

Simultaneous Nitrification and Denitrification in an Oxidation Ditch Plant

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The performance of a full-scale oxidation ditch plant that was aerating at a low level of oxygen concentration is presented. The plant receives an influent wastewater with high COD (around 1500 mg l⁻¹) and nitrogen (about 200 mg l⁻¹) concentrations. The plant achieved high levels of COD and nitrogen removal at low dissolved oxygen (DO) mass concentration without alternating aerobic and anoxic phases, either in time or in space. Simultaneous nitrification and denitrification was responsible for such high nitrogen removal, about 90 %. The plant achieved higher nitrogen removal at this low level of DO than when it was intermittently aerating at higher dissolved oxygen concentration. BOD removal, however, was not affected. Bench scale studies confirmed that fact and simultaneous nitrification and denitrification occurred at DO concentrations as low as 0.2 mg l⁻¹. Nitrogen removal rates were found between 12.2 – 19.5 mg l⁻¹ h⁻¹ depending on MLVSS and DO concentrations. Specific removal rates were found to lie between 0.14 – 0.19 mg N per mg MLVSS per day, with higher removal rates for lower DO mass concentrations. With every mg N removed, between 5.5 – 6.3 mg COD was removed.

Keywords:

Nitrogen removal, biological nutrient removal, specific removal rate, anoxic/aerobic systems

Introduction

Nitrogen removal from wastewater is almost entirely achieved through biological means. The usual method of nitrogen removal is through the conversion of ammonia to nitrate in the presence of high levels of oxygen (Nitrification). This can be achieved in the same reactor through which COD is removed or in a separate reactor. Nitrate is then converted to nitrite and then to nitrogen gas during the denitrification step in the absence of molecular oxygen (anoxic condition). Denitrification can either be performed in a separate reactor or in the same reactor through which BOD removal and nitrification take place.¹ One difficulty, that usually arises in denitrification, is the fact that the denitrifying organisms require a source of carbon for growth. The amount of organic carbon necessary for denitrification² is approximately equal to 3 g BOD per g N. Isaacs and Henze³ estimated the value to be in the range 3.5 – 4.5 g COD per g N, which is in agreement with Eckenfelder's suggestion.

Recently, however, it was observed that nitrification could be achieved at lower oxygen concentration than previously thought. Oxygen concentration as low as 0.3 mg l⁻¹ achieved nitrification.⁴ Similarly, denitrification was observed to occur without the need for complete anoxic conditions.

Denitrification occurred⁵ at dissolved oxygen concentration as high as 1.5 mg l⁻¹. Two potential reasons were given to explain that. The first is that the denitrifying organisms are not entirely anaerobic and that they can live, grow, and denitrify at low levels of dissolved oxygen.⁶ The second explanation is that the process is related to limitations in the penetration of oxygen to the entire biological floc. In other words, at low levels of dissolved oxygen, the outer areas of the flocs are aerobic and, therefore, perform the nitrification process. Whereas, the inside portion of the floc is anoxic due to oxygen transfer limitations.^{4,7,8} This phenomenon was called simultaneous nitrification/denitrification (SND).

Simultaneous nitrification/denitrification has been reported⁹ to occur at a full scale extended aeration plant at dissolved oxygen (DO) concentration of 0.4 mg l⁻¹. In a lab scale sequencing batch reactor, SND occurred at DO levels between 0.3 and 0.8 mg l⁻¹. The degree of SND was 100 % at 0.3 mg l⁻¹ DO and about 80 % at about 0.8 mg l⁻¹ DO concentration. Nitrification rate, however, was lower at DO concentration of 0.3 mg l⁻¹ than at 0.8 mg l⁻¹ DO mass concentration.⁴

Munch and others¹⁰ found, that higher than usual, denitrification occurred during the aerated react period of a bench scale sequencing batch reactor, and that the rate of denitrification decreased

with time over this period. Nitrite, not nitrate, was the main nitrogen species in the effluent. This was ascribed to inhibition of *Nitrobacter* species in their experiments. In order to accurately estimate the extent of aerobic denitrification, the concentration of nitrite should be measured along with ammonia and nitrate.

SND has also been reported in attached growth rotating biological contactors (RBC) treating landfill leachate,¹¹ in fluidized bed reactors,¹² as well as in an aerated biological filter.¹³

The present study reports on SND in an oxidation ditch plant treating high strength domestic wastewater in northern part of Jordan. This is the first time that SND has been reported in wastewater treatment plants in the country. Lab scale experiments were run to confirm that SND was occurring. Nitrogen removal rates and the amount of COD required for complete SND, have been estimated.

