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Review

The presence of organic matter during autotrophic nitrogen removal: Problem or opportunity?

Elisa A. Giustinianovich [a], José-Luis Campos [b], Marlene D. Roeckel [a,*]

[a] Department of Chemical Engineering, University of Concepción, Concepción, Chile
[b] Faculty of Engineering and Sciences, Universidad Adolfo Ibañez, Viña del Mar, Chile

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The simultaneous nitrification, Anammox and denitrification (SNAD) process discovered six years ago is an adaptation of the autotrophic denitrification process that allows for treating nitrogen-rich wastewater streams with moderate amounts of organic carbon. Several authors have noted that it is possible to utilize organic carbon to promote nitrogen removal via the action of denitrifying microorganisms, which can remove the remnant nitrate produced by Anammox bacteria. Thus, SNAD systems can achieve nitrogen removal efficiencies higher than 89%, which is what is expected under autotrophic conditions. Three bacterial groups are responsible for SNAD reactions: ammonium-oxidizing bacteria (AOB), anaerobic ammonium-oxidizing bacteria (AnAOB) and heterotrophic bacteria (HB). Because HB will compete with AOB and AnAOB for oxygen and nitrite, respectively, the system should be operated in such way that a balance among the different bacterial populations is achieved. Here, the results reported in the literature are analyzed to define suitable characteristics of effluents for treatment and operational conditions to allow the SNAD process to be carried out with different types of technologies.

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1. Introduction

To fulfill disposal requirements, conventional nitrification–denitrification (ND) processes are generally used to remove both organic compounds and nitrogen from municipal and industrial wastewaters. These processes are well known, and their efficiency and reliability are beyond doubt. However, these processes have a major drawback: the availability of sufficient organic matter to carry out denitrification. Thus, ND processes can be applied only to effluents with chemical organic demand to nitrogen (COD/N) ratios higher than 5 [40]. The addition of an external organic carbon source required for COD/N ratios lower than 5 results in a consequent increase in operational costs [13]. Furthermore, application of the ND processes suggests that a portion of the organic matter present in the effluent is wasted by the aerobic route and cannot be used to produce biogas via anaerobic digestion [54]. To overcome this drawback, the application of partial nitrification-Anammox processes, instead of conventional ND

* Corresponding author at: Chemical Engineering Department, University of Concepción, Casilla 160-C, Concepción, Chile.
E-mail address: mroeckel@udec.cl (M.D. Roeckel).

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processes, is being promoted because these processes occur under autotrophic conditions, and organic matter and nitrogen can therefore be removed in separate processes [46,56].

Partial nitrification-Anammox processes involve two reactions in series. The first reaction (Eq. (1), [5] consists of aerobic oxidation of ammonium to nitrite by ammonia-oxidizing bacteria (AOB), and the second (Eq. (2), [39] is anoxic oxidation of ammonium to nitrogen gas using nitrite as an electron acceptor by the action of anaerobic ammonium-oxidizing bacteria (AnAOB).

$$NH_4^+ + 1.5O_2 \rightarrow NO_2^- + H_2O + 2H^+ \quad (1)$$

$$NH_4^+ + 1.3NO_2^- + 0.066HCO_3^+ + 0.03H^+ \rightarrow 1.02N_2 + 0.26NO_3^- + 0.066CH_2O_{0.5}N_{0.15} + 2H_2O \quad (2)$$

To couple these reactions, approximately half of the ammonium must be oxidized to nitrite by partial nitrification; thus, an appropriate substrate for AnAOB is obtained, as shown in Eq. (3) [30].

$$NH_4^+ + 0.85O_2 \rightarrow 0.11NO_3^- + 0.445N_2 + 0.14H^+ + 1.43H_2O \quad (3)$$

Autotrophic nitrogen removal can be carried out in two-reactor systems, one for partial nitrification (PN) and a second for Anammox, or by coupling the reactions in a single reactor operated under controlled dissolved oxygen (DO) levels. The latter configuration is the one applied most frequently at an industrial scale because it involves less complex control systems, lower investment costs, reduced risk of AnAOB inhibition by nitrite and lower N_2O emissions [50]. In the past decade, a variety of technologies have been developed for performing PN-Anammox processes in a single-stage system, which can be divided into three types depending on the aggregation state of the biomass: suspended sludge, granular biomass and biofilm technologies.

Suspended sludge technologies utilize a mixed sludge containing flocculent bacteria (ammonia-oxidizing bacteria) and granular Anammox biomass. This technology includes a hydrocyclone to separate the granular Anammox bacteria from the flocculent biomass. The Anammox granules are returned to the reactor, whereas the flocs are separated and purged to avoid the proliferation of nitrite-oxidizing bacteria and thereby maintain a stable system operation [55]. When granular biomass or biofilms are used, AOB can grow in the outer part of the granule/biofilm and produce nitrite and consume oxygen, generating anoxic conditions in the inner part of the granule/biofilm. In this anoxic zone, ammonium and nitrite (produced during partial nitrification) must be present to allow the growth of Anammox bacteria [7,47].

