COMBINED NITROGEN AND PHOSPHORUS REMOVAL FROM WASTEWATERS

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Activated sludge pilot-plant experiments on nitrification, post and pre-denitrification and intermittent aeration with and without ferrous sulphate addition were conducted to find a reliable and simple method for the simultaneous removal of organic compounds, phosphorus and nitrogen from domestic sewage. Nitrification was inhibited at dosages exceeding 30 g m^{-3} Fe (II). The post-denitrification process did not give proper results. In the pre-denitrification process the nitrification rate was over 80 %, total N reduction 70 % and effluent P less than 1.5 mg l^{-1}. The results were similar in the intermittent aeration process. Ferrous sulphate had an inhibitory effect also on denitrification.

Index words: Nitrogen removal, nitrification, denitrification, phosphorus removal, activated sludge, sewage, ferrous sulphate.

1. INTRODUCTION

The primary concern of waste water treatment in Finland was first the removal of organic compounds in order to reduce the oxygen depletion in the receiving watercourses. This was achieved in most cases with activated sludge processes and in some instances with trickling filters. The second stage of treatment was the inclusion of phosphorus removal to abate eutrophication, because the limiting growth factor in Finnish watercourses is mainly phosphorus. Today there are appr. 560 treatment plants in Finland treating 95 % of the raw municipal wastewater. The main process is activated sludge combined with simultaneous precipitation of phosphorus by adding ferrous sulphate to the aeration basin (370 plants) giving, when properly operated, a BOD$_7$-removal of 80 % and effluent phosphorus of less than 1.0 mg l^{-1}.

Nitrogen has not, until recently, been considered of importance and the technical applications for nitrogen control have been considered too difficult. Today attention is paid to the adverse effects of ammonia and demands for ammonia removal have been made for five wastewater plants.

The technical problems of ammonia and total nitrogen removal in Finland are the low temperature during wintertime and possible adverse effects of ferrous sulphate on the biological nitrification and denitrification processes.

The objective of this study was to find out if simultaneous precipitation could be combined to ammonia removal and denitrification in a simple activated sludge process modification.

Experiments were made with four different processes: normal nitrifying one-stage activated sludge, nitrification-denitrification with one sludge and separate reactors (here called the nd process), predenitrification process (dn process) and intermittent aeration in one reactor.

2. HAZARDS AND SOURCES OF NITROGEN

The hazards of nitrogenous compounds, e.g. ammonia, nitrate and nitrite are well documented. The primary concern has been eutrofication in places where nitrogen is the limiting growth factor. In Finland, however, this is the case in only some limited locations along the coastline and in some specific lakes. The most adverse effect of ammonia is dissolved oxygen depletion caused by the oxidation of ammonia to nitrate. One gram of ammonia uses 4.6 g oxygen for nitrification.

Depending on the pH, ammonia can be toxic to fish at concentrations above 0.2 mg l^{-1}. Salmon and trout are very vulnerable.

In potable water systems ammonia causes an increased chlorination demand with subsequent formation of hazardous organohalogen compounds and increased treatment costs. High concentrations of ammonia have occurred in some heavily loaded rivers during dry weather conditions. In the river Vantaa, which used to serve as the raw water source of the city of Helsinki, the highest concentrations reported have been 3 mg l^{-1} of ammonia nitrogen. The chlorination costs were 1.5 MFM a^{-1} in 1976 in the city of Helsinki water works due to ammonia (Vakkuri 1981).

Ammonia increases the corrosion rate of copper and copper alloys by complexing the copper in normally protective oxide or carbonate surface films (Nalco 1979).

Nitrate and nitrite can also serve as nutrients for eutrophication but the main concern is given to the health hazards. Infant methemoglobinemia is a well known disease caused by increased levels of nitrate in drinking water. A more recent observation is the formation of nitrosoamines and amides which are carcinogenic compounds (Mirvish 1977). In Finland the limits of nitrate and nitrite nitrogen in potable water are set to 6.8 mg l^{-1} and 0.06 mg l^{-1} (expressed as N).

The main load of nitrogen to recipients in Finland is from diffused sources.

Table 1. Main sources of nitrogen and phosphorus in Finland (Vesihallitus 1979).

Source	Phosphorus 10^3 kg a^{-1}	Nitrogen 10^3 kg a^{-1}
Diffused sources		
Erosion	3 000	61 000
Rain	300	15 000
Agriculture	1 700	24 000
Stock raising	600	18 000
Others	200	3 000
Point sources		
Municipalities (Untreated/treated)	4 200/800	19 600/13 600
Industry		
Pulp and Paper	587	3 900
Metal	10	1 150
Chemical	64	1 010
Food	39	350
Others	9	510
Fish Production	66	320

Point sources such as muncipalities and industry represent only 13 % of the total load. If fixation is taken into account, the point sources stand for an even smaller part of the total nitrogen load (Table 1).

The main part of the nitrogen received by the watercourses is inorganic. Untreated wastewater usually contains 30—40 mg l^{-1} of total nitrogen of which 50-70 % is ammonia and the rest urea and organic compounds. After biological treatment 95 % of the nitrogen is either ammonia or nitrate.

Trade effluents contain ammonia and nitrate but also organic compounds are found in effluents from textile industry and laundries. Effluents from food industry contain proteins and amino acids, effluents from pulp and paper industry contain ammonia and organic nitrogen and effluents from metal industry mainly nitrates.

The nitrogen from diffused sources is mainly nitrate because of nitrification in the soil and a better retention of ammonia to soil particles.

3. PROCESSES FOR NITROGEN CONTROL

Nitrogen control comprises of ammonia removal either by complete elimination or oxidation to nitrate, and nitrate removal.

Several physical-chemical processes for ammonia and nitrate removal have been developed: stripping or desorption into air, selective ion exchange, break-point chlorination, electrolysis, precipitation as ammonium magnesium phosphate and adsorption to manganeseoxide. Nitrate removal is more difficult but processes for desalination like ion-exchange, electrodialysis, and reverse osmosis can be used.

These processes, however, have not been considered to be suitable for municipal wastewater treatment in Finland because of high costs and technical complexity. For certain industrial wastewaters they could be adopted.

In Finland biological nitrification and denitrification processes are considered most feasible for nitrogen control. Several process configurations have been studied and full scale plants have been built in the United States, South-Africa and Europe. Rewiews of these have been given by EPA (1975), Henze (1977) and Gromiec et al. (1982).

In principle, nitrification and denitrification can be performed in activated sludge or fixed media reactors and the processes can be devided in one, two or three sludge systems. In one-sludge systems the removal of organic compounds, nitrification and denitrification is performed with one sludge in one or two reactors. In two-sludge systems denitrification is separated and an external carbon source, e.g. methanol, must be added. In three-sludge systems the removal of organic compounds and nitrification are further separated from each other. It can be expected that two and three sludge systems give better and more consistent removal of nitrogen than one-sludge systems, but to higher construction and operating costs. It has, however, been shown that one sludge systems like the Bardenpho process, Carrousel plants, the Orbal process, the Bio-Denitro process and others have given consistenty high removal rates of nitrogen (Stensel et al. 1978, Barnard 1978, Drews and Greef 1975, Tholander 1977, Matché 1980).

4.   EXPERIMENTAL METHODS

The experiments were carried out at the research station of the Technical Research Centre of Finland next to the Espoo Municipal sewage treatment plant.

4.1 Apparatus

The experiments were carried out with two parallel pilot-plant units, which consisted of 1.3 and/or 3 m^3 cylindrical reactors and upflow clarifiers with a surface area of 0.79 m^2 and volume of 0.6 m^3. The aerobic reactors were provided with fine bubble tube diffusers, the anoxic reactors with variable speed mixers. Pumps were variable speed positive displacement screw pumps. Continuous measurements of DO, pH, redox potential and temperature were made and recorded. Flow proportional composite samples were taken with automatic samplers.

n - process

nd - process

dn - process

intermittent aeration

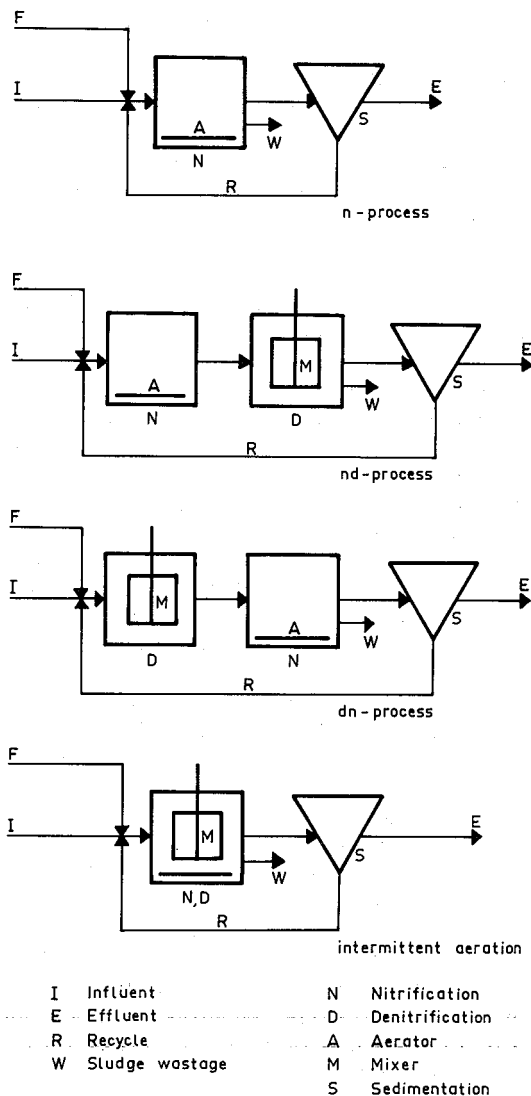| I | Influent | N | Nitrification |
E	Effluent	D	Denitrification
R	Recycle	A	Aerator
W	Sludge wastage	M	Mixer
		S	Sedimentation

Fig. 1. Diagrams of experimental processes.

Ferrous sulphate was dosed as a 2 % solution of commercial $FeSO_4 \cdot 7H_2O$ by a plunger metering pump into the influent feed line to faciliate complete mixing.

The screened Espoo Municipal wastewater was pumped to a head tank in the research station and after sieving (5 mm sieve) pumped to the pilot-plants. Diagrams of the processes are presented in Fig. 1.

4.2 Sampling and analyses

Flow proportional 24 hour composite samples were taken from the influent and effluent five days weekly starting on Sunday at 8 A.M. Grab samples were taken on weekdays from the reactors and return sludge. The analytical program and measurements are presented in Table 2.

The analytical methods conform to the methods used by the National Board of Waters (1981) with the following exceptions.
— COD was analysed as potassium permanganate (Vesianalyysitoimikunnan mietintö 1968)
— Total nitrogen was analysed with Kjelldahl digestion and DEVARDA and distillitation and titration of ammonia (Vesianalyysitoimikunnan mietintö 1968). A Tecator digestion and distillation unit was used.

Table 2. Analytical program and measurements.

	Influent	Effluent	n-unit	d-unit	recycle
Temperature	m		m	m	
pH	m,c	c	m	m	
Alcality	c	c			
Conductivity	c	c			
Suspended solids	c	c	g	g	(g)
Volatile suspended solids			g	g	
BOD$_7$	c	c			
COD (KMnO$_4$)	c	c			
Total phosphorus	c	c			
Soluble phosphorus		c	g	g	
Total nitrogen	c	c			
Ammonia	c	c	g	g	
Nitrite		(c)			
Nitrate		c	g	g	
Dissolved oxygen			m	(m)	
Redox-potential			m	m	
Settleability ½ h			g	g	g

m   is continuous measurement
c   is composite sample
g   is grab sample
( ) is occasionally

— Nitrate was analyzed with an Orion research ionic-specific nitrate electrode 93—07 and an Orion 90—02 double junction reference electrode. The "known additon" method was used.
— Ammonia was analyzed with an Orion Research ammonia electrode 95—10 and the "known addition" method was used.

4.3 Working routine and time table

The different processes were studied as follows:
1. Nitrification   1.5.—30.12.1977
2. nd process   1.1.—30.04.1978
3. dn process   1.5.—30.12.1978
4. Intermittent aeration   1.1.1979—30.12.1980

The working routine for all the processes was the same.
— The samples were collected every weekday at 7.30—8.00 and analyzed on the same day.
— Surplus sludge was removed directly from the reactors after sampling on weekdays.
— The flows were controlled every day.
— The electrodes were cleaned and the intsruments calibrated weekly and after disturbances.
— The DO in the aerobic reactor or phase was manually set to 2—4 mg l^{-1} daily.
— The recorders were read daily and a value representing a mean value during the preceding day was chosen.
A detailed programme for each process is described later.

4.4 Data analysis

In principle, when working with biological processes treating natural wastewaters, one cannot assume that the system is in steady state conditions, because the quality of the wastewater with respect to concentrations and temperature varies both daily and hourly. Toxic substances can cause disturbances of different magnitude and duration in the process. Solvents and soluble compounds can cause acute toxicity, which can be strong but of short duration. Mineral oils and fats, heavy metals and other compounds which accumulate in the sludge can cause disturbances of long duration.

Considering the hydraulics of the treatment plants it can be assumed that theoretically steady state in the water phase is achieved in 2—4 days when the hydraulic detention time is 10—24 h. If a

change was made on Friday, the steady state was achieved on Monday to Tuesday. Considering the sludge phase, the time to achieve steady state could take 40—120 d when the sludge age varies from 10 to 30 d, which is normal for nitrifying and denitrifying systems in low temperatures. The adaptation of the sludge can be faster, but when considering the inorganic fraction, and in this study the ferrous fraction of the sludge, steady state is indeed achieved after several weeks of operation.

Because of these facts, theoretical steady state models for determining kinetic constant for the bacteria (heterotrophic bacteria and nitrifying bacteria separately) were not adopted.

Dynamic models could not be used, because this would have demanded continuous measurements of several compounds like ammonia, nitrate, nitrite, organic carbon and bacteria and a vastly increased analytical program, which would have exceeded the laboratory capacity.

Regression analysis and t-tests were used when comparing groups of data. Stepwise discriminant analysis was used in process comparision. Readymade statistical program packages were used.

5.   RESULTS
5.1 Wastewater composition

The influent consists of domestic sewage (90 %) and industrial waste water (10 %). Rainstorms and melting snow increased the flow by a factor of three, with consequent dilution. An acetylene plant, metal plating, pharmaceutical and technochemical industries caused occasional wide pH fluctuations and shock loads of heavy metals, sol-

vents and other chemicals which had inhibitory effects on the biological performance of the pilot plants (Table 3).

5.2 Effect of ferrous sulphate on nitrification and phosphorus removal

The effect of ferrous sulphate on nitrification was studied with a single-stage activated sludge process (n process). One unit was fed with ferrous sulphate and the dosage was gradually increased from 4 to 60 g m^{-3} Fe^{2+}. The other unit was run as a control without addition of chemicals. Both units were otherwise run identically (Table 4).

The results grouped according to ferrous sulphate feed are presented in Appendix 1.

5.21 Nitrification

The nitrification rate was calculated from equation (1)

$$NR = \frac{N_{tot,i} - N_{NH4,e}}{N_{tot,i}} \qquad (1)$$

Where
NR   is nitrification rate
N_{tot} is total influent nitrogen
$N_{NH4,}$ is total ammonia nitrogen

Subscripts i and e refer to influent and effluent respectively.

Table 3. Average influent composition in pilot-plants.

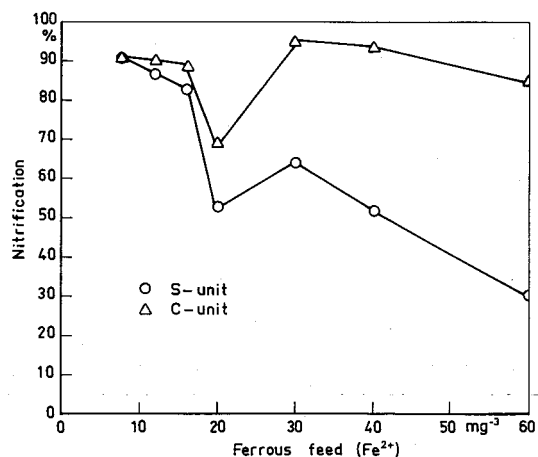|		Mean ± standard error of mean	1 st quartile	3 rd quartile
pH		7.2 ± 0.02	7.0	7.3
alkalinity	mmol l^{-1}	4.5 ± 0.1	3.8	5.1
conductivity	mS m^{-1}	61 ± 11	55	68
suspended solids	mg l^{-1}	193 ± 7	140	250
BOD$_7$	mg l^{-1}	139 ± 5	100	160
COD (KMnO$_4$)	mg l^{-1}	230 ± 9	163	267
total phosphorus	mg l^{-1}	6.1 ± 0.2	4.2	7.6
total nitrogen	mg l^{-1}	29.7 ± 1.2	21.6	37.0
ammonia-nitrogen	mg l^{-1}	23.3 ± 0.1	15.4	30.2
temperature	°C	13.2 ± 0.5	10.6	16.5

Fig. 2. Nitrification at different ferrous sulphate dosages.

