Partial nitrification activated sludge operation as an appropriate nitrogen removal scheme for the Mediterranean region

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Abstract Wastewater Treatment Plants (WWTPs) operation under conventional fully nitrifying activated sludge BNR schemes, although favoured by the temperate climate conditions prevailing around the Mediterranean region, may prove quite inefficient in terms of both capital and O&M costs when recipient body characteristics do not pose similar requirements; especially more so, when treated effluents are intended for reuse in agriculture and nitrogen content may well serve as fertilizer. This paper presents some experimental evidence that single-reactor partial nitrification schemes, allowing for nitrogen removal to the extent needed under seasonally varying plant loading conditions and effluent quality requirements, and securing reliable and efficient plant operation, may be a more suitable alternative for similar cases.

Keywords Fertilizer; intermittent aeration; irrigation; nitrification rate; simultaneous nitrification-denitrification; small-scale WWTPs; tourist resort areas

Introduction

The biochemical processes of nitrification and denitrification are widely employed in municipal wastewater treatment plants as a means to achieve efficient biological nitrogen removal (BNR). Activated sludge systems employing these processes are most often applied in the form of single sludge predenitrification – nitrification schemes with two (or more) separate reactors (or reactor segments) in series and internal mixed liquor recirculation, or alternating tank configurations. However, under certain conditions, the application of similar systems may sometimes prove to be inappropriate or even undesirable.

In temperate climate regions such as those around the Mediterranean Sea, under relatively high temperatures (in the reactor) of $T \geq 18^\circ C$ throughout the year, enhanced nitrification is practically unavoidable, even at low sludge retention times (SRTs) of 4 to 6 days. This temperature influence however, favourable when full nitrification is required, turns adverse when recipient body characteristics do not require complete ammonia nitrogen oxidation; it is leading to: (a) increased aeration requirements and therefore excess power installation resulting in respectively increased capital and O&M costs and (b) a need for high denitrification efficiencies and hence increased reactor volume requirements and construction costs, in order to avoid plant operation problems such as rising sludge phenomena (particularly triggered by high temperature conditions as well) in final settling tanks.

Recipient body characteristics on the other hand, may not be the only factor rendering high nitrification or nitrogen removal performance undesirable or unnecessary. For almost all arid or semi-arid regions in the Mediterranean countries, with fresh water reserves at a critical point (Lazarova et al., 2001) and under severe pressure as well (Marecos do Monte et al., 1996), recycling of treated wastewater already is or in the near future will be a very valuable resource for use in agriculture; a very significant component of economic activity in these countries, especially under the warm and sunny climatic conditions allowing for
intensive cultivation of high value agricultural produce exported to colder climate countries.

From this perspective, it would seem that high nitrogen removal from wastewater (usually associated with effluent concentrations of $\text{NH}_3-N \leq 1.0 \text{ mg/L}$), may be an irrational exercise, both in terms of energy and resource utilization. Especially if/when coupled with fertilizer application practices (very often intensive, in order to boost production). It would also seem that under similar circumstances, fertirrigation (Angelakis et al., 1999), i.e. utilizing the fertilizing properties of treated wastewater by irrigation, may be the answer to most of the problems that farmers “paying for fertilizer and praying for rain” (to paraphrase a saying quoted by Sala and Mujeriego, 2001) face. Also, from another perspective on the same issue of technologies appropriate for wastewater treatment and reuse in the Region, it may be argued that small-scale treatment plants, such as those that operate or are planned for at the numerous semi-arid islands of the Aegean Sea and other Mediterranean islands, (that almost certainly will be soon forced to rapidly develop water reuse schemes) inherently require a relative simplicity in operation. Conventional systems consisting of several physical parts (tanks or reactor segments) under different operating conditions at any one time, that may require frequent adjustment with respect to each other, may not be particularly suitable for such cases.

It follows from the above that under similar conditions, i.e. when only some nitrogen removal is required, preferably together with a relative simplicity in operation and control, then it becomes necessary to apply respectively suitable schemes. Schemes that, while limiting or allowing for partial nitrification only, will at the same time achieve substantial nitrogen removal through denitrification, thus securing reliable and efficient (both in terms of performance and economy) plant operation and providing treated effluents of the desired quality. Such conditions do not in general apply to Northern and Central Europe (with acute eutrophication problems in the Baltic and Northern Sea and inland waterbodies and – adversely adding to that, due to the consequent nitrification requirements – relatively low temperatures) or to N. America; it is therefore reasonable that they have not yet been examined to a significant extent. However they are particularly representative of regions around the Mediterranean Sunbelt.

It is the purpose of this paper, to present some experimental evidence that it is possible to efficiently deal with similar cases by employing relatively simple in operation single-reactor partial nitrification configurations and to discuss the mode of operation of such systems, contributing in this way to the relatively limited available experience of similar schemes normally and continuously operating for nitrogen removal per se.

