denitrification processes but with smaller volumes (20% less, considering the flowrates treated in the two sections of the plant).

The second plant

Experimental results are summarised in Table 3.

As far as the first experimental period is concerned, the following observations can be made:

- very high COD and ammonia removal efficiencies were achieved in the experimental basin; total nitrogen removal is not very high due to the relatively low denitrification efficiency;
- the nitrification rate in the "microaerated" zone (v_{Nanox}) is lower than expected (mainly due to the low DO concentration and high concentration of organic carbon in the anoxic zone); the nitrification rate in the aerobic zone (v_{Nox}) is instead in the typical range for activated sludge plants treating municipal wastewater; the denitrification rate is high if we consider that denitrification took place with 0.5 mg/L of dissolved oxygen;

- the experimental section and the conventional process had the same nitrification efficiency; the denitrification efficiency (and also total nitrogen removal efficiency) is higher in the experimental process (probably due to the larger volume with low-DO conditions): this means that it was not limited by the DO concentration but by the influent characteristics (lack of readily degradable organic substance); the higher COD removal in the experimental section is in agreement with the higher denitrification efficiency. These results have been obtained in a reactor with 25% less volume than the conventional pre-denitrification system.

Table 3. Second plant: experimental results

	Period I (24/6/97 to 1/8/97)		**Period II (16/12/97 to 29/1/98)**	
Parameter	**Simult. nit.-den.**	**Predenitrification**	**Simult. nit.-den.**	**Predenitrification**
η_{COD} (%)	90	85	84	92
η_{NIT} (%)	95	98	94	97
η_{DEN} (%)	50	43	43	58
$\eta_{N\ TOT}$ (%)	53	48	49	62
$v_{D\ anox}$ (20°)	1.89	2.05*	1.51	6.79*
$v_{N\ anox}$ (20°)	0.87	-	2.04	-
$v_{N\ ox}$ (20°)	1.90	-	1.70	-

° Working without mixed-liquor recirculation

^ "Microaerated" zone in the simultaneous nitrification-denitrification process; anoxic zone in the pre-denitrification process

* Calculated supposing that all nitrogen gassification occurs in the anoxic basin (actually, the presence of dead spaces in the aerobic tank, with very low oxygen concentration, allows partial denitrification also in the nitrification basin, besides residual denitrification was observed in the final clarifier).

During the second experimental phase, the aim was to increase the simultaneous nitrification-denitrification zone, without decreasing nitrification efficiency. Thus the "microaerated" zone was extended up to 50% of the total reactor volume and the DO concentration was increased.

The following observations arise from an analysis of the collected data:

- COD removal efficiency is good; almost complete ammonia removal was obtained; nitrogen removal is limited by denitrification efficiency;
- the nitrification rate in the "microaerated" zone was enhanced: it is similar to that recorded in the aerobic zone; even the denitrification rate in the "microaerated" zone has an appreciable value;
- the same nitrification efficiency was achieved in the experimental and in the conventional plant; the denitrification efficiency was lower in the experimental section (despite the high denitrification rate) due to the relatively high DO concentration (similar ORP values were measured in the "microaerated" and aerobic zones) and the low temperature; the lower denitrification efficiency of the experimental process resulted in a lower nitrogen removal; the lower denitrification efficiency is also in agreement with a lower COD removal.

In the second phase of the experiments, operating parameters were not set to optimal values, in fact a lower nitrogen removal was obtained with respect to the conventional process, even if the reactor volume availability was the same (same F/M ratio) and despite the interruption of mixed-liquor recirculation in the latter. Actually, residual denitrification in the final clarifier cannot be excluded for the conventional process (effluent analyses were carried out on samples taken at the outlet point of the oxidation basin for the non conventional process, while samples were taken after the sedimentation tank for the conventional plant).

ECONOMIC ASPECTS

An economic analysis was carried out in order to check possible savings (with respect to the pre-denitrification treatment) in the application of the non conventional process. Calculations refer to the realisation of a new plant, considering that the same performances can be achieved with smaller reactor volumes (20% less), lower DO concentrations (a concentration of 0.6 mg/L is enough), no mixed-liquor recirculation, no mixing in the denitrification tank. Calculations have been carried out for a wastewater treatment plant with design size of 100,000 p.e. In Table 4, the results are reported (only cost items with different values are specified).

Table 4. Cost evaluation for the pre-denitrification and the non conventional processes

	Pre-denitrification plant	**Non conventional plant**
	Investment costs (Millions Lit.*)	
Oxidation reactor	1,300	1,900
Denitrification reactor	1,000	-
Air supply system	680	470
Mixed-liquor recirculation	180	-
Submerged mixers	320	-
Other items°	11,120	11,120
TOTAL	**14,600**	**13,490**
	Operating costs (Millions Lit.* / year)	
Electric energy	1,200	600
Other items^	1,508	1,508
TOTAL	**2,708**	**2,108**

* Costs are calculated in Italian lire (Lit.): 1 US$ ≅ 1,700 Lit.

° Pre-treatments, final clarifier, disinfection, sludge thickening and dewatering

^ Chemicals, sludge disposal, maintenance, personnel

As can be seen from Table 4, the realisation of a plant with a simultaneous nitrification-denitrification process leads to a saving of almost 10% as far as investment costs are concerned; besides, lower operating costs have been estimated (saving is over 20%).

CONCLUSIONS

Based on our experiences and results published in the literature, we can conclude that establishing a simultaneous nitrification-denitrification process is a suitable way to upgrade extended aeration wastewater treatment plants for nitrogen removal. In particular we think that:

- the same COD and nitrogen removal efficiencies can be obtained with smaller volumes (20% less than a conventional pre-denitrification process) and lower energy consumption (50% less);
- as far as operating conditions are concerned the optimum ORP value must be determined for each specific case, based on influent characteristics, although it is probably in the range 130-160 mV. The effluent nitrogen must be considered: higher ORP values promote full nitrification, then most of total nitrogen consists of nitrate nitrogen; for lower ORP values, high ammonia nitrogen concentrations can be found in the effluent; dissolved oxygen should be maintained in the range 0.3-0.6 mg/L; F/M ratio is typical of an extended aeration process;
- due to the potential nitrite accumulation, it is better to have at least a small aerated zone before the sedimentation tank;
- ORP measurement should be employed for a better aeration system control, nevertheless, due to possible difficulties related to the ORP electrode performance (see required cleaning operations), ORP measurements should be always coupled with DO measurements.

AUTHOR'S CONTRIBUTION

Carlo Collivignarelli carried out scientific supervision of the work. Giorgio Bertanza carried out the experimental work and data elaboration. Conclusions have been drawn by the authors together.

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