Table 4. Process parameters of n-process during different periods in simultaneous precipitation unit (S) and control unit (C).

Process parameter	Period											
	1		2		3		4		5		6	
	S	C	S	C	S	C	S	C	S	C	S	C
Sludge load, kg kg^{-1} d^{-1}	0.10	0.15	0.08	0.11	0.14	0.15	0.11	0.11	0.14	0.14	0.11	0.17
Sludge age, d	12	12	12	12	12	12	13	13	15	15	12	12
Retention time, h	5.90	5.90	6.50	6.50	5.40	5.40	5.20	5.20	5.20	5.20	5.20	5.20
Recirculation, %	100	100	100	100	100	100	100	100	100	100	100	100
Ferrous feed, g m^{-3} (Fe^{2+})	11.2	0	16.0	0	20.0	0	29.0	0	40.8	0	50.0	0
Hydraulic surface load, m^3 m^{-2} h	0.28	0.28	0.25	0.25	0.30	0.30	0.32	0.32	0.32	0.32	0.32	0.32
Sludge volume load, m^3 m^{-2} h^{-1}	0.22	0.17	0.21	0.21	0.18	0.19	0.10	0.10	0.08	0.09	0.08	0.16
Temperature, °C	18.2	18.1	18.0	18.1	16.5	16.7	14.3	14.8	12.5	12.8	12.4	12.7
Time of run, d	19	19	12	12	82	82	10	10	12	12	12	12

Equation (1) does not take into account assimilation of ammonia into the sludge and complete ammonification is assumed.

From the results it can be clearly seen that when the ferrous feed was increased, the nitrification rate dropped from 90 to 20 % while nitrification in the control unit was 80—90 % (Fig. 2). When comparing the rates between both units after arc sin $\sqrt{x}$ transformations, the difference was significant at 95 to 99 % confidence level, when the ferrous sulphate feed was 20 g m^{-3} Fe^{2+} and very significant at 99.9 % confidence level, when the ferrous feed was more than 16 g/m^3 Fe^{2+} (Table 5).

The nitrification rate k_n, expressed as g of ammonia-nitrogen removed divided by MLVSS and time was 0.4—1.1 g kg^{-1} d^{-1} in the simultaneous unit and 1.0—1.9 g kg^{-1} d^{-1} in the control unit

(Table 6). k_n was calculated from equation (2).

$$k_n = \frac{(N_{tot,i} - N_{NH4,e} \cdot Q)}{MLVSS \cdot V} \qquad (2)$$

where Q is flow
V is reactor volume

5.22 Phosphorus removal

Total effluent phosphorus was 0.5—3 mg l^{-1} and soluble phosphorus 0.2—2 mg l^{-1} in the simultaneous precipitation unit depending on the Fe:P molar ratio in the feed and 4—6 mg l^{-1} in the control unit. When the molar ratio exceeded 1.0 the soluble phosphorus decreased below 1.0 mg l^{-1}

Table 5. Ammonia removals and t-test between units after arc sin $\sqrt{x}$-transformation in nitrification process at different Fe-feeds (S is simultaneous precipitation, C is control).

Fe^{2+}-feed	Ammonia removal %		t-test
g m^{-3}	S	C	
11.2	86	90	1.26
16.0	83	89	1.29
20.0	56	69	2.25*
29.2	64	95	7.67***
40.8	52	94	7.55***
50.0	30	85	10.0***

Table 6. Nitrification rates (k_n) with standard error of mean in n-process during different periods and t-test between units (S is simultaneous precipitation, C is control).

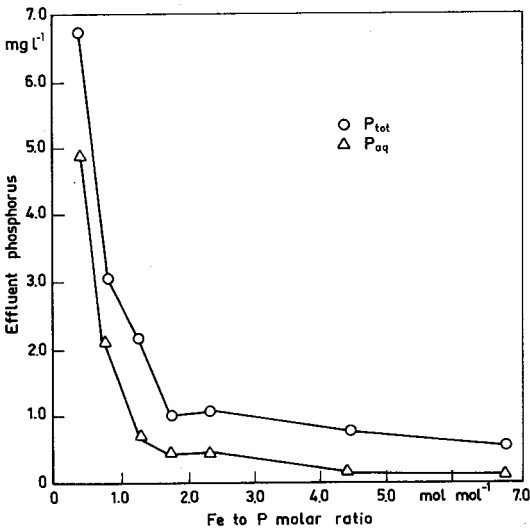| Fe^{2+} feed	Nitrification rate, g kg^{-1} h^{-1}		t-test
g m^{-3}	S	C	
11.2	0.8 ± 0.05	1.02 ± 0.13	0.86
16.0	0.74 ± 0.12	1.03 ± 0.14	1.56
20.0	0.83 ± 0.08	1.14 ± 0.10	2.33*
29.2	1.07 ± 0.12	1.72 ± 0.10	4.14***
40.8	0.97 ± 0.10	1.74 ± 0.11	5.47***
50.0	0.41 ± 0.04	1.93 ± 0.16	9.05***

Fig. 3. Effluent phosphorus at different Fe to P molar ratio in n process.

(Fig. 3). The total effluent phosphorus was mainly bound to the suspended solids.

5.23 SVI and suspended solids

The SVI was 40—130 ml g^{-1} in the simultaneous precipitation unit and 80—140 ml g^{-1} in the control unit. A significant difference between the units was observed when the ferrous sulphate feed was increased above 30 g m^{-3} as Fe^{2+}. The SVI remained then well below 70 ml g^{-1} in the simultaneous unit and was about 100 ml g^{-1} in the control unit (Appendix 1).

The effluent suspended solids concentration was 10-80 mg l^{-1} in both units and no positive correlation was observed with either the SVI value, Fe^{2+} feed or hydraulic loading of the units.

The effluent suspended solids concentration increases occasionally when the pH dropped below 6.0 due to the total loss of alcalinity caused by effective nitrification. The SVI value did not, however, increase.

BOD and COD-removal was typical for activated sludge plants and no difference could be observed between the units (Appendix 1).

5.3 nd process

The nd process (nitrification followed by denitrification) was studied with two parallel units. One unit was fed with ferrous sulphate and the other was run as a control unit. The ferrous sulphate dose was 5—15 g m^{-3} Fe^{2+}. Otherwise the units were run identically.

The process was started by taking a seed from a working activated sludge plant and aerating both reactors for approximately two weeks. When the nitrification rate was constantly high, the second reactor was turned anoxic with only slow mixing of

Table 7. Process parameters of nd-process during different periods in simultaneous precipitation unit (S) and control unit (C).

Process parameter	Period											
	1		2		3		4		5		6	
	S	C	S	C	S	C	S	C	S	C	S	C
Sludge load, kg kg^{-1} d^{-1}	0.08	0.08	0.06	0.06	0.09	0.08	0.07	0.05	0.05	0.05	0.05	0.04
Sludge age, d	23	24	14	17	17	27	(> 30)	(> 30)	(> 30)	29	29	18
Retention time n-reactor, h	7.5	7.5	8.7	8.7	8.7	8.7	8.7	8.7	6.5	6.5	6.5	7.5
Retention time d-reactor, h	8.4	8.4	7.7	7.7	10.0	10.0	11.3	11.3	7.6	7.6	7.5	7.5
Recirculation, %	200	200	200	200	150	150	200	200	210	210	200	200
Ferrous feed, g m^{-3} (Fe^{2+})	2	0	2	0	10	0	10	0	10	0	10	0
Hydraulic surface load, m^3 m^{-2} h^{-1}	0.29	0.29	0.20	0.20	0.19	0.19	0.19	0.19	0.25	0.25	0.25	0.25
Sludge volume load, m^3 m^{-2} h^{-1}	0.13	0.20	0.16	0.17	0.06	0.12	0.08	0.10	0.19	0.16	0.20	0.13
Temperature, °C	10.9	11.1	10.0	10.5	11.2	11.5	11.6	11.8	9.9	10.1	10.4	10.4
Time of run, d	14	14	17	17	21	21	21	21	15	15	15	15

the sludge. The controlled parameters were influent flow, detention times, quantity of excess sludge and Fe dosage (Table 7).

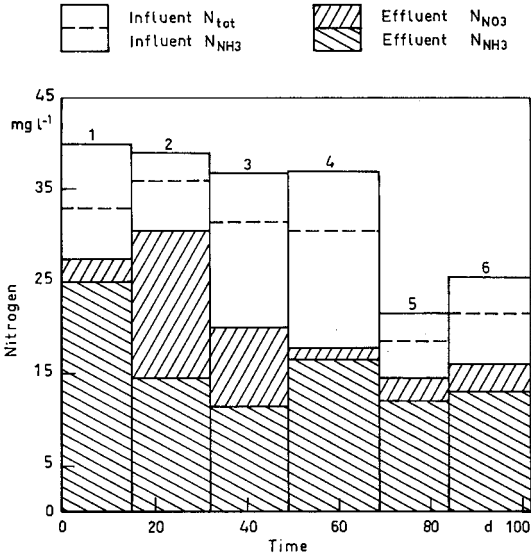The results grouped into periods based on time are presented in Appendix 2.

Fig. 4. Average influent total nitrogen (N_{tot}), ammonia (N_{NH4i}) and effluent ammonia ($N_{NH4,e}$) and nitrate ($N_{NO3,e}$) in nd process simultaneous precipitation unit during different periods.
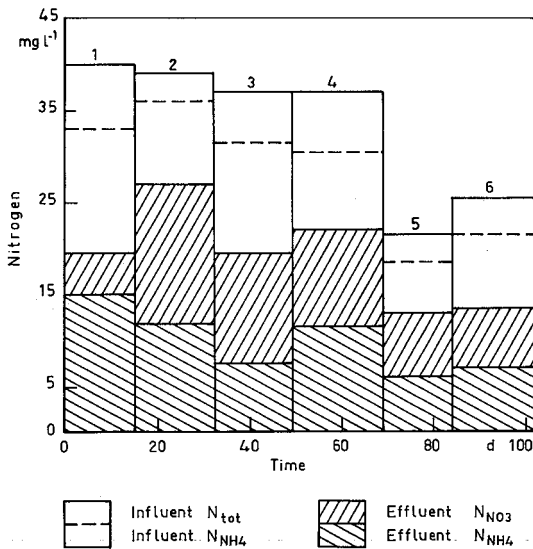

Fig. 5. Average influent total nitrogen (N_{tot}), ammonia (N_{NH4i}) and effluent ammonia ($N_{NH4,e}$) and nitrate ($N_{NO3,e}$) in nd process control unit during different periods.

5.31 Nitrogen removal

The nitrification rate was 20—70 % in the simultaneous precipitation unit and 50 to 80 % in the control unit. Total nitrogen removal was subsequently 20—50 % and 30—50 % (Fig. 4 and 5, Table 8). The control unit was more effective in respect to nitrification during periods 1 and 3 to 6 but there were no actual differences in total nitrogen removal except during period 1, when total nitrogen removal was 50 % in the control unit compared with 31 % in the simultaneous precipitation unit. The nitrification rates k_n were 0.5—1.3 g kg^{-1} h^{-1} and 0.8—1.4 g kg^{-1} h^{-1} and the denitrification rates k_d 0.3—0.8 g kg^{-1} h^{-1} and 0.3—0.7 g kg^{-1} h^{-1} in the simultaneous precipitation and control unit, respectively (Table 9).

5.32 Phosphorus removal

Effluent total phosphorus varied between 1.0 and 5.0 mg l^{-1} depending on the Fe:P molar ratio. Soluble phosphorus was 0.3—4.5 mg l^{-1}. The Fe:P-molar ratio was 0—3 mol mol^{-1} (Fig. 6).

5.33 SVI, suspended solids, BOD and COD

The SVI was rather high in both reactors of both units. No consistent difference between the units and reactors could be observed (Appendix 2).
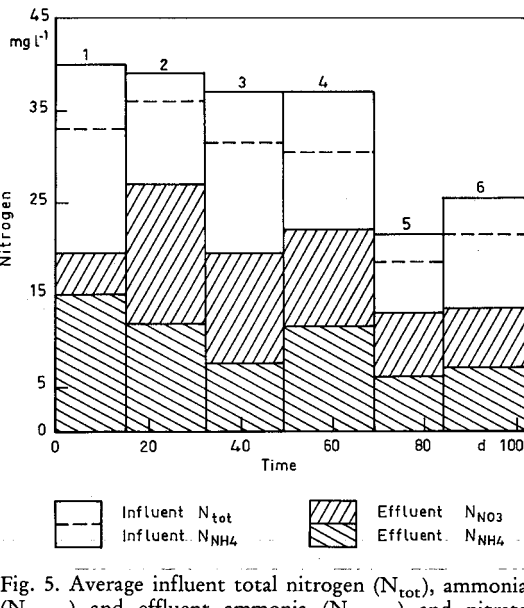

Fig. 6. Effluent phosphorus at different Fe to P molar ratios in nd process.

Table 8. Ammonia removal, nitrogen removal and t-test between units after arc sin $\sqrt{x}$ transformations in nd-process during different periods (S is simultaneous precipitation, C is control).

Period	Nitrification rate, %			Nitrogen removal, %		
	S	C	t-test	S	C	t-test
1	37	62	4.86***	31	50	4.39***
2	63	69	1.09	22	30	1.06
3	69	79	2.50*	44	46	0.29
4	55	69	2.39*	51	40	2.02°
5	44	72	4.05***	32	39	0.52
6	47	71	5.20***	36	45	1.72

Table 9. Nitrification rate (k_n) and denitrification rate (k_d) and their standard error of mean in nd-process during different periods (S is simultaneous precipitation, C is control).

Period	Nitrification rate, g kg^{-1} h^{-1}		Denitrification rate, g kg^{-1} h^{-1}	
	S	C	S	C
1	0.93 ± 0.15	1.36 ± 0.12	0.45 ± 0.06	0.63 ± 0.04
2	0.81 ± 0.07	0.90 ± 0.08	0.33 ± 0.07	0.39 ± 0.06
3	1.32 ± 0.08	1.29 ± 0.07	0.70 ± 0.07	0.65 ± 0.06
4	1.29 ± 0.15	1.23 ± 0.09	0.82 ± 0.10	0.53 ± 0.04
5	0.60 ± 0.07	0.87 ± 0.09	0.38 ± 0.08	0.38 ± 0.07
6	0.74 ± 0.07	1.17 ± 0.07	0.46 ± 0.05	0.41 ± 0.03

Table 10. Process parameters of dn-process, simultaneous precipitation unit, during different periods.

		Period							
		1	2	3	4	5	6	7	8
Sludge load	kg kg^{-1} d^{-1}	0.08	0.11	0.17	0.12	0.11	0.12	0.08	0.05
Sludge age	d	32	39	38	22	19	22	41	53
Retention time, n-reactor	h	8.0	8.0	8.0	8.0	8.0	8.0	10.0	10.0
Retention time, d-reactor	h	5.2	5.2	5.2	5.2	6.5	6.5	6.5	6.5
Recirculation	%	200	400	400	400	400	400	400	400
Ferrous feed	g m^{-3} (Fe^{2+})	16	16	20	20	20	26	26	26
Hydraulic surface load	m^3 m^{-2} h^{-1}	0.32	0.32	0.32	0.32	0.25	0.25	0.25	0.25
Sludge volume load	m^3 m^{-2} h^{-1}	0.21	0.10	0.06	0.06	0.07	0.08	0.15	0.20
Temperature	°C	16.6	16.5	18.1	18.0	15.8	14.5	14.1	12.2
Time of run	d	19	25	12	15	46	12	22	43

Effluent suspended solids concentration was below 15 mg l^{-1}, BOD$_7$ below 25 mg l^{-1} and KMnO$_4$ below 75 mg l^{-1} in both units. There were no differences between the units (Appendix 2).