Materials and methods

Wadi Hassan treatment plant (WHTP) located in Irbid, Jordan, is an oxidation ditch plant designed to operate in an alternating aeration scheme in which the whole aeration plant is aerated for, both, BOD and nitrification to take place. The aeration is then turned off to give time for denitrification to take place. This operation achieved high BOD removal but nitrogen removal was not very effective. During the course of this work, the whole aeration plant was aerated continuously at low levels of DO. The plant surprisingly achieved higher nitrogen removal at this new operating condition than that achieved when intermittently aerating at higher DO concentrations. The results obtained from this plant during a number of sampling periods are reported.

WHTP consists of two identical oxidation ditch aeration tanks working in the extended aeration mode of activated sludge. Each tank has a volume of 2040 m³. The plant does not have any primary sedimentation tanks. Two secondary sedimentation tanks, each with a volume of 360 m³, are present. At the time of this work (2003) only one track was in operation due to the low influent discharge to the plant. The plant is designed to give a hydraulic retention time of 20 h. During the present study, even with one track operating, the hydraulic retention times were generally more than 4 days.

Bench scale batch reactors with total volume of 2 l were used to confirm that SND was responsible for the removal of nitrogen in the oxidation ditch. The reactors were fed from the influent to the aeration tanks in WHTP. They were then inoculated with sludge from the return line of the aeration tank. They were mixed using magnetic stirrers and

aerated to provide the necessary dissolved oxygen concentration. The concentration of ammonia, nitrate, nitrite, and COD, were evaluated according to Standard Methods for the Examination of Water and Wastewater 2000.¹⁴

Results and discussion

Full Scale results

Dissolved oxygen measurements were conducted at 5 locations along the oxidation ditch, with pH and temperature measurements. Influent and effluent COD, ammonia and nitrate were determined. Mixed liquor suspended solids and Mixed Liquor Volatile Suspended Solids (MLVSS) in the aeration tank were also determined. Table 1 shows the operating conditions of the plant, while table 2 shows the COD and nitrogen removal efficiencies.

From these tables it can be seen that the average COD removal efficiency was higher than 95 percent, while average nitrogen removal efficiency was more than 90 percent at average DO mass concentrations in the aeration tank, between 0.6–1.3 mg l⁻¹.

The removal efficiencies in the above case, where the plant was aerating continuously at this low DO mass concentrations, were compared to other periods when the plant was aerating at higher DO concentrations either continuously or intermittently. When intermittent aeration was used, the plant was aerated for half an hour at DO concentrations between 2 and 4 mg l⁻¹, and then the aeration was turned off for another half hour. In the aeration period, both COD and nitrification take place, while in the no aeration period denitrification takes place. When continuous aeration was practiced, only COD removal and nitrification are supposed to take place. No nitrogen removal, except for assimilation in body cells, is expected to occur.

Figures 1–4 show comparisons in effluent COD, NH₄-N, NO₃-N, and pH, respectively. These figures show comparisons of 7 periods. The 7 periods for the different aeration schemes have nothing to do with each other. For example, period 1 for the continuous aeration with low DO concentration scheme has nothing to do with period 1 or with any other period of the intermittent aeration scheme. The results that these periods show were obtained at different times and with different influent and operating conditions at the plant, depending on the influent and operating conditions at that period. They were put in the same graph to show a general comparison of the different schemes. Each period represent the average results of four days of sampling at the plant.

Table 1 – WHTP full-scale plant average operating conditions during the study period

Quantity	Period						
	I	II	III	IV	V	VI	VII
HRT	105 h (4.4 d)	105 h (4.4 d)	108 h (4.5 d)	124 h (5.2 d)	102 h (4.3 d)	111 h (4.6 d)	160 h (6.6 d)
MLVSS / mg l ⁻¹	4500	6130	4770	4520	4180	3790	4670
Inf. COD / mg l ⁻¹	1332	1430	1608	1872	1532	2280	1084
F/M / kg kg ⁻¹ d ⁻¹	0.068	0.053	0.074	0.080	0.086	0.13	0.035
DO / mg l ⁻¹	0.69	0.68	1.12	0.69	0.61	1.26	0.95
Inf. NH ₄ -N / mg l ⁻¹	159	186	259	176	158	178	152
Inf. NO ₃ -N / mg l ⁻¹	7.5	7.9	9.4	7.8	11.6	12	6.6
COD/N* / g g ⁻¹	7.2	6.6	5.4	9.2	8.2	10.8	6.2

* Assuming that the summation of NO₃+NH₄ is 90 % of total nitrogen mass concentration. This was based on a limited number of experiments.