**Experimental**

In order to examine the performance of similar systems, simultaneous nitrification-denitrification (N-DN) low dissolved oxygen schemes and alternating nitrification/denitrification (N/DN) intermittent aeration schemes, were operated in a large scale pilot plant installation. Conventional fully aerobic and two reactor pre-denitrification (preDN) configurations were also operated in parallel as control systems.

The pilot plant, developed at the Sanitary Engineering Research and Development Center (SERDC) of Athens Water and Sewerage Company (EYDAP S.A.), is a municipal wastewater (domestic with some light industry effluents, COD $\approx 550 \text{ mg/L}$, TKN $\approx 55 \text{ mg/L}$ and carbon to nitrogen ratio $C/N \approx 10$) treatment works installation. The biological stage of the plant, fed with primary sedimentation effluents, comprises (Figure 1) five parallel activated sludge diffused aeration units: one 60 m$^3$ preDN (anoxic volume $V_{anox.}= 30\% V_{tot.}$, mechanically mixed) plug flow reactor (A1), three 20 m$^3$ completely mixed tanks that were operated as a) a fully aerobic – low F/M system, b) an intermittently aerated N/DN system

and c) a low DO simultaneous N-DN system (A2.1, A2.2 and A2.3 respectively), as well as a 20 m$^3$ completely mixed tank operated as a fully aerobic – high F/M system (A3), each with its respective final sedimentation tank. Applied hydraulic retention times (HRTs) were in the range of 13 to 15 h.

**Results and discussion**

**Simultaneous N-DN low DO system**

During operation under the low reactor DO scheme, nitrification (or more accurately, influent ammonia nitrogen removal/conversion, i.e. due to both nitrification and nitrogen incorporation to biomass) seemed to be rather unstable and quite sensitive to DO concentration variations. As it can be seen in Figure 2, under an organic loading of $F/M = 0.10–0.20$ kgBOD$_5$/kgMLSS·d, equivalent to $SRT = 21–9$ d, the DO levels necessary for relatively stable but not complete nitrification, were approximately $DO = 1.0$ mg/L. These levels are significantly higher than respective values of $DO = 0.20–0.40$ mg/L that proved sufficient (Hatziconstantinou, 2000) for a stable and partial nitrification performance of approximately 70% in a lab scale pilot plant ($SRT = 7–9$ d, influent C/N = 5, $T = 20–21°C$, $HRT = 6$ h) operated under a low DO scheme with synthetic wastewater. However, even this relatively high concentration, although for certain periods seemed sufficient for nitrification of up to 80%, in other cases eventually led to nitrification loss.

Denitrification performance also varied depending on DO levels and more so on temperature. For $DO > 1.5$ mg/L and winter temperatures of $T = 18°C$, it was practically absent and nitrogen removal by the system resulted entirely as synthesis requirements. For $DO = 1.0$ mg/L and during increased nitrification, total nitrogen removal was low at approximately 35% under winter temperatures, but significantly higher at almost 70%, under summer temperatures of $T > 22°C$.

Actual nitrification and denitrification rates varying significantly during the experimental period and depending on the operational conditions, were 0.40–0.70 mgN/gMLSS·h and up to 0.50 mgN/gMLSS·h respectively (referring and associated to total reactor volume), in terms of monthly mean values.

The relatively high DO levels, necessary for stable nitrification in this large scale municipal wastewater pilot plant, were attributed to: (a) the relatively high influent C/N ratio resulting in nitrifiers *neighbourhood* within the activated sludge floc crowded with higher numbers of heterotrophs and thus making their access to oxygen more difficult, as well as to (b) occurrence of inhibition phenomena, as evidenced by effluent ammonia nitrogen
concentrations fluctuations in the conventional fully aerobic nitrification (control) system running in parallel, unjustifiable by operating conditions and attributed to industrial contributions.

This sensitivity of nitrification performance to DO concentration, in relation with the applied organic loading and incoming wastewater characteristics (mainly in terms of C/N ratio) in similar single-reactor systems, is considered to reveal a possibility for system control with respect to the desired levels of nitrification (and denitrification) performance; system control that can be achieved by means of reactor aeration intensity and system sludge retention time manipulation.

The occurrence of simultaneous nitrification and denitrification under low dissolved oxygen concentrations is primarily attributed to the formation of anoxic zones in the interior of sludge flocs due to oxygen diffusion limitations, posed by floc structure and microorganisms oxygen demand. Many researchers have dealt with these phenomena and simulated the processes (Mueller et al., 1968; Matson and Characlis, 1976; Smith, 1984).