5.4 dn process

The dn process (denitrification followed by nitrification and with increased recirculation rate) was studied with two parallel units. The units were run independently of each other one as a simultaneous unit and the other as a biological unit. The controlled parameters were influent flow, detention times, quantity of excess sludge removed and Fe-dosage (Tables 10 and 11). The results grouped into periods based on time are presented in Appendix 3 and 4.

5.41 Nitrogen removal

In the simultaneous precipitation unit the nitrification rate was more than 80 % during all periods except periods 6 and 7 when it decreased to 45—55 %. In the control unit the lowest rates were 70—80 % during periods 5 to 7, during periods 1 to 4 the rate was more than 90 %.

Total nitrogen removal varied between 35 and 70 % in the simultanous precipitation unit and between 45 and 60 % in the control unit (Fig. 7 and 8).

The nitrification rates k_n were 0.80—3.0 g kg^{-1} h^{-1} and 0.5—2.6 g kg^{-1} h^{-1} and the denitrification
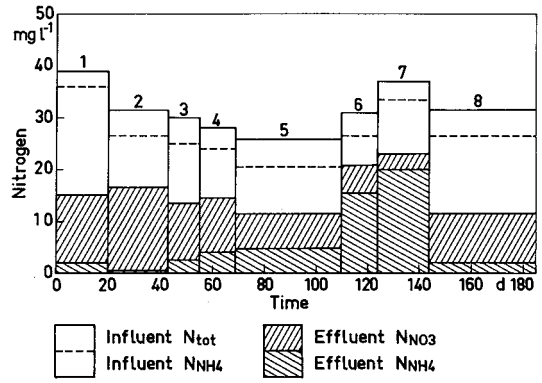
Fig. 7. Average influent total nitrogen ($N_{tot,i}$) ammonia ($N_{NH4,i}$) and effluent ammonia ($N_{NH4,e}$) and nitrate ($N_{NO3,e}$) in dn process simultaneous precipitation unit at different periods.
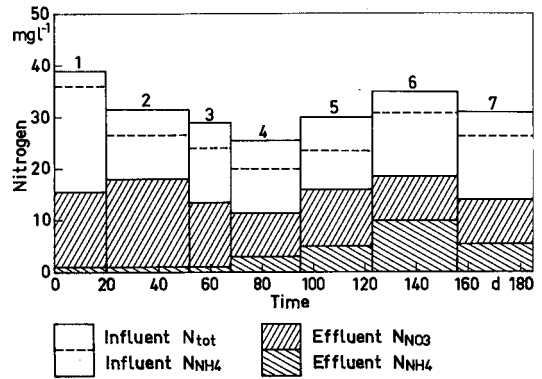
Fig. 8. Average influent total nitrogen ($N_{tot,i}$) ammonia ($N_{NH4,i}$) and effluent ammonia ($N_{NH4,e}$) and nitrate ($N_{NO3,e}$) in dn process control unit at different periods.

Table 11. Process parameters of dn-process, control unit, during different periods.

		Period						
		1	2	3	4	5	6	7
Sludge load	kg kg^{-1} d^{-1}	0.11	0.12	0.16	0.21	0.13	0.08	0.04
Sludge age	d	17	19	12	13	19	32	50
Retention time, n-reactor	h	8.0	8.0	8.0	8.0	8.0	8.0	10.0
Retention time, d-reactor	h	5.2	5.2	5.2	6.5	6.5	6.5	6.5
Recirculation	%	200	400	400	400	400	400	400
Ferrous feed	g m^{-3} (Fe^{2+})	0	0	0	0	0	0	0
Hydraulic surface load	m^3 m^{-2} h^{-1}	0.32	0.32	0.32	0.25	0.25	0.25	0.25
Sludge volume load	m^3 m^{-2} h^{-1}	0.11	0.09	0.07	0.05	0.09	0.18	0.24
Temperature	°C	17.8	17.3	18.0	17.2	15.1	13.5	12.1
Time of run	d	19	36	15	32	25	35	29

rates k_d were 0.75—2.9 g kg^{-1} h^{-1} and 0.5—2.3 g kg^{-1} h^{-1} in the simultaneous precipitation and control unit respectively (Tables 12 and 13).

Table 12. Nitrification rate (k_n) and denitrification rate (k_d) and their standard error of mean in dn-process, simultaneous precipitation unit, during different periods.

Period	Nitrification rate g kg^{-1} h^{-1}	Denitrification rate g kg^{-1} h^{-1}
1	1.53 ± 0.16	1.57 ± 0.26
2	1.89 ± 0.20	1.13 ± 0.23
3	3.09 ± 0.39	2.89 ± 0.75
4	1.61 ± 0.12	1.31 ± 0.18
5	1.54 ± 0.15	1.27 ± 0.16
6	1.14 ± 0.15	1.00 ± 0.18
7	0.82 ± 0.12	0.80 ± 0.10
8	0.80 ± 0.03	0.79 ± 0.04

Table 13. Nitrification rate (k_n) and denitrification rate (k_d) and their standard error of mean in dn-process, control unit, during different periods.

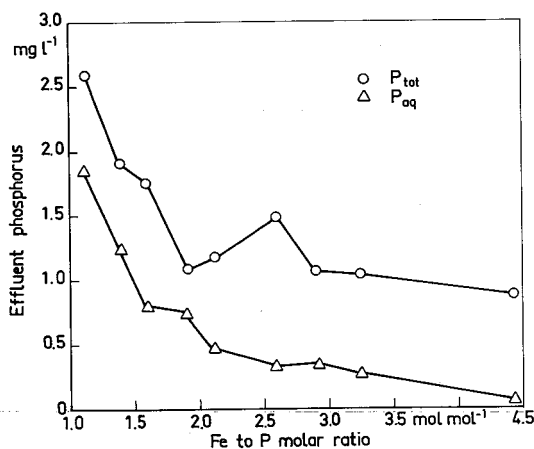| Period	Nitrification rate g kg^{-1} h^{-1}	Denitrification rate g kg^{-1} h^{-1}
1	2.19 ± 0.22	2.20 ± 0.36
2	2.41 ± 0.31	2.21 ± 0.49
3	1.77 ± 0.14	2.30 ± 0.97
4	2.54 ± 0.19	2.04 ± 0.21
5	2.23 ± 0.43	1.86 ± 0.47
6	1.16 ± 0.11	0.98 ± 1.26
7	0.51 ± 0.03	0.52 ± 0.06

Fig. 9. Effluent phosphorus at different Fe to P molar ratios in dn process.

5.42 Phosphorus removal

Phosphorus removal in the simultaneous precipitation unit was typical for this precipitation process.

Effluent total phosphorus was 1.0—2.3 mg l^{-1} and soluble phosphorus 0.4—1.1 mg l^{-1} depending on the Fe-P molar ratio, which varied between 2.5 and 1.5 mol mol^{-1} (Fig. 9). No significant difference in soluble phosphorus between the anoxic and aerobic unit could be noticed (Appendix 3).

5.43 SVI, suspended solids, BOD and COD

The SVI-value of the simultaneous precipitation unit was 60—135 ml g^{-1} without any significant difference between the reactors. The control unit had somewhat higher values: 100—180 ml g^{-1} (Appendix 4).

Effluent suspended solids were 10—50 mg l^{-1} and 15—30 mg l^{-1} in the simultaneous precipitation unit and control units respectively.

The BOD reduction was 85—95 % and 71—85 % and COD-reduction 70—80 % and 60—80 % in the simultaneous precipitation units and control unit respectively. Effluent BOD$_7$ was 10—20 mg l^{-1} in the simultaneous precipitation unit and 15—35 mg l^{-1} in the control unit. Corresponding values of COD were 45—65 mg l^{-1} (KMnO$_4$) (Appendix 3).

5.5 Intermittent aeration

The intermittent aeration process was run with two parallel units during approx two years. During the first year the reactor volume was 1.3 m^3 and one unit was fed with ferrous sulphate and the other was used as a control unit. During the second year the reactor volume was 2.8 m^3 and both units were fed with ferrous sulphate. The controlled parameters were detention time, sludge age, chemical dosage and oxic/anoxic times (Tables 14 and 15). The results grouped according to test periods are presented in Appendix 5—7.

5.51 Nitrogen removal

The nitrification rate was usually better than 80 % except for periods no 1, 7, 13 and 20 in unit 1 and periods no 1, 6, 11, 14, 16 to 18 in unit 2. Total nitrogen removal varied between 30 and 65 % and

Table 14. Process parameters of intermittent aeration, unit 1 during different periods.

Period	Sludge load kg kg⁻¹ d⁻¹	Sludge age d	Retention time h	Aerobic time h	Anaerobic time h	Recirculation %	Ferrous feed g m⁻³ Fe²⁺	Hydraulic surface load m³ m⁻² h⁻¹	Sludge volume load m³ m⁻² h⁻¹	Temperature °C	Time of run d
1	0.07	79	8.7	2.0	2.0	150	16	0.22	0.18	11.3	13
2	0.06	109	13.0	2.0	2.0	100	16	0.13	0.12	10.9	13
3	0.03	70	13.0	2.0	1.0	100	16	0.13	0.12	9.5	21
4	0.02	71	13.0	2.0	1.5	100	32	0.13	0.12	8.6	21
5	0.03	49	13.0	2.0	1.0	100	16	0.13	0.12	14.1	18
6	0.06	20	13.0	2.0	1.5	100	16	0.13	0.12	16.4	5
7	0.10	27	8.7	2.0	2.0	150	16	0.19	0.17	18.9	19
8	0.06	31	8.7	2.0	2.0	150	16	0.19	0.15	17.2	21
9	0.11	32	8.7	2.0	1.0	150	16	0.19	0.16	16.2	19
10	0.06	34	8.7	2.0	1.5	150	16	0.19	0.17	13.8	19
11	0.04	39	8.7	2.0	1.5	150	20	0.19	0.17	11.0	20
12	0.05	35	8.7	2.0	1.5	150	20	0.19	0.17	10.5	22
13	0.08	37	13.0	2.0	1.5	200	16	0.31	0.25	10.7	27
14	0.06	39	13.0	1.5	1.0	200	16	0.25	0.24	9.4	17
15	0.05	39	13.0	1.5	1.0	200	16	0.25	0.24	9.9	27
16	0.05	43	13.0	1.5	1.0	200	20	0.25	0.24	11.6	20
17	0.04	43	13.0	1.5	1.0	200	20	0.25	0.23	15.3	28
18	0.05	27	13.0	0.75	0.75	200	20	0.25	0.23	18.5	27
19	0.05	19	13.0	0.75	0.75	200	20	0.25	0.20	17.8	21
20	0.05	19	13.0	0.75	0.75	200	20	0.25	0.18	16.7	22
21	0.06	16	14.0	0.75	0.75	200	24	0.25	0.07	13.2	23
22	0.06	21	14.0	0.75	0.75	200	24	0.25	0.07	10.2	19
23	0.05	21	14.0	1.0	1.0	200	24	0.25	0.07	9.3	18

Table 15. Process parameters of intermittent aeration process, unit 2 during different periods.

Period	Sludge load kg kg⁻¹ d⁻¹	Sludge age d	Retention time h	Aerobic time h	Anaerobic time h	Recirculation %	Ferrous feed g m⁻³ Fe²⁺	Hydraulic surface load m³ m⁻² h⁻¹	Sludge volume load m³ m⁻² h⁻¹	Temperature °C	Time of run d
1	0.09	30	6.5	2.0	2.0	200	0	0.24	0.22	12.2	13
2	0.08	34	13.0	2.0	2.0	100	0	0.13	0.11	14.5	13
3	0.19	31	13.0	2.0	1.0	100	0	0.13	0.10	12.5	21
4	0.04	38	13.0	2.0	1.5	100	0	0.13	0.12	10.3	26
5	0.02	39	13.0	2.0	1.0	100	0	0.13	0.12	15.3	34
6	0.11	17	8.7	2.0	2.0	150	0	0.19	0.14	20.3	19
7	0.08	15	8.7	2.0	2.0	150	0	0.19	0.09	17.7	21
8	0.13	16	8.7	2.0	1.0	150	0	0.19	0.17	15.8	19
9	0.06	23	8.7	2.0	1.5	150	0	0.19	0.16	12.9	39
10	0.06	20	8.7	2.0	1.5	150	0	0.19	0.16	11.7	21
11	0.03	22	26	2.0	1.5	100	16	0.25	0.17	11.1	28
12	0.03	24	26	1.5	1.0	100	16	0.13	0.07	9.4	17
13	0.03	24	26	1.5	1.0	100	16	0.13	0.06	9.9	27
14	0.03	23	26	1.5	1.0	100	16	0.13	0.08	11.6	20
15	0.03	23	26	1.5	1.0	100	16	0.13	0.08	15.3	28
16	0.06	27	13	1.5	1.5	200	20	0.25	0.19	18.5	28
17	0.05	19	13	1.0	1.0	200	20	0.25	0.17	15.7	44
18	0.04	16	13	1.0	1.5	200	20	0.25	0.18	13.0	11
19	0.04	24	13	1.0	1.5	200	20	0.25	0.23	10.6	19
20	0.05	23	13	1.0	1.5	200	20	0.25	0.24	10.2	18

the best reductions were approximately 70 % (Fig. 10 and 11).

The nitrification rates k_n were 0.28—1.62 g kg^{-1} h^{-1} in unit 1 and 0.46—2.19 g kg^{-1} h^{-1} in unit two. The denitrification rates k_d were 0.27—1.46 and 0.33—1.61 g kg^{-1} h^{-1} respectively (Tables 16 and 17).

k_n and k_d were calculated from equations 3 and 4:

$$k_n = \frac{(N_{tot,i} - N_{NH4,e})}{t_d \cdot MLVSS} \cdot \frac{t_o}{t_a + t_o} \qquad (3)$$

$$k_d = \frac{(N_{tot,i} - N_{NH4,e} - N_{NO3,e})}{t_d \cdot MLVSS} \cdot \frac{t_a}{t_a + t_o} \qquad (4)$$

where
t_d is hydraulic detention time, h
t_o is oxic period, h
t_a is anoxic period, h

5.52 Phosphorus removal

Total effluent phosphorus was 0.8—2 mg l^{-1} and soluble phosphorus 0.1—1.0 mg l^{-1} depending on the Fe:P molar ratio, which varied between 0.5 and 4.5 mol mol^{-1} (Fig. 12, Appendix 5 and 6).

5.53 SVI, suspended solids, BOD and COD

The SVI was 60—135 ml g^{-1} in unit 1 and 80—170 ml g^{-1} in unit two, which can be considered normal for nitrifying sludge (Appendix 7).

Effluent suspended solids were rather high in both units: 20—40 mg l^{-1}. Effluent BOD$_7$ was usually less than 25 mg l^{-1} and COD (KMnO$_4$) less than 70 mg l^{-1} which corresponded to removal rates of 80 % and 70 %. No differences could be observed between the units (Appendix 5 and 6).
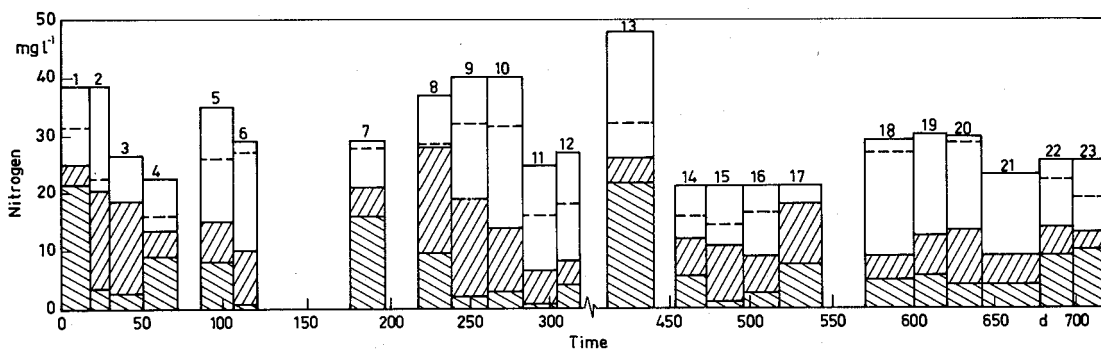
Fig. 10. Average influent total nitrogen (N_{tot}), ammonia ($N_{NH4,i}$) and effluent ammonia ($N_{NH4,e}$) and nitrate ($N_{NO3,e}$) in intermittent aeration process, unit 1 during different periods.