Table 2 – WHTP average effluent concentrations and removal efficiencies

Quantity	Period						
	I	II	III	IV	V	VI	VII
Eff. COD / mg l ⁻¹	45	82	75	71	68	63	20
COD removal / %	96.6	94.3	95.3	96.2	95.6	97.2	98.2
Eff. NH ₄ -N / mg l ⁻¹	3.4	18.3	7.2	4.0	2.4	5.5	2.1
Eff. NO ₃ -N / mg l ⁻¹	5.8	3.9	4.6	5.8	9.0	8.0	16.0
NH ₄ -N+NO ₃ -N / mg l ⁻¹	9.2	22.2	11.8	9.8	11.4	13.5	18.1
NH ₄ + NO ₃ removal / %	94.5	88.6	95.6	94.7	93.3	92.9	88.6

Figure 1 shows that COD removal efficiencies were high in all three aeration schemes. This is mainly due to the higher detention time in the aeration tank than the design value. The present detention time is more than 4 days, whereas the design detention time is 20 h. Figure 2 shows that the effluent ammonia in the plant was lower when the plant was aerating continuously at high DO concentrations. This is an expected result, as nitrification at this high DO should proceed at all times and at higher rates than the other two alternatives. The difference in effluent concentrations is however minimal. For the intermittent aeration scheme, and the continuous aeration with low DO, the plant achieved somewhat similar results.

In figure 3, the nitrate concentration, as expected, was higher when continuously aerating at high DO concentration. This suggests that denitrification was absent or minimal during this aeration scheme. On the other hand, the effluent nitrate concentration for the case of continuous aeration at low DO concentrations was much lower than the other two aeration schemes. It is surprising that this scheme achieved higher nitrogen removal (similar

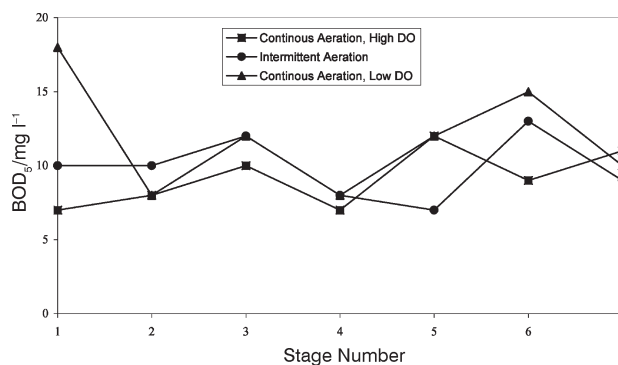


Fig. 1 – Comparison of effluent BOD₅ mass concentrations in WHTP for different aeration schemes

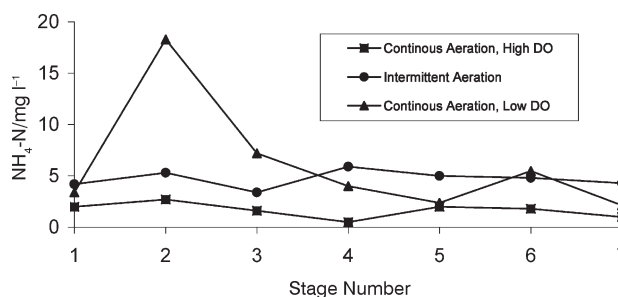


Fig. 2 – Comparison of effluent NH₄-N mass concentrations in WHTP for different aeration schemes

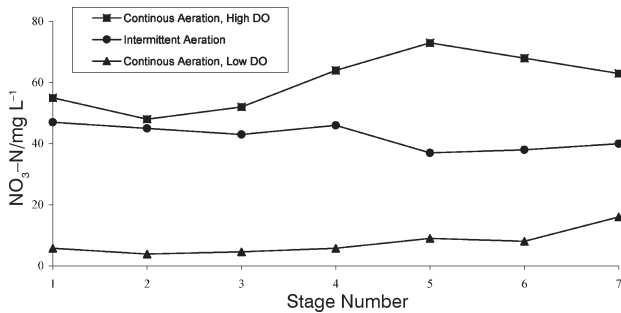


Fig. 3 – Comparison of effluent $\text{NO}_3\text{-N}$ mass concentrations in WHTP for different aeration schemes