Based on Fick’s second Law and relating DO concentration to oxygen uptake rate, floc size and distance from floc center, models have been used to conclude (Lau et al., 1984) that e.g. for flocs 200 µm in size and liquid phase dissolved oxygen concentration of DO = 0.3 mg/L, 40% of floc volume is under anoxic conditions of DO = 0.01 mg/L, reducing to 25% for a liquid phase DO = 1.0 mg/L. On the basis of experimental investigation on cells in suspension, Krul (1976) reported qualitatively similar findings, while some references on nitrification under low dissolved oxygen concentration can also be found in the literature (Hanaki et al., 1990). Further reports however, with detailed performance data from full-scale or pilot plant single-reactor systems, operating under partial or restricted nitrification conditions, similar to those reported in this present work, are generally lacking.

Figure 2 Pilot plant (unit A2.3), low DO simultaneous N-DN configuration: (a) system operating parameters (DO and organic loading) and (b) nitrogen removal performance
Alternating N/DN intermittent aeration system

Results from pilot plant operation under the alternating N/DN intermittent aeration scheme are shown in Figure 3. As it can be seen, stable nitrification was not possible during an initial period of high organic loading. After stabilization however, of the mixed liquor concentration and of the organic loading and under equal aerobic/anoxic phase duration of 0.5 h, nitrification was also stabilized. Nitrification performance reached values of 85–95%, higher under winter temperatures of \( T = 18^\circ C \) and organic loading of \( F/M = 0.15 \) kgBOD\(_5\)/kgMLSS·d (equivalent SRT≈ 12 d) and lower under elevated temperatures of \( T = 22^\circ C \) and organic loading of approximately \( F/M = 0.25 \) kgBOD\(_5\)/kgMLSS·d (equivalent SRT≈ 7 d).

This small difference in nitrification performance, under different temperature and loading conditions, may be again considered as indicative of the possibility for nitrification and system operation control, through aeration/anoxia phase duration and (aerobic) sludge age. Total nitrogen removal by the system was quite high, almost 70% under winter temperatures and over 80% under summer temperatures. Actual nitrification rate during periods of stable performance, varied in the range of 1.6–2.5 mgN/gMLSS·h, in monthly mean values, while the denitrification rate ranged around 0.8–1.2 mgN/gMLSS·h during winter and at approximately 1.6 mgN/gMLSS·h under high temperatures (rates referring and associated to respective phases).

In the literature there are numerous reports concerning two reactor systems under alternating aerobic and anoxic conditions. Those concerning however one reactor systems, are relatively limited and are mainly intended to show the usefulness of ammonia and nitrate nitrogen and/or ORP sensors for optimising aeration and nitrogen removal (Kayser and Ermel, 1984; Balsev et al., 1996; Plisson-Saune et al., 1996; Zhao et al., 1999) under complete and stable nitrification conditions or refer to sequencing batch reactor type of

![Figure 3](https://iwaponline.com/ws/article-pdf/3/4/153/407572/153.pdf)
systems. Operation of similar systems for efficient nitrogen removal, or the possibility for nitrification control and restriction under low to medium organic loading conditions have not yet been adequately investigated, neither has the potential for substantial nitrogen removal under partial nitrification conditions.

**Conventional systems**

In the control systems that were operated in parallel under fully aerobic as well as under pre-DN schemes, nitrification was stable and practically complete. Incoming ammonia nitrogen removal/conversion was approximately 95% (for organic loading conditions of up to $F/M = 0.40 \text{ kgBOD}_5/\text{kgMLSS-d}$ under summer temperatures of $T = 21–25^\circ\text{C}$, and up to $F/M = 0.20 \text{ kgBOD}_5/\text{kgMLSS-d}$ under winter temperatures of $T = 17–18^\circ\text{C}$), at the pilot plant units A1, A2.1 and A3; not higher, mainly because of isolated but not unusual incidents of relatively high ammonia concentrations leaking due to inhibition phenomena, as already mentioned.

Total nitrogen removal in fully aerobic nitrification systems resulted almost entirely from synthesis requirements, while it was quite high under the pre-DN scheme, over 80%. With the condition however of well regulated mixed liquor recirculation and absence of dissolved oxygen in an adequately sized anoxic reactor, a task not always easy to accomplish, both from a designer’s and an operator’s perspective.

**Operation aspects**

It can be concluded from the above, that in single reactor systems and under the conditions of relatively high temperatures encountered in the Mediterranean region and low to medium organic loading conditions investigated in this paper, substantial denitrification and nitrogen removal is possible. Comparable to some extent with conventional systems performance, when at the same time nitrification may be restricted for economic and operational reasons or agronomic purposes by means of aeration intensity/duration and aerobic sludge age.