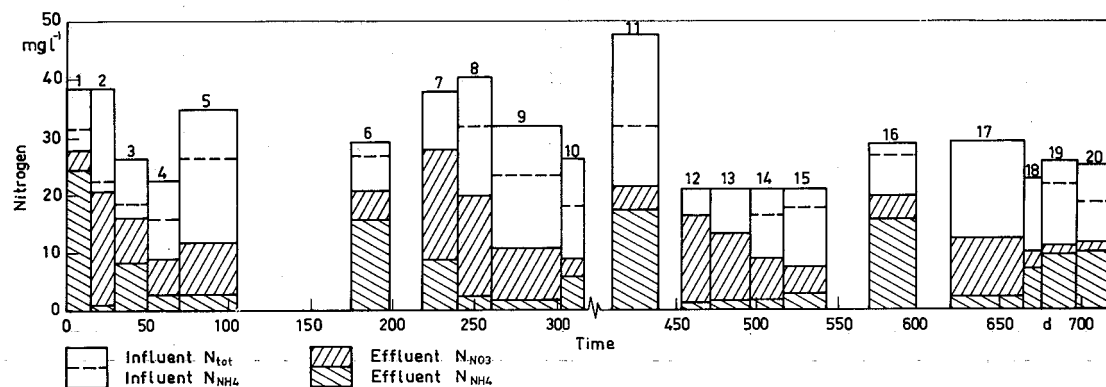Fig. 11. Average influent total nitrogen (N_{tot}), ammonia ($N_{NH4,i}$) and effluent ammonia ($N_{NH4,e}$) and nitrate ($N_{NO3,e}$) in intermittent aeration process, unit 2 during different periods.
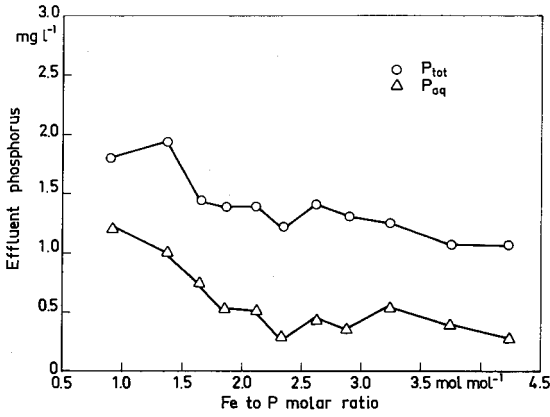
Fig. 12. Effluent phosphorus at different Fe to P molar ratios in intermittent aeration process.

Table 17. Nitrification rates (k_n) and denitrification rates (k_d) with standard error of mean in intermittent aeration process, unit 2 during different periods.

Period	Nitrification rate g kg^{-1} h^{-1}	Denitrification rate g kg^{-1} h^{-1}
1	0.70 ± 0.10	0.52 ± 0.07
2	0.96 ± 0.11	1.35 ± 0.26
3	0.79 ± 0.13	1.14 ± 0.20
4	0.69 ± 0.09	0.68 ± 0.09
5	0.71 ± 0.30	1.08 ± 0.57
6	1.10 ± 0.17	0.81 ± 0.13
7	2.19 ± 0.28	0.38 ± 0.26
8	1.46 ± 0.13	1.61 ± 0.29
9	1.25 ± 0.09	1.26 ± 0.10
10	0.89 ± 0.14	0.96 ± 0.23
11	0.59 ± 0.12	0.65 ± 0.15
12	0.47 ± 0.03	0.28 ± 0.05
13	0.46 ± 0.04	0.35 ± 0.05
14	0.56 ± 0.03	0.41 ± 0.04
15	0.51 ± 0.08	0.40 ± 0.03
16	0.53 ± 0.04	0.42 ± 0.05
17	0.98 ± 0.11	0.79 ± 0.13
18	0.97 ± 0.18	0.52 ± 0.08
19	0.82 ± 0.11	0.51 ± 0.08
20	0.70 ± 0.08	0.43 ± 0.05

Table 16. Nitrification rates (k_n) and denitrification rates (k_d) with standard error of mean in intermittent aeration process, unit 1 during different periods.

Period	Nitrification rate g kg^{-1} h^{-1}	Denitrification rate g kg^{-1} h^{-1}
1	0.53 ± 0.11	0.48 ± 0.08
2	0.59 ± 0.15	0.64 ± 0.25
3	0.51 ± 0.06	0.61 ± 0.13
4	0.28 ± 0.04	0.27 ± 0.03
5	0.34 ± 0.04	0.51 ± 0.06
6	0.91 ± 0.09	0.68 ± 0.08
7	0.89 ± 0.08	0.67 ± 0.10
8	1.62 ± 0.10	0.48 ± 0.21
9	1.27 ± 0.16	1.46 ± 0.23
10	1.26 ± 0.11	1.15 ± 0.08
11	0.91 ± 0.04	0.98 ± 0.13
12	0.71 ± 0.12	0.71 ± 0.17
13	0.63 ± 0.10	0.64 ± 0.12
14	0.67 ± 0.04	0.70 ± 0.04
15	0.63 ± 0.07	0.60 ± 0.11
16	0.52 ± 0.04	0.57 ± 0.05
17	0.76 ± 0.11	0.68 ± 0.19
18	0.78 ± 0.07	0.65 ± 0.07
19	1.01 ± 0.13	0.78 ± 0.08
20	0.89 ± 0.12	0.62 ± 0.10
21	1.14 ± 0.09	0.86 ± 0.10
22	0.91 ± 0.11	0.74 ± 0.11
23	0.76 ± 0.10	0.59 ± 0.09

6. DISCUSSION
6.1 Nitrification and nitrogen removal

Nitrification was usually better than 80 % in the dn process and intermittent aeration process in both the control and simultaneous precipitation units, when the ferrous sulphate dosage was less than 130 g m^{-3}. With higher ferrous dosages there was a definite inhibition in the normal activated sludge process (n process), compared with the control unit. The inhibitory effect was lower in the dn process and intermittent aeration process when the loading rate was lower and the sludge age subsequently higher. In the nd process the Fe feed was only 13 g m^{-3} and severe inhibition of nitrification occurred.

The nitrification rates k_n varied between 0.28 and 3.09 g kg^{-1} h^{-1}. By using stepwise discriminant analysis it was concluded that the k_n values were not dependent of either process, or unit and a regression model could be developed using all data. The independent variables tested were temperature, sludge age, ferrous sulphate feed, aerobic and anoxic times, BOD:COD ratio and BOD:N_{tot} ratio. The BOD:COD ratio was chosen because it could indicate toxicity of the wastewater. A change in the BOD:N_{tot} ratio would cause a change in the sludge

composition giving a higher proportion of nitrifiers in the sludge at lower $BOD:N_{tor}$ ratios. The effect of DO was not tested, because it was always more than 2 mg l^{-1}. The pH value was also not taken into consideration, because the processes were not buffered which means that at high k_n rates and effective nitrate formation the pH would drop and on the other hand denitrification increases the pH.

The regression equation was then

$$k_n = 0.93 + 0.10 \cdot T - 0.0068 \cdot t_s - 0.0023 \cdot FE - 0.20 \cdot BN \qquad (5)$$

where
T   is temperature, °C
t_s is sludge age, d
FE   is ferrous sulphate feed, g m^{-3}
BN   is BOD_7 to N_{tot} ratio in influent

The model had a significance of 99.9 %, squared multiple correlation 0.58 and F-statistic 23.1. The coefficients significance level was more than 99 % except for the coefficient for G, which had a sifnificance level of 97.5 %. The residual mean square was 0.143 and the residuals were normally distributed. The model is physically logical, but it is valid only when G is 10—50 d, T is 10—18°C, and ferrous sulphate feed 8—40 g m^{-3} of Fe^{2+}. It is especially important to note that the reduction of sludgeage to a value were wash-out of the nitrifying organisms occur, totally inhibits nitrification. This is usually the case, when sludge age is less than 10 d at 10°C and 5 d at 20°C in normal activated sludge processes (EPA 1975). It can be concluded that temperature had the most strongest effect on the k_n-value. The effect of ferrous dosage in the model was less pronounced compared with the observations on nitrification in the normal activated sludge runs, but this could be explained by the fact that high dosages were used only for a very brief period (1.5 months) and in only unit compared to the total research which lasted 42 months.

The unexplained variation in the model was high, 42 % and no transformation or other independent variables improved the model. This is due to the heterogenous data, short test periods and unsystematic variations in the influent with respect to toxic substances.

The denitrification rates varied between 0.1 and 2.89 g kg^{-1} h^{-1}. From the results of discriminant analyses it was concluded, that the k_d values differed between the processes so that the values in the dn process were higher than in the other processes. No regression model could be developed for k_d and no systematic changes or correlations with other variables were found.

The denitrification rates were lower than stated in literature. In the nd process the k_d value were 0.33—0.82 g kg^{-1} h^{-1} in both units while work by Wuhrman (1968), Johnson (1972) and Sutton et al. (1979) arrived to 0.5—1.6 g kg^{-1} h^{-1} in the same temperature range. In the nd process the denitrification rate is limited by endogenours respiration rate, because the organic compounds in the influent are oxidized in the nitrification stage already and only endogenous respiration and oxidation of adsorbed and stored organic matter takes place in the d unit. It can be postulated that when the organic loading is high into the nunit, the k_d value is also higher, because a grater part of the adsorbed organic matter is available for denitrification.

The denitrification rates in the dn process were 0.79—2.30 mg g^{-1} l^{-1} in the simultaneous precipitation unit and 0.52—2.89 mg g^{-1} l^{-1} in the control unit. The rates were appr. 50 % lower than stated in literature (Balakrishnan 1969, Schuster 1970, Johnson 1972). During 5 periods out of 6 the rates were higher in the control unit.

This could indicate that ferrous sulphate had an inhibitory effect on denitrification either due to the sulphate ion which competes with the nitrate ion or due to diffusion limitation caused by the ferrous hydroxide matrix surrounding the bacterial cells. The former cause is less probable because the increase of sulphate ions was only 50—70 % compared to the control unit. The true mechanism of inhibition was not ascertained. Compared with the nd process the denitrification rate was higher because the influent organic carbon was immediately available for denitrification and the reaction rate was only partly limited by the endogenous respiration rate.

In the intermittent aeration process the k_d · values were 0.27—1.41 g kg^{-1} h^{-1} with ferrous sulphate and 0.52—1.61 g kg^{-1} h^{-1} without ferrous sulphate. Also in this process the inhibition of denitrification by ferrous sulphate was observed. The rates were lower than in the dn process. This is thought to be due to the lower organic load to the reactor tank compared with the load to the denitrification tank in the dn-process. The ''best'' results according to total nitrogen removal of the different processes is presented in table 18.

From the point of view of nitrification, equally good results were gained with the dn process and intermittent aeration the nd process giving unacceptable ammonia removal. The ''best'' total nitrogen removals were achieved with intermittent aeration, but no real systematic difference could be observed compared with the results of the dn process. The total nitrogen removal of the nd process was poor because of the low nitrification rate.

Table 18. Summary of best nitrogen removals at two temperature levels (S is simultaneous precipitation, C is control).

	nd-process		dn-process		Intermittent aeration	
	S-unit	control unit	S-unit	control-unit	S-unit	control unit
Nitrification rate, %	55	71	95	95	96	91
Total N-removal, %	51	45	66	55	69	50
k_n, g kg^{-1} h^{-1}	1.29	1.19	0.80	0.51	0.59	1.25
k_d, g kg^{-1} h^{-1}	0.82	0.41	0.79	0.52	0.64	1.26
T, °C	11.6	10.4	12.2	12.1	10.8	12.8
Sludge load, kg kg^{-1} d^{-1}	0.065	0.042	0.048	0.041	0.06	0.06
SRT, d	18	18	53	50	70	23
Total detention time, h	10	15	16.5	16.5	13	8.7
Nitrification rate, %			95	98	99	89
Total N-removal, %			59	58	58	70
k_n, g kg^{-1} h^{-1}			1.53	2.19	0.76	0.96
k_d, g kg^{-1} h^{-1}			1.57	2.20	0.69	1.35
T, °C			17.8	17.8	15.3	14.5
Sludge load, kg kg^{-1} d^{-1}			0.08	0.11	0.04	0.08
SRT, d			32	17	43	34
Total detention time, h			13.2	13.2	13	13

Altogether the reaction rates and total nitrogen removals were considerably lower than stated in other experiments and already existing full scale applications. This was true both for the simultaneous precipitation units and control units. This is thought to be due to the toxic compounds in the influent.

6.2 Phosphorus removal

The effluent total phosphorus in the simultaneous precipitation units varied between 0.45 and 3.0 mg l^{-1} and soluble phosphorus between 0.04 and 2.6 mg l^{-1}. Stepwise descriminant analysis did not indicate that there was any difference between the processes. Especially it was noticeable that during the anoxic conditions no dissolving of precipitated phosphorus occurred. It is assumed that as long as there was nitrate present in the reactors, the redox potential was high enough to keep the precipitated iron in an oxidated and thus insoluble state.

Regression equations were calculated for total and soluble effluent solids using as independent variables Fe:P molar ratio, temperature, effluent pH and alcalinity, anoxic detention time, sludge load and sludge volume load. Stepwise regression gave the following equations:

$$P_{tot} = 0.93 + 1.05/M_{FeP} \qquad (6)$$
$$(R^2 = 0.96 \; F = 206^{***})$$

The significance of the coefficients were better than 99.9 % and the residuals were normally distributed.

$$P_{sol} = 0.11 + 1.130/M_{FeP}$$
$$(R^2 = 0.97, F = 287^{***})$$

The significance of the intercept was 99 % and the coefficient 99.99 %. (Fig. 13).

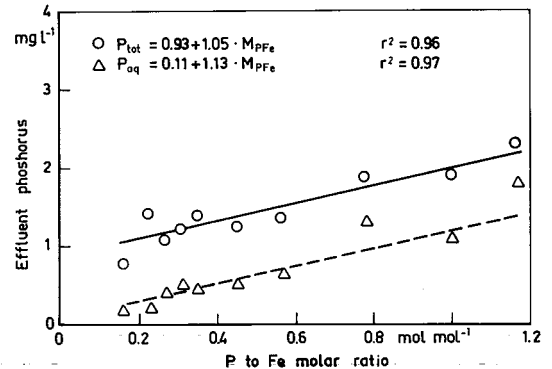Fig. 13. Effluent total phosphorus (P_{tot}) and soluble phosphorus (P_{aq}) at different P to Fe molar ratios (M_{PFe}) in all processes combined.

In seven full-scale activated sludge plants with simultaneous precipitation, the mean effluent total phosphorus was appr. 1 mg l^{-1} and soluble phosphorus 0.5 mg l^{-1} at Fe:P molar ratio 1.5 mol mol^{-1}. The soluble phosphorus decreased to 0.2 mg l^{-1} at Fe:P molar ratio 3 mol mol^{-1} (Niemelä 1982). In this study the corresponding values were 1.6 mg l^{-1} total P and 0.80 mg l^{-1} soluble P at 1.5 mol mol^{-1} and 0.5 mg l^{-1} soluble P at 3.0 mol mol^{-1} indicating somewhat poorer phosphorus removals.

6.3 Suspended solids, BOD$_7$ and COD

The effluent suspended solids concentration was rather high in all processes and units except for the nd process. No systematic changes were found and no correlations with the hydraulic characteristics as surface load, or sludge volume surface load could be found for either all units and processes separately or combined. The highest suspended solids concentration in the effluent were in the intermittent aeration process, both in the simultaneous precipitation units and control unit (30—45 mg l^{-1}) and the lowest in the dn-process, simultaneous precipitation unit (9 mg l^{-1}). The high concentrations could be caused by the rather long sludge age, which causes deflocculation of the sludge and also by partial denitrification in the settling tank. Slow mixing prior to settling in the nd process did on the other hand improve flocculation of the sludge thus decreasing the effluent suspended solids. The high suspended solids concentrations were also reflected in the effluent BOD$_7$ and COD, which were higher than normally is expected from well-operated nitrifying activated sludge plants. Occasional analysis of soluble BOD$_7$ showed that the greater part of the total BOD$_7$ was bound to the suspended solids. Soluble BOD$_7$ was always less than 10 mg l^{-1}.