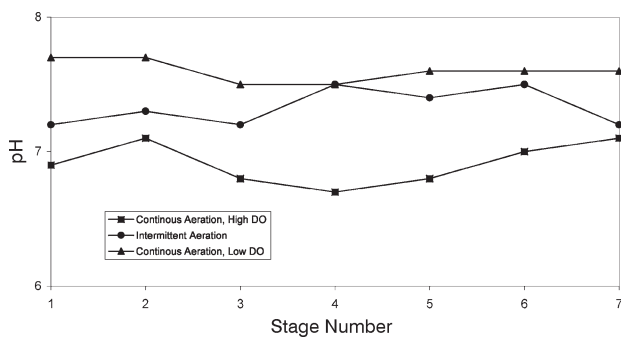


Fig. 4 – Comparison of effluent pH values in WHTP for different aeration schemes

ammonia concentration and much lower nitrate concentration) than the intermittent aeration scheme designed specifically for consecutive nitrification and denitrification with regard to time.

The effluent pH values for the three different aeration schemes are shown in Figure 4. As expected, the pH values followed the nitrification-denitrification efficiencies. As known, nitrification consumes alkalinity and reduces the pH value. On the other hand, denitrification restores back about half of the alkalinity consumed in nitrification for the same amount of nitrogen. In Figures 2 and 3, the continuous aeration with high DO scheme achieved high nitrification efficiency and no or minimal denitrification. This consumes the alkalinity without restoring any of it back. For the case of intermittent aeration, high nitrification effi-

ciency and only low denitrification efficiency were achieved. This again consumes alkalinity and restores only a small part of consumed alkalinity. For the case of continuous aeration with low DO concentration, the plant achieved, both, high nitrification and denitrification efficiencies. In this case, nitrification consumes a large portion of alkalinity, while denitrification restores back almost half of the consumed alkalinity. Therefore, the effluent pH values in this case remained higher than the other two alternatives.

Bench scale experiments

To validate the results obtained in the full-scale oxidation ditch plant, bench scale experiments were conducted on wastewater taken from the plant influent. The influent wastewater was inoculated with return sludge at a calculated proportion to provide an approximate MLVSS as close to the MLVSS present in the oxidation ditch as possible. Dissolved oxygen concentrations were varied to provide a relationship between DO and nitrogen removal rate due to simultaneous nitrification and denitrification. Results are shown in Tables 3 and 4.

Table 3 shows three cases in which DO or MLVSS mass concentrations were varied. In the first two experiments, initial MLVSS was kept constant at 2414 mg l⁻¹ and DO was either 0.2 or 0.8 mg l⁻¹. Initial (at time 0 in the table) ammonia, nitrate, and nitrite mass concentrations were measured. The concentrations of these three species were measured after 3 h of mixing and aerating at the specified DO. Nitrite concentrations were not included as these were almost constant and were generally about 1 mg l⁻¹ as N. The table shows that the rate of nitrification at DO 0.8 mg l⁻¹ (21.6 mg l⁻¹ h⁻¹ NH₄-N) was higher than the rate of nitrification at DO 0.2 mg l⁻¹ (19.5 mg l⁻¹ h⁻¹ NH₄-N), although the difference was not high. On the other hand the rate of nitrogen (NH₄ + NO₃) removal caused by the SND was higher at DO 0.2 mg l⁻¹ (19.5 mg l⁻¹ h⁻¹ N) than at DO of 0.8 mg l⁻¹ (16.5 mg l⁻¹ h⁻¹ N). The same trend can be said about the

Table 3 – Initial nitrogen removal rates at different experimental conditions in the bench scale study

	DO = 0.2, MLVSS = 2414 / mg l ⁻¹ (Initial)				DO = 0.8, MLVSS = 2414 / mg l ⁻¹ (Initial)				DO = 0.6, MLVSS = 1724 / mg l ⁻¹ (Initial)			
	0 h	3 h	Removal rate mg l ⁻¹ h ⁻¹	Specific removal rate d ⁻¹	0 h	3 h	Removal rate mg l ⁻¹ h ⁻¹	Specific removal rate d ⁻¹	0 h	3.5 h	Removal rate mg l ⁻¹ h ⁻¹	Specific removal rate d ⁻¹
NH ₄ -N / mg l ⁻¹	73.2	14.5	19.5	0.19	73.2	8.4	21.6	0.21	67.4	7.4	17.1	0.24
NO ₃ -N / mg l ⁻¹	5.0	5.2	—	—	5.0	20.1	—	—	3.9	11.0	—	—
NH ₄ -N+NO ₃ -N / mg l ⁻¹	78.1	19.7	19.5	0.19	78.1	28.6	16.5	0.16	61.1	18.4	12.2	0.17