Partial nitrification conditions, naturally result in relatively elevated bioreactor $\text{NH}_3$-$\text{N}$ concentrations of e.g. higher than 4–5 mg/L (or even higher depending on system operation and desired performance); complete nitrification operation on the other hand, is most often associated with concentrations of less than approximately 1.0 mg/L. As nitrification is widely accepted to follow Monod kinetics, actual specific (i.e per unit weight of biomass) nitrification rates $r_{\text{NH,act.}}$, can be expressed as:

$$r_{\text{NH,act.}} = \frac{\mu_N}{Y_N} \cdot \frac{\text{NH}}{(K_{\text{NH}} + \text{NH})}$$

where,

- $r_{\text{NH,act.}}$: actual specific nitrification rate (mgN/gMLSS·d)
- $\mu_N$: nitrifiers maximum specific growth rate (d$^{-1}$)
- $Y_N$: nitrifiers yield coefficient
- $K_{\text{NH}}$: nitrification half saturation constant (mg/L)
- $\text{NH}$: reactor ammonia nitrogen concentration (mg/L),
- $\text{NH}$: reactor ammonia nitrogen concentration (mg/L),

The respective saturation constant has a relatively low value, lying in the range of $K_{\text{NH}} = 0.3–0.7 \text{ mg/L}$ (Henze et al., 1995). As a result, it follows that nitrification rates realized in the aerobic reactor (or aerobic segment or during aerobic phases) of systems producing effluents only marginally different by just a few milligrams, e.g. NH$_3$-$\text{N} = 4.0$ versus 0.5 mg/L, may nevertheless differ quite significantly (or even dramatically, by approximately as high as almost 80% in this example, assuming $K_{\text{NH}} = 0.5 \text{ mg/L}$). The
conclusion that may be subsequently drawn is that partial nitrification schemes, as those
described in this paper, seem to be able to operate far more efficiently, in a sense that
system available nitrification potential can be actually exploited to a much higher degree as
opposed to fully nitrifying schemes.

This observation may prove quite significant if a particular characteristic of the
Mediterranean region is more closely considered; semi-arid areas of interest (i.e. those pri-
marily requiring development of reuse schemes) are very often tourist resort areas. And
these areas welcome large numbers of tourists, the type of tourism developed however
(frequently concentrated to no more than 100 summer days), resulting in peak summer
populations double (and not rarely triple, or even more) the winter ones. During such (dry)
periods of increased populations, several acute problems emerge: (a) increased potable
water demand, (b) very high volumes of wastewater to be treated, as opposed to reduced
winter flows, frustrating both plant designers and operators, and (c) increased irrigation
requirements by farmland quite often adjoining those tourist resort areas.

Fortunately some of these problems, in a way, may be or may hide a solution to the
others. WWTPs under partial nitrification schemes, operating more intensively and close to
their maximum attainable potential as previously described, can also prove suitable enough
in handling increased summer flows (destined for fertirrigation) as well; i.e. besides winter
ones, generally requiring higher levels of nitrogen removal prior to disposal than tolerated
for fertirrigation purposes. In this way, seasonally varying wastewater treatment require-
ments (with respect to both reactor volumes and aeration) may be smoothed away and efflu-
ent disposal and irrigation (and fertilizer) needs can be more efficiently met. Thus, saving
potable water supply for strictly domestic potable and personal hygiene uses.

The advantages of similar single-reactor systems operating under a relatively wide
range of conditions are not confined to the potential savings in capital cost (reactor volume
and aeration equipment) and O&M cost (energy for aeration and internal recirculation
pumping). They also include a relatively more simple operation as well as the possibility of
varying anoxic volumes application, and consequently the potential for a more precise
plant tuning. A goal which may be more difficult to achieve by means of internal recirculation
in conventional fixed anoxic volume pre-denitrification systems, or by means of phase
duration in alternating tank systems.

Similar features may be considered as particularly useful when frequent presence of
experienced process operators may not be available. As e.g. in the case of rural areas small
WWTPs, where effluent reuse for irrigation purposes very often can be an attractive (or
even compulsory) solution and robust plant operation is essential.

Conclusions
The conclusions reached in this paper, can be summarised as follows.
(a) Enhanced nitrification WWTPs operation, triggered by the relatively high temperatures
prevailing in the Mediterranean Region, may prove inefficient when recipient body
characteristics do not require similar treatment and especially when effluent reuse for
irrigation is practised.
(b) Single-reactor partial nitrification systems, under simultaneous N-DN low DO or alter-
nating N/DN intermittent aeration schemes and medium to low organic loading condi-
tions, can achieve substantial nitrogen removal when at the same time nitrification may
be restricted for economic, operational or agronomic reasons.
(c) Higher specific nitrification rates realized under partial nitrification conditions and
relatively increased effluent NH\textsubscript{3}-N concentrations, allow for a more efficient use of
available reactor volumes; and consequently for a more rationalized approach with
respect to the design and operation of treatment plants that are subjected to seasonally
varying loading conditions and effluent quality requirements (associated to disposal/reuse alternatives).

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