6.4 pH and alkalinity

One problem which arises from nitrification is the reduction of alkalinity with subsequent decrease in pH which again causes deflocculation of the sludge and increased suspended solids in the effluent. The reduction of alkalinity is 0.143 mol g^{-1} of ammonia nitrogen oxidized to nitrate. When denitrification is adopted, part of the lost alkalinity is regained.

The increase is 0.07 mol g^{-1} of nitrate nitrogen reduced to nitrogen gas. The addition of chemicals, eg. metal ions also reduces alcalinity. When adopting simultaneous precipitation with ferrous sulphate, the theoretical reactions are as follows:

$$Fe^{2+} \rightarrow Fe^{3+} + e^- \tag{8}$$
$$Fe^{3+} + HPO^{2-} \rightarrow FePO_4 + H^+ \tag{9}$$
$$Fe^{3+} + 3H_2O \rightarrow Fe(OH)_3 + 3H^+ \tag{10}$$
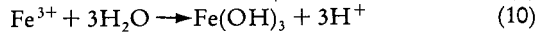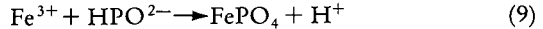
Equation (8) represents oxidation of Fe^{2+} to Fe^{3+} in the aeration basin. Equation (9) represents the precipitation of phosphorus with the liberation of 1 mol of H^+ for every mole of phosphorus precipitated. Equation (10) represents the hydrolysis of surplus Fe^{+3}, which is not bound to phosphorus. Another possible reaction is the formation of ferric carbonate, but this is not taken into consideration.

Combining all these reactions a total change of alkalinity, ΔALK can be calculated from equation (11)

$$\Delta ALK = 0.143 \cdot (N_{tot,i} - N_{NH4,e}) - 0.07 \cdot (N_{tot,i} - N_{NH4,e} - N_{NO3,e}) + \frac{3 \cdot Fe}{55} - \frac{2 \cdot (P_{tot,i} - P_{aq,e})}{31} \tag{11}$$

A fairly good correlation was achieved between the calculated and actual changes in alkalinity (Fig. 14). The mean calculated alkalinity change of the whole set of data was 2.85 mmol l^{-1} and the mean observed change was 2.87 mmol l^{-1}.
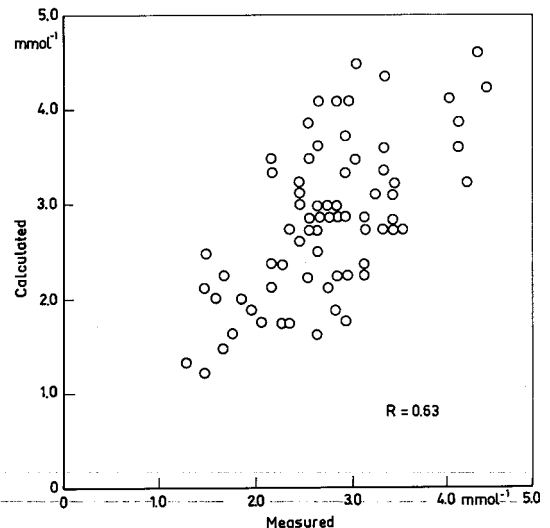

Fig. 14. Calculated and observed alkalinity changes in all processes.

In general it can be stated that when nitrification is adopted, also denitrification should be considered from the point of view of process operation. The addition of alcalinity in the form of lime is rather expensive and clogging problems in the process caused by calcium carbonates and sulphates can be expected.

7. SUMMARY AND CONCLUSIONS

Experiments on the possibilities to combine nitrification and denitrification with simultaneous precipitation of phosphorus with ferrous sulphate were carried out on pilot-plant scale. The processes which were studied were one-sludge normal nitrification with activated sludge (n process) nitrification-denitrification (nd process) pre-denitrification (dn process) and intermittent aeration.

The following conclusions were made:

1. Ferrous sulphate had an inhibitory effect on nitrification in the n process when the dosage exceeded 25 g m^{-3} Fe^{2+} at loading rates of 0.1 kg kg^{-1} d^{-1} (BOD$_7$/MLVSS), sludge age of 7—10 d and temperature range 10—17°C.

2. No effective nitrogen removal was achieved with the nd process when the organic sludge load was 0.04—0.08 kg kg^{-1} d^{-1} retention time in the n reactor 6.5—8.7 h and 8.4—10.7 h in the d reactor at 10—12°C. The system sludge age was 14—30 d.

   The limiting reaction was nitrification in the simultaneous precipitation unit (with a maximum ferrous sulphate feed of 13 g m^{-3} Fe^{2+}) and denitrification in the control unit.

3. In the dn process effective nitrification and up to 60 % total nitrogen removal was achieved when the organic load was 0.40—0.11 kg kg^{-1} d^{-1}, retention time in the d-reactor 6.0 h, n-reactor 10 h and temperature 10—17°C. The system sludge age was 19—53 d. The ferrous sulphate feed could be increased to 26 g m^{-3} Fe^{2+} without inhibition of nitrification. The limiting reaction was usually denitrification.

4. In the intermittent process effective nitrification and up to 70 % total nitrogen removal was achieved. The organic sludge load was 0.05—0.11 kg kg^{-1} d^{-1}, detention time 9—26 h, system sludge age 15—40 d, and temperatures 10—17°C. The oxic and anoxic times were 0.5—2 h. The limiting reaction was usually denitrification and ferrous sulphate had an inhibitory effect on denitrification. The ferrous sulphate feed was 16—26 g m^{-3} Fe^{2+}. Clogging of the diffusers

during simultaneous precipitation was experienced.

5. Effluent total phosphorus could be reduced to 1.5 mg l^{-1} and soluble phosphorus to 1.0 mg l^{-1} at an average ferrous to phosphorus molar ratio 2.5 mol mol^{-1}. In this study effective phosphorus removal and effective nitrogen removal could not be combined with any of the processes, because effective phosphorus removal (effluent phosphorus approx. 0.5 mg l^{-1}) would have needed approx. 4 mol mol^{-3} of ferrous sulphate, which again would have caused inhibition of both nitrification and denitrification.

6. Partial denitrification should be adopted in nitrifying activated sludge plants to counter balance the loss of alcalinity caused by nitrification.

7. When the wastewater to be treated contains toxic substances or the concentrations of phosphorus, nitrogen or organic compounds markedly differ from normal domestic sewage, pilot-plant tests should always be made before dimensioning a combined nitrification-denitrification-simultaneous precipitation process.

8. Further research is needed to evaluate the mechanism of inhibition of ferrous sulphate on both nitrification and denitrification.

LOPPUTIIVISTELMÄ

Rautasulfaatilla tapahtuvan jäteveden rinnakkaissaostuksen ja biologisen typenpoiston yhteensoveltuvuutta tutkittiin neljällä eri prosessilla pienoismitassa VTT:n Suomenojan tutkimusasemalla.

Tutkittavat prosessit olivat nitrifikaatio (n-prosessi), nitrifikaatio-denitrifikaatio-prosessi (nd-prosessi), denitrifikaatio-nitrifikaatio-prosessi (dn-prosessi) ja jaksottainen ilmastus. Tutkimuksista on aiemmin julkaistu väliraportit (Valve ja Vuontela 1980, Valve 1981, 1982).

n-prosessissa havaittiin, että rautasulfaatti inhiboi nitrifikaatiota, kun syöttö nousi yli 130 g m^{-3} ferrosulfaattia (26 g m^{-3} rautana) lieteiällä 7—10 d, lietekuormalla 0,10—0,14 10—15°C:ssa.

nd-prosessilla ei saavutettu tehokasta typenpoistoa. Rinnakkaissaostuslinjalla nitrifikaatio estyi jo rauta-annostuksella 13 g m^{-3} (Fe^{2+}) ja denitrifikaationopeus jäi varsin pieneksi hyvin nitrifoivalla vertailulinjalla. Lietekuorma oli 0,04—0,08 kg kg^{-1} d^{-1} lieteikä 14—30 d, n-yksikön viipymä 6,5—8,7 h ja d-yksikön viipymä 8,4—10,7 h 10—16°C:ssa.

dn-prosessin nitrifikaatio oli yleensä yli 80 % ja typenpoisto parhaimmillaan n. 70 %, vaikka ferrosulfaattia annosteltiin 26 g m^{-3} (Fe^{2+}). Kuormitusaste oli alhaisempi kuin nd-prosessissa: lietekuorma 0,04—0,17 kg kg^{-1} d^{-1}* ja lieteikä 19—53 d. Viipymä d-yksikössä oli 5,2—6,5 h ja n-yksikössä 8,7—10 h ja lämpötila oli 10—17°C. Erityisesti denitrifikaationopeus oli suurempi kuin nd-prosessissa kummallakin linjalla.

Jaksottaisella ilmastuksella saavutettiin yleensä yli 80 % nitrifikaatioaste ja parhaimmillaan n. 70 % typenpoisto lietekuormalla 0,04—0,06 kg kg^{-1} d^{-1}, lieteiällä 23—70 d ja viipymällä 8,7—13 h. Jaksotus oli 0,5—2,0 h ilmastus- ja taukoaikaa ja lämpötila 10—17°C. Nitrifikaationopeus oli samaa suuruusluokkaa kuin nd- ja dn-prosesseissa, mutta denitrifikaationopeus alhaisempi kuin dn-prosessissa.

Koko tutkimuksen aikana oli nitrifikaationopeus 0,3—3,0 g kg^{-1} h^{-1}. Voimakkaimmin vaikutti nitrifikaationopeuteen lämpötila. Lisäksi lieteiän pidentäminen, rauta-annostuksen lisääminen ja BOD$_7$-typpisuhteen suureneminen laskivat nitrifikaationopeutta.

Denitrifikaationopeudelle ei voitu laatia yhtenäistä regressiomallia, mutta rautasulfaatti inhiboi denitrifikaatiota. Toisaalta mitä ”tuoreempana” jätevesi saatiin d-yksikköön, sen suurempi oli denitrifikaationopeus. nd-prosessissa ja osin myös jaksottaisessa ilmastuksessa lietteen endogeenihengitys muodostui denitrifikaationopeutta rajoittavaksi tekijäksi.

Fosforin poistossa saavutettiin kokonaisjäännösfosforipitoisuus 1,5 mg l^{-1} ja liukoisen fosforin pitoisuus 1,0 mg l^{-1} Fe-P moolisuhteella 2,5 mol mol^{-1}, mikä vastasi keskimääräisesti toimivien suomalaisten rinnakkaissaostuslaitosten tulosta. dn-prosessin ja jaksottaisen ilmastuksen suurehko kiintoainepitoisuus käsitellyssä jätevedessä piti kokonaisfosforipitoisuuden korkeana. Tämä johtui

sekä selkeyttämössä tapahtuneesta denitrifikaatiosta, jolloin vapautuvat typpikuplat nostivat lietettä pinnalle, että matalasta kuorimitusasteesta, joka yleensä heikentää biologisen flokin muodostusta.

Loppuyhteenvetona voidaan todeta, että saavutettu typenpoisto oli heikompi kuin mihin muualla on päästy. Syynä oli todennäköisesti rautasulfaatti ja käsiteltävän jäteveden sisältämät myrkylliset yhdisteet. Tutkituista prosesseista ovat dn-prosessi ja jaksottainen ilmastus käyttökelpoisia, kun halutaan tehokas nitrifikaatio ja kohtuullinen fosforin poisto, jolloin denitrifikaatiovaiheen tarkoituksena on palauttaa osa nitrifikaation kuluttamasta alkaliteetista. Tällä tavoin säästytään kalkkiannostuksen aiheuttamilta kustannuksilta. Lisäksi saadaan osa nitraatteihin sidotusta hapesta uudelleen käyttöön prosessissa ja säästetään ilmastusenergiaa.

LIST OF SYMBOLS

ALK	alcalinity, mmol l^{-1}
BN	BOD$_7$ to N$_{tot}$ ratio in influent, g g^{-1}
DO	dissolved oxygen
FE	ferrous sulphate feed, expressed as Fe^{2+}, g m^{-3}
k_d	denitrification rate, g kg^{-1} h^{-1} (N$_{NO3}$/MLVSS)
k_n	nitrification rate, g kg^{-1} h^{-1} (N$_{tot}$/MLVSS)
M_{FeP}	Fe to P molar ratio mol mol^{-1}
M_{PFe}	P to Fe molar ratio, mol mol^{-1}
MLSS	activated sludge suspended solids concentration, kg m^{-3}
MLVSS	activated sludge volatile suspended solids concentration, kg m^{-3}
N$_{NH4}$	ammonia nitrogen, mg l^{-1}
N$_{NO3}$	nitrate nitrogen, mg l^{-1}
N$_{tot}$	total nitrogen, mg l^{-1}
NR	nitrification or ammonia removal, %
P$_{aq}$	soluble phosphorus, mg l^{-1}
P$_{tot}$	total phosphorus, mg l^{-1}
Q	flow, m³ h^{-1}
SVI	sludge volume index, ml g^{-1}
t_a	anoxic time, h
t_d	detention time, h
t_o	oxic or aeration time, h
t_s	sludge age, d
T	temperature, °C
V	reactor volume, m³
Δ ALK	change of alcalinity from ingluent to effluent, mmol l^{-1}

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Appendix 1. Influent and effluent composition in n-process during different periods (mean ± standard error of mean).

Sampling point	Period	pH	ALK mmol l⁻¹	SS mg l⁻¹	BOD₇ mg l⁻¹	COD mg l⁻¹	P_{tot} mg l⁻¹	P_{aq} mg l⁻¹	N_{tot} mg l⁻¹	N_{NH_4} mg l⁻¹	N_{NO_2} mg l⁻¹	N_{NO_3} mg l⁻¹	Fe_{tot} mg l⁻¹
I	1	7.4 ± 0.0	3.7 ± 0.1	132 ± 16	116 ± 6	188 ± 24	7.34 ± 0.63		31 ± 1	24 ± 2			
	2	7.3 ± 0.0	3.1 ± 0.1	97 ± 10	110 ± 12	190 ± 11	5.86 ± 0.54		32 ± 2	23 ± 3			
	3	7.4 ± 0.1	4.0 ± 0.1	131 ± 12	128 ± 8	227 ± 18	6.53 ± 0.26		33 ± 1	29 ± 2			
	4	7.2 ± 0.1	2.9 ± 0.2	107 ± 21	63 ± 8	175 ± 10	4.51 ± 0.48		25 ± 2	22 ± 2			
	5	7.2 ± 0.1	3.0 ± 0.2	88 ± 7	70 ± 7	188 ± 22	3.87 ± 0.21		23 ± 1	19 ± 1			
	6	7.3 ± 0.1	3.5 ± 0.3	120 ± 19	91 ± 4	181 ± 12	4.92 ± 0.43		28 ± 2	26 ± 3			
S,E	1	6.6 ± 0.1	0.9 ± 0.1	50 ± 8	26 ± 5	72 ± 9	2.88 ± 0.32	0.67 ± 0.17	22 ± 1	4 ± 1	0.1 ± 0.0	11 ± 3	2.2 ± 0.5
	2	6.6 ± 0.1	0.6 ± 0.1	7 ± 3	20 ± 4	52 ± 4	1.99 ± 0.54	0.80 ± 0.30	21 ± 1	5 ± 1	0.1 ± 0.0	9 ± 3	1.2 ± 0.1
	3	7.0 ± 0.1	1.4 ± 0.2	24 ± 4	21 ± 5	47 ± 2	1.46 ± 0.24	0.59 ± 0.06	25 ± 1	15 ± 1	0.6 ± 0.5	10 ± 6	1.7 ± 0.1
	4	6.7 ± 0.2	0.7 ± 0.1	21 ± 3	19 ± 2	38 ± 3	1.02 ± 0.14	0.36 ± 0.12	20 ± 2	9 ± 1	0.1 ± 0.0	12 ± 3	2.0 ± 0.3
	5	6.7 ± 0.1	0.5 ± 0.1	15 ± 2	15 ± 2	30 ± 3	0.49 ± 0.04	0.04 ± 0.01	17 ± 1	11 ± 1	0.0 ± 0.0	7 ± 3	2.7 ± 0.2
	6	6.5 ± 0.2	0.9 ± 0.3	14 ± 2	22 ± 5	42 ± 5	0.45 ± 0.03	0.13 ± 0.04	20 ± 1	18 ± 2	0.1 ± 0.0	0.5 ± 0.5	3.3 ± 0.9
C,E	1	6.5 ± 0.1	1.2 ± 0.5	81 ± 14	39 ± 11	100 ± 10	5.98 ± 0.31	4.47 ± 0.31	25 ± 1	3 ± 1	0.3 ± 0.0	14 ± 2	0.9 ± 0.9
	2	6.5 ± 0.1	0.6 ± 0.1	67 ± 19	43 ± 15	100 ± 17	6.78 ± 0.60	4.78 ± 0.52	23 ± 1	4 ± 1	0.2 ± 0.1	13 ± 1	2.3 ± 0.1
	3	6.9 ± 0.1	1.4 ± 0.2	44 ± 6	29 ± 5	60 ± 5	4.92 ± 0.29	4.03 ± 0.27	27 ± 1	10 ± 2	0.6 ± 0.5	16 ± 1	0.9 ± 0.1
	4	6.5 ± 0.1	0.4 ± 0.0	23 ± 6	22 ± 4	46 ± 1	3.51 ± 0.27	2.98 ± 0.24	22 ± 1	1 ± 0	0.1 ± 0.0	20 ± 1	0.4 ± 0.2
	5	6.5 ± 0.1	0.5 ± 0.1	16 ± 7	22 ± 2	40 ± 3	2.89 ± 0.24	2.40 ± 0.20	22 ± 1	1 ± 0	0.5 ± 0.0	15 ± 2	0.5 ± 0.3
	6	6.7 ± 0.2	1.0 ± 0.1	11 ± 1	26 ± 4	54 ± 3	1.76 ± 0.49	2.39 ± 0.55	16 ± 1	4 ± 1	0.1 ± 0.0	13 ± 1	0.3 ± 0.1

Properties of the activated sludge in n-process during different periods (mean ± standard error of mean).