Table 4 – Initial COD and nitrogen removal rates at different experimental conditions in the bench scale study

	DO = 0.8, MLVSS = 2295 / mg l ⁻¹ (Initial)				DO = 0.3, MLVSS = 2295 / mg l ⁻¹ (Initial)			
	0 h	3.5 h	Removal rate mg l ⁻¹ h ⁻¹	Specific removal rate d ⁻¹	0 h	3.5 h	Removal rate mg l ⁻¹ h ⁻¹	Specific removal rate d ⁻¹
NH ₄ -N / mg l ⁻¹	57.8	5.4	15.0	0.16	57.8	4.4	15.3	0.16
NO ₃ -N / mg l ⁻¹	3.3	10.1	—	—	3.3	5.9	—	—
NH ₄ -N + NO ₃ -N / mg l ⁻¹	61.1	15.5	13.0	0.14	61.1	10.3	14.5	0.15
COD / mg l ⁻¹	600	317	81.0	0.85	600	319	80.3	0.84
COD _{rem} /N _{rem} *	—	6.23	—	—	—	5.54	—	—

specific removal rate as both these experiments have the same initial MLVSS concentrations. It should be noted, that the MLVSS was not measured at the end of the 3 h aeration period. The specific removal rate was calculated by dividing the amount of removal on the initial MLVSS. At DO of 0.8 mg l⁻¹, nitrification rate was higher than the denitrification rate, as evidenced by the accumulation of nitrate. The overall removal was reduced because denitrification in this case was the rate-limiting step. At DO of 0.2 mg l⁻¹, the rates of nitrification and denitrification were similar as evidenced by the constant nitrate concentration during the experiment. No single step was limiting, and therefore the overall removal rate was higher.

The third experiment was conducted at DO of 0.6 mg l⁻¹ and initial MLVSS of 1724 mg l⁻¹. Nitrogen species concentrations were measured at the start of the experiment and 3.5 hours later. Nitrogen removal rate (12.2 mg l⁻¹ h⁻¹ N) was lower than the other two experiments due probably to lower MLVSS concentration. The specific nitrogen removal rate (0.17 mg nitrogen per mg MLVSS per day) was intermediate between the DO 0.2 mg l⁻¹ (0.19 mg nitrogen per mg MLVSS per day) and DO 0.8 mg l⁻¹ (0.16 mg nitrogen per mg MLVSS per day) cases.

Table 4 shows the COD removal rate along with nitrogen removal rates for the cases of DO 0.8 and 0.3 mg l⁻¹ at initial MLVSS of 2295 mg l⁻¹. The COD removal rate was about 80 mg l⁻¹ h⁻¹ in both these cases. The amount of COD removed, for each mg of nitrogen removed, was found to be equal to 5.54 and 6.23 mg, for DO concentrations of 0.3 and 0.8 mg l⁻¹, respectively. This is the combined amount of COD required by, both, the organics removing microorganisms and the denitrifying microorganisms. This is an important factor, as many wastewaters, especially industrial wastewaters, do not have such amount of COD/N ratio. If the amount of COD is higher than it is required for nitrogen removal, then additional treatment time have

to be provided for the extra COD concentration. On the other hand, if the COD concentration is lower than the above ratio, the extent of nitrogen removal will be limited by the amount of COD concentration present. The specific nitrogen removal rate in these two cases was equal to 0.14 and 0.15 mg N per mg MLVSS per day for the cases of DO 0.3 and 0.8 mg l⁻¹, respectively.

Conclusions

The following conclusions can be drawn from the present study:

1 – Simultaneous nitrification and denitrification (SND) at low dissolved oxygen (DO) concentrations was confirmed to occur at an oxidation ditch plant in Jordan, both, by full scale and lab scale studies.

2 – SND removal rates were found between 12.2–19.5 mg l⁻¹ h⁻¹ N depending on MLVSS and DO concentrations.

3 – Nitrogen specific removal rates varied between 0.14 – 0.19 mg mg⁻¹ d⁻¹, with higher specific removal rates for lower DO mass concentrations.

4 – The amount of COD required for every mg of nitrogen removed varied between 5.5 – 6.3 mg.

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