Most of the industrial-scale applications of partial nitrification–Anammox (PN-Anammox) processes are installed in Europe, though there is growing interest in both China and North America [3]. Currently, there are more than 100 plants in operation worldwide, and the most used technology is that based on suspended biomass (approximately 40% of the plants), followed by granular systems and biofilms [26]. Most of the industrial-scale facilities treat the supernatant of anaerobic sludge digesters with inlet ammonium concentrations of 500–1500 mg NH_4^+-N/L and COD/NH_4^+-N ratios of 0.5–1.5 [26]. The high hydraulic residence time (HRT) applied to anaerobic sludge digesters (20–30 d) guarantees almost no remaining biodegradable COD in the effluent, which could interfere with the autotrophic process.

Nevertheless, the HRTs applied in cases of anaerobic digester treatment of industrial effluents are shorter than those used for anaerobic sludge digesters; therefore, the presence of relatively high amounts of biodegradable COD in the effluents cannot be overlooked [6,30,34,36,48]. A similar situation can occur during the application of PN-Anammox processes to the mainstream of municipal wastewater treatment plants (WWTPs) because organic matter is previously removed by an aerobic stage operated at a low solids retention time (SRT); thus, remaining biodegradable COD of approximately 20% of the inlet COD is commonly found due to the low SRT [14,29]. For this reason, the effect of organic matter on the partial nitrification and Anammox process has been gaining attention over the past few years [21,25,32].

2. Effect of organic matter on the partial nitrification and Anammox processes

Because PN-Anammox systems were initially implemented in a two-stage configuration, the first works investigating the effect of organic matter focused on the Anammox process [12,2]. Most research has shown that low organic levels do not significantly affect ammonia or nitrite removal but improve total nitrogen removal by denitrifiers [37]. In fact, the nitrate generated by Anammox bacteria can be reduced to nitrite in the presence of organic matter by heterotrophic denitrifying bacteria and can then be removed via the Anammox process [51]. However, if the inlet $COD_{biodegradable}/NO_2$-N ratio is greater than 1.9–3.1, Anammox bacteria are unable to compete with heterotrophic denitrifiers for both space and the electron acceptor (nitrite), with failed reactor performance [37,41,42]. Nevertheless, the coexistence of Anammox biomass with heterotrophic denitrifying biomass in the presence of organic matter has been reported [4]. This fact could be related to the capacity of Anammox bacteria to oxidize organic matter to CO_2 using nitrate and/or nitrite as the electron acceptor [16].

With regard to the effect of organic matter on partial nitrification, Mosquera-Corral et al. [36] found that an inlet $COD_{biodegradable}/NH_4^+$-N higher than 0.8 caused the washout of AOB from a chemostat operated at an SRT of 1 day and 30 °C due to competition between the heterotrophs and AOB. This negative effect of organic matter on suspended nitrifying biomass can be overcome by increasing the SRT [17]. Such findings would indicate that inlet $COD_{biodegradable}/NH_4^+$-N should be controlled to avoid AOB loss when the reactor is operated at SRT values close to the minimum SRT for AOB (0.5 d at 30 °C).

In the case of granular or biofilm nitrifying systems operated without devices to retain flocculent biomass, competition between heterotrophs and AOB can be avoided by HRT manipulation. If the HRT is larger than the reciprocal maximum specific growth rate of the heterotrophic biomass, the bacteria grow in suspension and do not form biofilms over the nitrifying biomass, which limits oxygen availability for ammonia oxidation [44]. If the HRT applied is shorter than the reciprocal maximum specific growth rate of the heterotrophic biomass, a heterotrophic layer will be formed on the nitrifying granular biomass or on the nitrifying biofilm, and its effect on the ammonia oxidation efficiency will depend not only on the $COD_{biodegradable}/NH_4^+$-N but also on the surface specific substrate load [43,44].

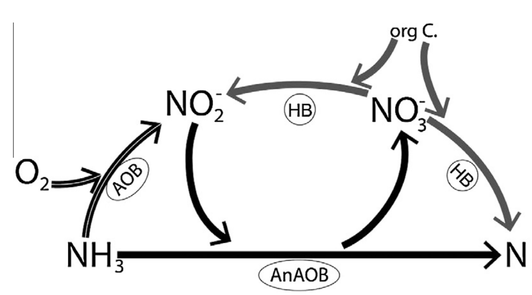

Fig. 1. SNAD process reactions. Different arrows indicate the different reactions mediated by AOB, AnAOB and HB, respectively.