Unit	Period	DO mg l⁻¹	MLSS g l⁻¹	MLVSS g l⁻¹	SVI ml g⁻¹	P_{sol} mg l⁻¹
S	1	2.3 ± 0.3	7.23 ± 0.30	4.81 ± 0.25	107 ± 8	1.07 ± 0.19
	2	4.0 ± 1.0	8.90 ± 0.50	6.02 ± 0.48	93 ± 3	1.33 ± 0.38
	3	2.7 ± 0.2	6.99 ± 0.33	4.24 ± 0.24	85 ± 3	0.77 ± 0.09
	4	2.5 ± 0.3	4.55 ± 0.15	2.83 ± 0.21	69 ± 3	0.46 ± 0.11
	5	2.9 ± 0.4	4.64 ± 0.18	2.36 ± 0.15	58 ± 6	0.31 ± 0.09
	6	3.0 ± 0.9	7.01 ± 0.66	3.76 ± 0.49	36 ± 2	0.18 ± 0.05
C	1	2.6 ± 0.4	5.79 ± 0.31	4.19 ± 0.25	114 ± 10	4.16 ± 0.66
	2	2.5 ± 0.2	6.17 ± 0.31	4.57 ± 0.27	129 ± 3	4.81 ± 0.66
	3	2.5 ± 0.1	5.40 ± 0.24	3.84 ± 0.20	117 ± 6	4.32 ± 0.27
	4	2.5 ± 0.4	3.79 ± 0.12	2.69 ± 0.11	86 ± 4	3.39 ± 0.33
	5	2.4 ± 0.4	3.50 ± 0.16	2.35 ± 0.15	83 ± 4	2.30 ± 0.08
	6	3.6 ± 0.4	3.95 ± 0.18	2.57 ± 0.17	118 ± 22	2.93 ± 0.40

I = influent
E = effluent
S = simultaneous precipitation unit
C = control unit

Appendix 2. Influent and effluent composition in nd-process during different periods (mean ± standard error of mean).

Sampling point	Period	pH	ALK mmol/l	SS mg/l	BOD_7 mg/l	COD mg/l	P_{tot} mg/l	P_{aq} mg/l	N_{tot} mg/l	N_{NH_3} mg/l	N_{NO_2} mg/l	N_{NO_3} mg/l	Fe_{tot} mg/l
I	1	7.1 ± 0.0	3.9 ± 0.2	129 ± 9	155 ± 5	251 ± 18	7.39 ± 0.12		40 ± 1	33 ± 1			
	2	7.2 ± 0.1	4.9 ± 0.2	107 ± 6	135 ± 7	228 ± 16	7.47 ± 0.19		39 ± 1	36 ± 1			
	3	7.1 ± 0.0	4.5 ± 0.1	71 ± 8	163 ± 24	192 ± 12	7.33 ± 0.32		37 ± 1	32 ± 1			
	4	7.4 ± 0.0	4.6 ± 0.2	90 ± 9	108 ± 11	172 ± 6	7.36 ± 0.29		37 ± 1	31 ± 2			
	5	7.3 ± 0.0	3.2 ± 0.1	52 ± 6	75 ± 13	122 ± 5	4.18 ± 0.17		21 ± 1	18 ± 1			
	6	7.3 ± 0.0	4.0 ± 0.4	61 ± 4	73 ± 6	141 ± 8	4.32 ± 0.13		25 ± 1	21 ± 1			
S,E	1	7.2 ± 0.1	2.8 ± 0.2	23 ± 4	30 ± 4	84 ± 7	4.70 ± 0.17	4.02 ± 0.15	28 ± 1	25 ± 2	0.0 ± 0.0	2 ± 2	0.7 ± 0.2
	2	6.9 ± 0.1	2.1 ± 0.4	7 ± 3	11 ± 2	56 ± 4	4.70 ± 0.24	4.38 ± 0.18	27 ± 1	15 ± 2	0.2 ± 0.0	16 ± 3	0.2 ± 0.0
	3	7.0 ± 0.0	1.8 ± 0.2	5 ± 1	15 ± 2	56 ± 3	1.82 ± 0.20	2.61 ± 0.33	21 ± 1	11 ± 1	0.5 ± 0.1	9 ± 1	0.4 ± 0.1
	4	7.4 ± 0.0	2.5 ± 0.1	4 ± 1	8 ± 2	49 ± 1	2.77 ± 0.27	2.42 ± 0.19	23 ± 1	17 ± 2	0.1 ± 0.0	1 ± 1	0.4 ± 0.1
	5	7.2 ± 0.0	1.8 ± 0.1	14 ± 2	15 ± 2	48 ± 2	1.77 ± 0.15	1.34 ± 0.13	16 ± 1	12 ± 1	0.1 ± 0.0	2 ± 1	1.9 ± 1.0
	6	7.3 ± 0.0	2.3 ± 0.3	16 ± 1	25 ± 2	49 ± 3	1.61 ± 0.14	1.05 ± 0.10	18 ± 1	13 ± 1	0.1 ± 0.0	3 ± 0	1.5 ± 0.1
C,E	1	7.1 ± 0.0	2.3 ± 0.2	10 ± 1	22 ± 2	69 ± 4	5.16 ± 0.16	4.63 ± 0.11	22 ± 1	15 ± 1	0.0 ± 0.0	5 ± 1	0.2 ± 0.0
	2	6.9 ± 0.0	2.1 ± 0.3	16 ± 8	14 ± 4	61 ± 6	5.22 ± 0.36	4.55 ± 0.23	24 ± 2	12 ± 1	0.3 ± 0.1	15 ± 2	0.5 ± 0.4
	3	6.9 ± 0.1	1.5 ± 0.1	5 ± 1	20 ± 3	59 ± 3	5.17 ± 0.26	4.99 ± 0.26	20 ± 1	7 ± 1	0.4 ± 0.1	12 ± 1	0.4 ± 0.1
	4	7.1 ± 0.1	1.9 ± 0.1	7 ± 2	11 ± 2	53 ± 2	5.13 ± 0.17	4.77 ± 0.28	22 ± 1	11 ± 1	0.4 ± 0.1	11 ± 1	0.6 ± 0.0
	5	7.1 ± 0.0	1.4 ± 0.1	11 ± 1	20 ± 3	52 ± 2	3.20 ± 0.14	2.97 ± 0.14	14 ± 1	6 ± 1	0.2 ± 0.0	7 ± 1	0.4 ± 0.1
	6	7.2 ± 0.1	1.9 ± 0.3	13 ± 1	33 ± 3	53 ± 2	3.06 ± 0.17	2.76 ± 0.14	16 ± 1	7 ± 0	0.2 ± 0.0	7 ± 0	0.3 ± 0.0

Properties of the activated sludge in the nd-process during different periods (mean ± standard error of mean).

Unit	Period	DO mg/l	MLSS g/l	MLVSS g/l	SVI ml/g	P_{sol} mg/l	Redox mV	DO mg/l	MLSS g/l	SVI mg/l	P_{sol} mg/l	Redox mV
S	1	4.2 ± 0.3	4.24 ± 0.13	3.25 ± 0.10	173 ± 5	4.33 ± 0.26	230 ± 7	0	4.59 ± 0.17	154 ± 8	4.91 ± 0.34	59 ± 7
	2	4.1 ± 0.3	5.00 ± 0.23	3.75 ± 0.21	180 ± 6	4.28 ± 0.38	260 ± 8	0	5.24 ± 0.26	183 ± 8	4.68 ± 0.30	95 ± 7
	3	3.7 ± 0.5	3.46 ± 0.05	2.60 ± 0.05	187 ± 8	4.86 ± 0.25	260 ± 10	0	3.59 ± 0.09	166 ± 8	5.15 ± 0.27	90 ± 7
	4	3.4 ± 0.5	3.25 ± 0.11	2.47 ± 0.08	168 ± 5	4.80 ± 0.16	290 ± 10	0	3.44 ± 0.08	163 ± 5	5.13 ± 0.14	110 ± 14
	5	3.8 ± 0.3	3.65 ± 0.14	2.61 ± 0.09	158 ± 3	3.23 ± 0.24	275 ± 8	0	3.47 ± 0.24	158 ± 8	3.50 ± 0.20	110 ± 14
	6	3.5 ± 0.3	3.34 ± 0.11	2.37 ± 0.08	141 ± 5	2.92 ± 0.20	330 ± 12	0	3.69 ± 0.11	155 ± 7	3.40 ± 0.22	80 ± 20
C	1	3.8 ± 0.3	3.77 ± 0.13	2.92 ± 0.11	170 ± 9	3.94 ± 0.24	255 ± 20	0	4.10 ± 0.12	167 ± 8	4.53 ± 0.30	145 ± 27
	2	4.1 ± 0.3	4.88 ± 0.22	3.71 ± 0.18	128 ± 10	4.58 ± 0.29	325 ± 7	0	4.88 ± 0.18	175 ± 9	4.92 ± 0.27	—
	3	3.9 ± 0.3	3.09 ± 0.11	2.24 ± 0.10	106 ± 6	2.35 ± 0.21	295 ± 8	0	3.55 ± 0.08	138 ± 5	2.78 ± 0.28	130 ± 25
	4	3.4 ± 0.4	2.83 ± 0.16	1.89 ± 0.08	162 ± 8	2.43 ± 0.28	295 ± 8	0	3.30 ± 0.08	200 ± 8	2.71 ± 0.34	30 ± 25
	5	3.4 ± 0.3	3.63 ± 0.06	2.32 ± 0.05	209 ± 10	2.20 ± 0.24	275 ± 8	0	3.87 ± 0.06	211 ± 10	2.40 ± 0.22	0 ± 25
	6	3.8 ± 0.3	3.78 ± 0.12	2.37 ± 0.08	208 ± 8	1.52 ± 0.15	305 ± 3	0	4.09 ± 0.05	206 ± 10	1.88 ± 0.16	15 ± 15

Appendix 3. Influent and effluent composition in dn-process during different periods (mean ± standard error of mean).

Sampling point	Period	pH	ALK mmol l⁻¹	SS mg l⁻¹	BOD₇ mg l⁻¹	COD mg l⁻¹	Ptot mg l⁻¹	Paq mg l⁻¹	Ntot mg l⁻¹	NNH₃ mg l⁻¹	NNO₂ mg l⁻¹	NNO₃ mg l⁻¹	Fetot mg l⁻¹
S,I	1	7.3 ± 0.0	3.7 ± 0.1	125 ± 10	134 ± 15	201 ± 14	6.05 ± 0.31		40 ± 3	36 ± 4			
	2	7.3 ± 0.1	3.2 ± 0.1	112 ± 10	109 ± 9	151 ± 10	6.13 ± 0.34		31 ± 4	27 ± 4			
	3	7.3 ± 0.0	3.3 ± 0.1	154 ± 33	150 ± 9	253 ± 23	7.56 ± 0.18		41 ± 8	38 ± 9			
	4	7.3 ± 0.0	3.5 ± 0.3	120 ± 9	129 ± 11	228 ± 21	6.22 ± 0.66		29 ± 2	24 ± 2			
	5	7.2 ± 0.1	2.2 ± 0.2	258 ± 46	119 ± 12	241 ± 15	6.01 ± 0.39		27 ± 1	20 ± 1			
	6	7.4 ± 0.1	3.2 ± 0.1	348 ± 86	165 ± 15	304 ± 22	8.54 ± 0.45		35 ± 2	27 ± 2			
	7	7.4 ± 0.0	2.7 ± 0.1	299 ± 66	134 ± 11	272 ± 26	8.26 ± 0.58		38 ± 9	34 ± 2			
	8	7.2 ± 0.0	3.1 ± 0.2	107 ± 13	128 ± 8	215 ± 11	6.06 ± 0.27		32 ± 1	27 ± 1			
S,E	1	6.4 ± 0.1	0.3 ± 0.0	24 ± 3	20 ± 2	57 ± 4	3.04 ± 0.33	2.33 ± 0.50	16 ± 3	2 ± 1	0.0 ± 0.0	13 ± 1	2.7 ± 0.5
	2	6.3 ± 0.1	0.3 ± 0.0	13 ± 1	13 ± 1	44 ± 2	1.41 ± 0.13	0.97 ± 0.13	20 ± 5	1 ± 0	0.0 ± 0.0	16 ± 0	1.6 ± 0.1
	3	6.2 ± 0.0	0.2 ± 0.0	13 ± 1	15 ± 1	50 ± 4	1.45 ± 0.15	0.90 ± 0.16	20 ± 5	3 ± 1	0.0 ± 0.0	12 ± 2	1.8 ± 0.1
	4	6.6 ± 0.0	0.5 ± 0.0	16 ± 1	16 ± 3	57 ± 4	1.61 ± 0.37	1.61 ± 0.83	14 ± 3	4 ± 1	0.0 ± 0.0	11 ± 1	2.7 ± 0.3
	5	7.0 ± 0.0	0.6 ± 0.1	51 ± 8	18 ± 2	63 ± 3	1.61 ± 0.20	1.04 ± 0.36	17 ± 2	5 ± 1	0.2 ± 0.2	7 ± 1	3.1 ± 0.4
	6	7.3 ± 0.8	1.9 ± 0.1	27 ± 9	21 ± 1	63 ± 2	2.30 ± 0.24	1.09 ± 0.16	28 ± 1	16 ± 2	0.0 ± 0.0	4 ± 0	3.2 ± 0.2
	7	7.3 ± 0.0	1.2 ± 0.1	26 ± 5	14 ± 1	51 ± 1	1.56 ± 0.25	0.95 ± 0.23	26 ± 4	20 ± 2	0.0 ± 0.0	3 ± 0	2.1 ± 0.2
	8	6.4 ± 0.1	0.4 ± 0.1	23 ± 3	12 ± 1	54 ± 2	1.09 ± 0.28	0.41 ± 0.15	14 ± 2	2 ± 1	0.0 ± 0.0	10 ± 1	2.6 ± 0.9
C,I	1	7.3 ± 0.0	3.7 ± 0.1	125 ± 10	134 ± 15	201 ± 14	6.95 ± 0.31		40 ± 3	36 ± 4			
	2	7.3 ± 0.0	3.2 ± 0.0	126 ± 13	123 ± 8	185 ± 14	6.61 ± 0.27		35 ± 3	30 ± 4			
	3	7.3 ± 0.0	3.5 ± 0.3	120 ± 9	129 ± 11	228 ± 21	6.22 ± 0.66		29 ± 2	24 ± 2			
	4	7.2 ± 0.1	2.4 ± 0.3	243 ± 87	115 ± 17	245 ± 21	5.71 ± 0.50		26 ± 2	20 ± 2			
	5	7.3 ± 0.0	2.5 ± 0.2	306 ± 48	144 ± 16	268 ± 16	7.54 ± 0.44		32 ± 2	24 ± 2			
	6	7.3 ± 0.1	2.6 ± 0.1	239 ± 44	134 ± 8	257 ± 18	7.39 ± 0.46		36 ± 1	31 ± 2			
	7	7.3 ± 0.0	3.4 ± 0.2	86 ± 14	126 ± 10	208 ± 12	6.13 ± 0.36		32 ± 1	27 ± 1			
C,E	1	6.8 ± 0.2	0.7 ± 0.1	43 ± 4	35 ± 5	77 ± 7	6.27 ± 0.26	5.09 ± 0.18	17 ± 4	1 ± 0	0.0 ± 0.0	14 ± 0	0.7 ± 0.1
	2	6.6 ± 0.1	0.5 ± 0.0	30 ± 3	22 ± 1	67 ± 3	4.52 ± 0.29	3.68 ± 0.25	21 ± 5	1 ± 0	0.0 ± 0.0	17 ± 0	0.8 ± 0.1
	3	6.9 ± 0.1	0.8 ± 0.1	27 ± 2	20 ± 2	65 ± 4	3.73 ± 0.03	3.13 ± 0.30	10 ± 3	1 ± 0	0.0 ± 0.0	13 ± 0	0.8 ± 0.0
	4	7.0 ± 0.0	0.8 ± 0.1	20 ± 4	15 ± 2	65 ± 3	3.46 ± 0.31	2.96 ± 0.28	21 ± 8	3 ± 1	0.4 ± 0.1	8 ± 1	0.6 ± 0.2
	5	7.1 ± 0.0	1.0 ± 0.1	46 ± 8	24 ± 2	72 ± 3	4.07 ± 0.31	2.88 ± 0.33	19 ± 2	7 ± 1	0.0 ± 0.0	10 ± 1	1.0 ± 0.1
	6	6.9 ± 0.1	0.9 ± 0.1	30 ± 5	25 ± 3	64 ± 3	4.90 ± 0.34	3.67 ± 0.30	17 ± 1	10 ± 1	0.0 ± 0.0	9 ± 0	0.8 ± 0.1
	7	6.9 ± 0.0	1.1 ± 0.1	27 ± 5	29 ± 2	67 ± 3	4.74 ± 0.36	3.65 ± 0.31	16 ± 4	6 ± 1	0.0 ± 0.0	8 ± 1	0.6 ± 0.0

Appendix 4. Properties of the activated sludge in the nd-process during different periods (mean ± standard error of mean).

Unit	Period	d-reactor						n-reactor				
		DO mg l⁻¹	MLSS g l⁻¹	MLVSS g l⁻¹	SVI ml g⁻¹	P_sol mg l⁻¹	Redox mV	DO mg l⁻¹	MLSS g l⁻¹	SVI mg g⁻¹	P_sol mg l⁻¹	Redox mV
S	1	0	5.72 ± 0.13	3.40 ± 0.09	122 ± 8	3.79 ± 0.49	−15 ± 97	3.1 ± 0.3	5.78 ± 0.14	116 ± 6	3.40 ± 0.54	405 ± 25
	2	0	3.72 ± 0.32	2.05 ± 0.21	83 ± 6	1.57 ± 0.24	79 ± 48	4.4 ± 0.3	3.72 ± 0.32	76 ± 7	1.55 ± 0.26	450 ± 5
	3	0	3.03 ± 0.19	1.63 ± 0.14	66 ± 5		75 ± 12	3.1 ± 0.3	3.03 ± 0.19	62 ± 3		395 ± 5
	4	0	3.30 ± 0.12	1.90 ± 0.08	80 ± 5	0.52 ± 0.14	−3 ± 80	3.4 ± 0.2	3.13 ± 0.08	61 ± 2	0.60 ± 0.13	390 ± 25
	5	0	3.97 ± 0.12	2.02 ± 0.10	81 ± 5	0.58 ± 0.08	87 ± 164	4.7 ± 0.4	4.41 ± 0.94	66 ± 8	0.76 ± 0.19	290 ± 25
	6	0	4.43 ± 0.10	2.36 ± 0.08	83 ± 8	0.84 ± 0.15	−4 ± 187	3.9 ± 0.4	4.06 ± 0.10	77 ± 1	0.81 ± 0.19	305 ± 20
	7	0	5.48 ± 0.24	2.93 ± 0.13	127 ± 6	0.83 ± 0.13	−63 ± 84	3.1 ± 0.9	5.04 ± 0.23	117 ± 8	0.87 ± 0.16	315 ± 15
	8	0	7.61 ± 0.22	4.08 ± 0.16	98 ± 2	0.48 ± 0.15	50 ± 53	2.5 ± 0.4	7.14 ± 0.17	109 ± 3	0.24 ± 0.05	400 ± 5
C	1	0	3.45 ± 0.09	2.45 ± 0.06	112 ± 10	5.78 ± 0.07	35 ± 20	4.3 ± 0.4	3.45 ± 0.09	97 ± 5	5.78 ± 0.26	340 ± 20
	2	0	3.14 ± 0.07	1.87 ± 0.07	103 ± 8	3.57 ± 0.25	75 ± 10	3.8 ± 0.2	3.14 ± 0.07	87 ± 5	3.73 ± 0.32	435 ± 5
	3	0	2.81 ± 0.28	1.82 ± 0.18	109 ± 5	4.20 ± 0.20	0 ± 25	3.6 ± 0.2	3.06 ± 0.12	77 ± 8	2.80 ± 0.69	365 ± 25
	4	0	2.36 ± 0.12	1.28 ± 0.09	109 ± 5	2.82 ± 0.41	−10 ± 20	4.7 ± 0.7	2.38 ± 0.13	83 ± 4	2.24 ± 0.38	360 ± 25
	5	0	3.32 ± 0.31	2.01 ± 0.21	124 ± 12	2.78 ± 0.53	−45 ± 20	3.3 ± 0.2	3.77 ± 0.22	112 ± 8	3.24 ± 0.48	165 ± 35
	6	0	4.50 ± 0.20	2.99 ± 0.16	176 ± 15	3.12 ± 0.51	−50 ± 10	2.2 ± 0.3	4.42 ± 0.21	167 ± 12	3.52 ± 0.29	375 ± 20
	7	0	6.69 ± 0.17	4.37 ± 0.19	146 ± 11	3.62 ± 0.38	−100 ± 30	3.6 ± 0.1	6.42 ± 0.09	151 ± 7	3.42 ± 0.24	200 ± 5

Appendix 5. Influent (I) and effluent (F) composition in intermittent aeration process, unit 1, during different periods (mean ± standard error of mean).

Sampling point	Period	pH	ALK mmol l⁻¹	SS mg l⁻¹	BOD₇ mg l⁻¹	COD mg l⁻¹	P_{tot} mg l⁻¹	P_{aq} mg l⁻¹	N_{tot} mg l⁻¹	N_{NH_4} mg l⁻¹	N_{NO_2} mg l⁻¹	N_{NO_3} mg l⁻¹	Fe_{tot} mg l⁻¹
I	1	7.4 ± 0.1	4.6 ± 0.3	144	153 ± 12	293 ± 15	6.46 ± 0.51		39 ± 2	31 ± 2			
	2	7.3 ± 0.1	4.0 ± 0.3	170 ± 25	210 ± 15	297 ± 16	5.79 ± 0.48		36 ± 3	22 ± 4			
	3	7.1 ± 0.0	4.3 ± 0.2	176 ± 26	107 ± 10	199 ± 14	4.03 ± 0.50		29 ± 3	18 ± 2			
	4	7.0 ± 0.0	3.7 ± 0.1	138 ± 12	98 ± 9	164 ± 12	4.41 ± 0.21		26 ± 1	16 ± 1			
	5	7.2 ± 0.1	4.6 ± 0.1	159 ± 14	145 ± 11	247 ± 18	5.56 ± 0.29		36 ± 1	26 ± 1			
	6	7.3 ± 0.1	4.9 ± 0.3	168	138 ± 11	350 ± 24	3.77 ± 0.18		36 ± 1	27 ± 1			
	7	7.1 ± 0.0	4.9 ± 0.4	239	167 ± 12	290 ± 20	5.69 ± 0.47		37 ± 1	28 ± 2			
	8	7.1 ± 0.1	5.3 ± 0.5	220 ± 20	113 ± 10	267 ± 22	5.40 ± 0.37		38 ± 1	28 ± 1			
	9	7.1 ± 0.1	5.1 ± 0.4	233 ± 21	187 ± 16	294 ± 18	6.06 ± 0.53		42 ± 3	32 ± 2			
	10	7.2 ± 0.1	5.2 ± 0.3	172	140 ± 11	186 ± 18	7.68 ± 0.61		40 ± 2	31 ± 2			
	11	6.8 ± 0.2	4.0 ± 0.3	87	88 ± 9	145 ± 16	5.12 ± 0.49		26 ± 2	16 ± 3			
	12	7.0 ± 0.0	4.6 ± 0.2	165 ± 21	111 ± 9	243 ± 19	6.06 ± 0.59		27 ± 3	18 ± 3			
	13	6.9 ± 0.0	5.2 ± 0.2	277 ± 32	186 ± 21	222 ± 19	8.09 ± 0.59		48 ± 3	32 ± 2			
	14	7.0 ± 0.0	4.2 ± 0.3	161 ± 20	143 ± 15	203 ± 18	4.86 ± 0.26		21 ± 1	16 ± 1			
	15	6.7 ± 0.2	3.8 ± 0.1	204 ± 18	134 ± 14	158 ± 10	6.95 ± 0.40		21 ± 1	14 ± 1			
	16	6.9 ± 0.0	4.3 ± 0.0	224 ± 25	137 ± 11	204 ± 11	8.76 ± 0.39		21 ± 2	17 ± 3			
	17	7.0 ± 0.0	4.5 ± 0.1	208 ± 21	128 ± 11	207 ± 11	7.15 ± 0.48		21 ± 3	18 ± 1			
	18	7.1 ± 0.1	5.3 ± 0.4	267 ± 33	201 ± 16	349 ± 26	9.44 ± 0.71		29 ± 2	27 ± 3			
	19	7.5 ± 0.1	5.0 ± 0.4	217	169 ± 21	250 ± 21	8.08 ± 0.58		30 ± 1	30 ± 2			
	20	7.7 ± 0.3	3.4 ± 0.1	245	149 ± 16	168 ± 14	6.11 ± 0.57		30 ± 3	29 ± 2			
	21	7.4 ± 0.2	4.2 ± 0.2	211	103 ± 20	174 ± 13	4.63 ± 0.30		23 ± 3	23 ± 3			
	22	7.3 ± 0.1	4.1 ± 0.3	178 ± 26	94 ± 13	160 ± 14	4.47 ± 0.22		26 ± 1	22 ± 1			
	23	7.3 ± 0.1	3.8 ± 0.3	160 ± 22	102 ± 13	162 ± 14	4.91 ± 0.24		26 ± 3	19 ± 1			
E	1	7.2 ± 0.1	1.8 ± 0.1	26 ± 5	26 ± 5	66 ± 4	1.41 ± 0.22	0.38 ± 0.66	30 ± 2	22 ± 3	0.0 ± 0.0	6 ± 3	4.3 ± 0.2
	2	6.7 ± 0.0	0.6 ± 0.0	13 ± 1	12 ± 2	72 ± 4	0.69 ± 0.15	0.28 ± 0.05	12 ± 1	4 ± 3	0.0 ± 0.0	17 ± 3	1.9 ± 0.1
	3	6.7 ± 0.0	0.9 ± 0.0	41 ± 8	13 ± 1	39 ± 2	0.67 ± 0.16	0.20 ± 0.10	18 ± 1	3 ± 2	0.0 ± 0.0	12 ± 1	1.8 ± 0.4
	4	6.1 ± 0.0	0.6 ± 0.0	41 ± 10	15 ± 4	44 ± 5	1.31 ± 0.21	0.28 ± 0.10	16 ± 2	9 ± 1	0.0 ± 0.0	5 ± 1	3.0 ± 0.4
	5	6.8 ± 0.1	1.1 ± 0.1	5 ± 2	35 ± 6	86 ± 6	0.99 ± 0.19	0.58 ± 0.06	30 ± 1	8 ± 3	0.0 ± 0.0	7 ± 1	1.6 ± 0.1
	6	6.8 ± 0.1	1.5 ± 0.1	22 ± 7	19 ± 4	99 ± 6	0.70 ± 0.11	0.30 ± 0.08	15 ± 1	0 ± 0	0.0 ± 0.0	10 ± 1	2.2 ± 0.1
	7	6.9 ± 0.2	2.0 ± 0.3	38 ± 11	40 ± 9	59 ± 3	1.29 ± 0.25	0.58 ± 0.10	15 ± 1	17 ± 3	0.0 ± 0.0	5 ± 6	1.4 ± 0.1
	8	6.4 ± 0.1	0.8 ± 0.1	28 ± 5	10 ± 1	67 ± 4	1.62 ± 0.30	0.68 ± 0.11	25 ± 2	9 ± 1	0.0 ± 0.0	20 ± 1	2.3 ± 0.1
	9	6.7 ± 0.2	0.7 ± 0.2	25 ± 5	24 ± 4	60 ± 4	1.46 ± 0.30	0.72 ± 0.13	20 ± 2	3 ± 1	0.0 ± 0.0	17 ± 2	1.8 ± 0.2
	10	6.7 ± 0.2	1.1 ± 0.1	20 ± 3	18 ± 3	62 ± 3	2.16 ± 0.42	1.29 ± 0.28	13 ± 2	3 ± 1	0.1 ± 0.0	11 ± 1	1.0 ± 0.1
	11	6.4 ± 0.0	0.7 ± 0.1	11 ± 1	12 ± 1	67 ± 4	1.15 ± 0.33	0.79 ± 0.16	13 ± 1	1 ± 1	0.2 ± 0.1	6 ± 1	1.2 ± 0.0
	12	6.6 ± 0.0	1.0 ± 0.1	25 ± 8	16 ± 2	49 ± 2	0.81 ± 0.15	0.35 ± 0.02	12 ± 2	4 ± 0	0.1 ± 0.0	4 ± 1	1.7 ± 0.1
	13	6.8 ± 0.2	2.7 ± 0.3	35 ± 15	20 ± 4	53 ± 4	2.01 ± 0.19	1.81 ± 0.17	26 ± 1	22 ± 3	0.0 ± 0.0	4 ± 1	2.8 ± 0.2
	14	6.5 ± 0.1	1.1 ± 0.2	42 ± 14	14 ± 4	35 ± 4	0.87 ± 0.14	0.34 ± 0.03	13 ± 1	6 ± 1	0.0 ± 0.0	7 ± 1	1.1 ± 0.1
	15	6.4 ± 0.1	0.6 ± 0.0	35 ± 16	11 ± 2	31 ± 3	0.65 ± 0.13	0.38 ± 0.03	12 ± 2	1 ± 0	0.0 ± 0.0	10 ± 2	1.0 ± 0.0
	16	6.7 ± 0.2	1.1 ± 0.0	58 ± 21	23 ± 8	46 ± 2	1.69 ± 0.21	0.72 ± 0.08	10 ± 2	2 ± 0	0.5 ± 0.2	6 ± 1	2.4 ± 0.1
	17	6.8 ± 0.1	1.0 ± 0.1	33 ± 13	12 ± 5	46 ± 4	1.21 ± 0.17	0.91 ± 0.10	9 ± 1	0 ± 0	0.4 ± 0.2	8 ± 2	1.2 ± 0.0
	18	6.9 ± 0.2	1.8 ± 0.1	46 ± 11	25 ± 4	61 ± 5	2.34 ± 0.31	1.45 ± 0.15	15 ± 2	5 ± 0	0.1 ± 0.0	4 ± 1	1.5 ± 0.0
	19	6.9 ± 0.2	2.0 ± 0.2	45 ± 11	27 ± 4	66 ± 5	2.58 ± 0.30	1.59 ± 0.15	14 ± 3	6 ± 1	0.0 ± 0.0	7 ± 2	2.8 ± 0.3
	20	7.2 ± 0.1	1.2 ± 0.1	51 ± 20	15 ± 3	47 ± 4	2.34 ± 0.98	1.12 ± 0.15	13 ± 1	4 ± 0	0.0 ± 0.0	10 ± 3	1.9 ± 0.0
	21	6.9 ± 0.3	0.9 ± 0.0	46 ± 18	9 ± 2	49 ± 2	1.03 ± 0.11	0.22 ± 0.09	11 ± 1	4 ± 0	0.0 ± 0.0	5 ± 2	3.5 ± 0.2
	22	6.9 ± 0.1	1.6 ± 0.1	42 ± 16	16 ± 8	46 ± 2	1.00 ± 0.10	0.32 ± 0.05	14 ± 1	9 ± 2	0.0 ± 0.0	5 ± 0	3.1 ± 0.3
	23	7.0 ± 0.0	1.6 ± 0.2	43 ± 16	18 ± 6	49 ± 3	0.91 ± 0.10	0.25 ± 0.02	17 ± 1	11 ± 2	0.0 ± 0.0	3 ± 0	3.0 ± 0.3

Appendix 6. Influent (I) and effluent (F) composition in intermittent aeration process, unit 2, during different periods (mean ± standard error of mean).

Sampling point	Period	pH	ALK mmol l⁻¹	SS mg l⁻¹	BOD₇ mg l⁻¹	COD mg l⁻¹	P_tot mg l⁻¹	P_liq mg l⁻¹	N_tot mg l⁻¹	N_NH₃ mg l⁻¹	N_NO₂ mg l⁻¹	N_NO₃ mg l⁻¹	Fe_tot mg l⁻¹
I	1	7.4 ± 0.1	4.6 ± 0.4	144 ± 10	153 ± 14	293 ± 15	6.46		38 ± 2	31 ± 2			
	2	7.3 ± 0.1	4.0 ± 0.3	170 ± 15	210 ± 15	297 ± 16	5.79 ± 0.48		38 ± 2	22 ± 4			
	3	7.1 ± 0.0	4.3 ± 0.2	176 ± 26	107 ± 10	199 ± 14	4.03 ± 0.50		27 ± 3	18 ± 2			
	4	7.0 ± 0.0	3.7 ± 0.1	138 ± 12	98 ± 9	164 ± 12	4.41 ± 0.21		23 ± 1	16 ± 1			
	5	7.2 ± 0.1	4.6 ± 0.1	159 ± 14	145 ± 11	247 ± 18	5.56 ± 0.29		35 ± 2	26 ± 1			
	6	7.1 ± 0.1	4.9 ± 0.2	239 ± 17	167 ± 14	290 ± 15	5.69 ± 0.33		29 ± 2	28 ± 1			
	7	7.1 ± 0.0	5.3 ± 0.4	220 ± 20	113 ± 10	267 ± 22	5.40 ± 0.37		38 ± 3	28 ± 2			
	8	7.1 ± 0.1	5.1 ± 0.4	233 ± 21	187 ± 16	294 ± 18	6.06 ± 0.53		42 ± 3	32 ± 2			
	9	7.0 ± 0.0	4.6 ± 0.4	128 ± 19	113 ± 12	213 ± 17	6.37 ± 0.33		32 ± 4	24 ± 2			
	10	7.0 ± 0.0	4.6 ± 0.2	165 ± 21	111 ± 9	243 ± 19	6.06 ± 0.59		27 ± 3	18 ± 3			
	11	6.9 ± 0.0	5.2 ± 0.2	277 ± 32	186 ± 21	222 ± 19	8.99 ± 0.59		42 ± 3	32 ± 2			
	12	7.0 ± 0.0	4.2 ± 0.3	161 ± 20	143 ± 15	203 ± 18	4.86 ± 0.26		21 ± 1	16 ± 1			
	13	6.7 ± 0.2	3.8 ± 0.1	204 ± 18	134 ± 14	158 ± 10	6.95 ± 0.40		21 ± 1	14 ± 1			
	14	6.9 ± 0.0	4.3 ± 0.0	224 ± 25	137 ± 11	204 ± 11	8.76 ± 0.39		21 ± 2	17 ± 3			
	15	7.0 ± 0.0	4.5 ± 0.1	208 ± 21	128 ± 11	207 ± 11	7.15 ± 0.48		21 ± 3	18 ± 1			
	16	7.1 ± 0.1	5.3 ± 0.4	267 ± 33	201 ± 16	349 ± 26	9.44 ± 0.71		29 ± 2	27 ± 3			
	17	7.5 ± 0.1	4.1 ± 0.3	221 ± 24	156 ± 12	208 ± 17	7.08 ± 0.65		30 ± 1	29 ± 2			
	18	7.4 ± 0.1	4.2 ± 0.4	211 ± 25	103 ± 8	174 ± 13	4.63 ± 0.30		23 ± 2	23 ± 3			
	19	7.3 ± 0.1	4.1 ± 0.3	178 ± 26	94 ± 13	160 ± 14	4.47 ± 0.22		26 ± 1	22 ± 3			
	20	7.3 ± 0.1	3.8 ± 0.3	160 ± 22	102 ± 13	162 ± 14	4.91 ± 0.24		26 ± 3	19 ± 1			
E	1	7.2 ± 0.1	3.0 ± 0.1	24 ± 3	28 ± 7	96 ± 9	4.97 ± 0.81	3.17 ± 0.71	30 ± 4	25	0.0 ± 0.0	3 ± 1	0.8 ± 0.1
	2	6.9 ± 0.1	1.1 ± 0.2	39 ± 5	26 ± 5	63 ± 3	5.00 ± 0.71	3.63 ± 0.68	15 ± 2	1 ± 0	0.0 ± 0.0	20 ± 4	0.7 ± 0.1
	3	6.9 ± 0.1	1.9 ± 0.1	47 ± 4	34 ± 4	91 ± 9	3.79 ± 0.42	2.45 ± 0.40	18 ± 4	9 ± 2	0.0 ± 0.0	7 ± 1	0.6 ± 0.1
	4	6.6 ± 0.1	1.3 ± 0.3	35 ± 4	25 ± 4	62 ± 2	2.60 ± 0.25	2.45 ± 0.20	13 ± 3	3 ± 0	0.0 ± 0.0	6 ± 1	0.9 ± 0.2
	5	6.8 ± 0.1	1.2 ± 0.1	32 ± 3	21 ± 5	67 ± 6	3.39 ± 0.28	1.85 ± 0.19	13 ± 2	3 ± 0	0.1 ± 0.0	9 ± 1	0.8 ± 0.1
	6	7.0 ± 0.0	2.7 ± 0.3	47 ± 5	78 ± 10	102 ± 19	4.79 ± 0.31	1.64 ± 0.19	15 ± 2	16 ± 4	0.2 ± 0.0	5 ± 0	0.8 ± 0.1
	7	6.4 ± 0.2	1.1 ± 0.1	53 ± 5	26 ± 8	94 ± 15	4.72 ± 0.40	2.19 ± 0.31	30 ± 4	9 ± 3	0.1 ± 0.0	23 ± 3	0.6 ± 0.0
	8	6.7 ± 0.1	0.9 ± 0.2	54 ± 6	31 ± 4	65 ± 6	4.57 ± 0.31	2.87 ± 0.20	22 ± 1	3 ± 0	0.1 ± 0.0	18 ± 4	0.9 ± 0.1
	9	6.6 ± 0.1	1.4 ± 0.1	16 ± 2	18 ± 3	73 ± 4	4.36 ± 0.29	3.51 ± 0.20	15 ± 2	2 ± 0	0.1 ± 0.0	9 ± 2	0.6 ± 0.1
	10	6.6 ± 0.0	2.0 ± 0.2	24 ± 4	15 ± 3	57 ± 6	4.09 ± 0.36	2.85 ± 0.51	14 ± 2	6 ± 1	0.4 ± 0.0	3 ± 0	0.8 ± 0.1
	11	6.7 ± 0.0	2.5 ± 0.5	43 ± 4	39 ± 4	92 ± 7	2.26 ± 0.19	1.60 ± 0.11	20 ± 4	18 ± 2	0.0 ± 0.0	4 ± 0	2.9 ± 0.3
	12	6.4 ± 0.2	0.8 ± 0.1	47 ± 4	26 ± 5	54 ± 9	2.42 ± 0.18	0.94 ± 0.05	18 ± 4	1 ± 0	0.2 ± 0.0	15 ± 3	2.5 ± 0.2
	13	6.4 ± 0.2	0.9 ± 0.2	43 ± 4	16 ± 2	43 ± 5	1.43 ± 0.10	0.72 ± 0.03	15 ± 3	2 ± 0	0.2 ± 0.1	12 ± 1	1.4 ± 0.1
	14	6.8 ± 0.1	1.3 ± 0.1	40 ± 5	21 ± 2	43 ± 3	1.74 ± 0.08	1.11 ± 0.04	13 ± 2	2 ± 0	0.2 ± 0.1	7 ± 1	1.4 ± 0.3
	15	6.9 ± 0.1	1.6 ± 0.1	42 ± 4	15 ± 4	48 ± 4	2.80 ± 0.20	1.79 ± 0.06	13 ± 1	3 ± 0	0.1 ± 0.0	4 ± 0	1.0 ± 0.1
	16	6.9 ± 0.1	2.3 ± 0.3	46 ± 6	31 ± 3	67 ± 8	1.78 ± 0.01	0.68 ± 0.07	15 ± 2	16	0.2 ± 0.0	4 ± 0	2.5 ± 0.4
	17	7.2 ± 0.2	1.1 ± 0.0	40 ± 5	25 ± 4	49 ± 6	1.76 ± 0.01	0.84 ± 0.02	13 ± 2	3 ± 0	0.0 ± 0.0	10 ± 2	2.1 ± 0.5
	18	7.1 ± 0.1	1.6 ± 0.2	43 ± 4	22 ± 1	48 ± 7	1.11 ± 0.06	0.48 ± 0.02	12 ± 1	8 ± 1	0.0 ± 0.0	4 ± 0	1.6 ± 0.2
	19	7.1 ± 0.0	1.9 ± 0.1	33 ± 4	29 ± 2	45 ± 7	1.19 ± 0.05	0.50 ± 0.01	11 ± 1	10 ± 2	0.0 ± 0.0	1 ± 0	2.4 ± 0.3
	20	7.1 ± 0.0	1.9 ± 0.2	41 ± 4	25 ± 2	47 ± 8	0.99 ± 0.02	0.41 ± 0.03	13 ± 1	11 ± 2	0.1 ± 0.0	2 ± 0	2.4 ± 0.4

Appendix 7. Properties of activated sludge in intermittent aeration process during different periods (mean ± standard error of mean).

Unit	Period	DO mg l^{-1}	MLSS g l^{-1}	MLVSS g l^{-1}	SVI ml g^{-1}	P_{sol} mg l^{-1}
1	1	2.4 ± 0.6	8.19 ± 0.36	5.60 ± 0.31	118 ± 8	0.34 ± 0.09
	2	3.4 ± 0.2	10.80 ± 0.42	6.96 ± 0.28	91 ± 6	0.20 ± 0.05
	3	3.6 ± 0.2	10.70 ± 0.71	6.62 ± 0.47	101 ± 9	0.23 ± 0.04
	4	3.0 ± 0.3	12.00 ± 0.40	7.02 ± 0.25	83 ± 4	0.45 ± 0.19
	5	3.0 ± 0.6	15.80 ± 0.60	9.85 ± 0.61	60 ± 3	0.39 ± 0.06
	6	3.0 ± 0.3	9.52 ± 0.02	5.69 ± 0.11	102 ± 11	0.72 ± 0.03
	7	2.1 ± 0.3	8.16 ± 0.45	4.75 ± 0.33	122 ± 11	0.68 ± 0.12
	8	3.3 ± 0.5	6.85 ± 0.11	4.24 ± 0.19	42 ± 4	0.68 ± 0.08
	9	1.8 ± 0.3	8.81 ± 0.44	5.39 ± 0.34	91 ± 6	0.67 ± 0.06
	10	2.9 ± 0.5	9.09 ± 0.31	5.52 ± 0.21	99 ± 7	0.74 ± 0.44
	11	1.5 ± 0.1	9.63 ± 0.18	5.85 ± 0.23	95 ± 6	1.17 ± 0.15
	12	1.9 ± 0.1	9.72 ± 0.12	5.64 ± 0.06	91 ± 8	0.62 ± 0.08
	13	1.7 ± 0.4	6.73 ± 0.25	4.18 ± 0.19	135 ± 9	1.89 ± 0.44
	14	1.7 ± 0.7	6.12 ± 0.36	3.83 ± 0.21	166 ± 15	0.58 ± 0.19
	15	1.6 ± 0.4	7.98 ± 0.11	4.94 ± 0.06	118 ± 11	0.56 ± 0.10
	16	1.5 ± 0.6	8.81 ± 0.28	5.21 ± 0.28	108 ± 11	0.84 ± 0.46
	17	1.4 ± 0.8	8.94 ± 0.73	5.59 ± 0.46	100 ± 12	1.08 ± 0.13
	18	1.8 ± 0.6	10.10 ± 0.23	6.31 ± 0.14	89 ± 6	2.05 ± 0.21
	19	1.4 ± 0.7	8.63 ± 0.27	5.42 ± 0.16	90 ± 8	1.61 ± 0.22
	20	1.6 ± 0.7	7.69 ± 0.21	4.85 ± 0.18	93 ± 7	0.95 ± 0.15
	21	1.7 ± 0.8	4.69 ± 0.16	2.95 ± 0.10	61 ± 6	0.24 ± 0.06
	22	1.7 ± 0.6	4.69 ± 0.12	2.89 ± 0.08	63 ± 6	0.26 ± 0.06
	23	2.4 ± 0.4	5.09 ± 0.30	3.32 ± 0.25	85 ± 8	0.19 ± 0.06
2	1	2.9 ± 0.2	7.25 ± 0.35	5.86 ± 0.27	126 ± 11	2.05 ± 0.28
	2	2.8 ± 0.1	7.00 ± 0.52	5.69 ± 0.41	131 ± 11	3.09 ± 0.33
	3	3.7 ± 0.1	4.85 ± 0.50	3.72 ± 0.47	162 ± 10	1.97 ± 0.19
	4	3.2 ± 0.4	6.09 ± 0.27	4.44 ± 0.20	168 ± 19	1.62 ± 0.33
	5	2.2 ± 0.4	13.30 ± 0.82	8.91 ± 0.90	76 ± 6	1.83 ± 0.40
	6	2.6 ± 0.4	7.12 ± 0.55	5.09 ± 0.43	102 ± 9	2.11 ± 0.44
	7	4.4 ± 0.8	4.88 ± 0.27	3.53 ± 0.022	97 ± 5	2.89 ± 0.41
	8	3.3 ± 0.2	6.39 ± 0.17	4.41 ± 0.15	139 ± 15	3.18 ± 0.20
	9	2.3 ± 0.3	6.54 ± 0.22	4.64 ± 0.19	138 ± 8	3.66 ± 0.36
	10	1.6 ± 0.3	5.96 ± 0.14	4.36 ± 0.29	144 ± 6	2.59 ± 0.34
	11	2.3 ± 0.2	6.85 ± 0.25	4.46 ± 0.15	98 ± 7	2.39 ± 0.12
	12	2.6 ± 0.3	5.16 ± 0.14	3.39 ± 0.06	107 ± 7	1.96 ± 0.31
	13	1.9 ± 0.1	5.04 ± 0.31	3.31 ± 0.08	93 ± 10	0.77 ± 0.24
	14	1.9 ± 0.3	5.25 ± 0.44	3.39 ± 0.06	119 ± 11	0.96 ± 0.11
	15	1.8 ± 0.4	6.02 ± 0.33	3.88 ± 0.11	115 ± 12	1.23 ± 0.13
	16	1.6 ± 0.2	8.87 ± 0.68	5.23 ± 0.05	83 ± 11	1.41 ± 0.28
	17	2.4 ± 0.2	7.06 ± 0.71	4.56 ± 0.05	94 ± 11	0.65 ± 0.16
	18	2.3 ± 0.3	7.21 ± 0.70	4.66 ± 0.07	134 ± 10	0.34 ± 0.06
	19	2.0 ± 0.3	6.47 ± 0.51	4.16 ± 0.06	141 ± 8	0.60 ± 0.13
	20	2.0 ± 0.2	6.08 ± 0.56	4.65 ± 0.05	116 ± 6	0.86 ± 0.34