Improvement of nitrogen and phosphorus removal in the anaerobic-oxic-anoxic-oxic (AOAO) process by stepwise feeding

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Abstract This investigation incorporated a stepwise feeding strategy into the biological process containing anaerobic/oxide/anoxic/oxide (AOAO) stages to enhance nitrogen and phosphorus removal efficiencies. Synthetic wastewater was fed into the experimental reactors during the anaerobic and anoxic stages and the substrates/nutrients were successfully consumed without recycling either nitrified effluent or external carbon source. An intrinsic sufficient carbon source developed during the anoxic stage and caused the NOx (NO2-N+NO3-N) concentration to be reduced from 11.85mg/l to 5.65mg/l. The total kjeldahl nitrogen (TKN) removal rate was between 81.81%~93.96% and the PO4-P removal ratio ranged from 93%~100%. The three difference experiments contained within this study produced Q1/ Q2 that varied from 7/3, 8/2, and 9/1. The AOAO process saved nearly one-third of the energy compared with typical biological nutrient removal (BNR) system A2O processes.

Key Words A2O process, AOAO process, denitrification, external carbon sources, step feeding

Introduction Increasingly stringent effluent criteria combined with increasing polluted loading and limited land requires more efficient wastewater treatment. Biological nutrient removal (BNR) can fulfill the above mentioned goals while simultaneously supplying sufficient electron donors for the denitrifying process (Su and Ouyang, 1996). Conventional activated sludge processes require external carbon sources for nitrogen removal since they lack appropriate electron donors and adequate COD/N ratios (Barker and Dold, 1996). Possible carbon sources include [methanol, ethanol, acetate], and raw wastewater (Rensink et al., 1991). Numerous treatment systems have recently been developed to rearrange the layout of the anaerobic, anoxic and aerobic reactors (Comeau et al., 1986; Gerber et al., 1987; Hascoet et al., 1985). This study adopts the Wisestep Feeding concept that was applied in a novel approach AOAO process that used raw wastewater as the external carbon source for denitrification.

A net uptake of phosphorus under anoxic conditions can be achieved in both batch and continuous tests (Comeau et al., 1986), while poly-phosphorus (poly-P) organisms can effect denitrification (Gerber et al., 1987; Hascoet et al., 1985; Malnou et al., 1984; Su and Ouyang, 1996). Nevertheless, Wentzel et al. (1989) reported that only a small fraction of the poly-P organisms have the capacity for denitrification. According to their results, the nitrate removal rates in anoxic reactors of enhanced culture systems do not differ from corresponding rates in the mixed systems (BEPR and non-BEPR) (Gerber et al., 1987; Hascoet et al., 1985; Malnou et al., 1984). Other researchers (Malnou et al., 1984; Gerber et al., 1987) have reported that phosphorus is released when formate, acetate, and propionate are added in the presence of nitrate. Adding acetate and propionate led not only to a rapid release of phosphorus, but it also rapidly consumes nitrate and substrate (Rensink and Eggers, 1991). The phosphorus profile in a batch test without nitrate or any additional substrate remained constant until the entire nitrate was consumed.
Numerous modified A2O processes have been employed to sequence the reactors of an anaerobic/anoxic/oxide unit (Su and Ouyang, 1996). The nitrified liquor must be returned to the anoxic zone for denitrification in these processes. Ethanol has been used as an extra carbon source to achieve denitrification as the total nitrogen removal efficiencies with or without ethanol were 67% and 35%, respectively (Hallin et al., 1996). However, this denitrification method has limited applications because the external carbon source is economically unfeasible. Therefore, this study presents a biological nutrient removal process that reduces the dosage costs by utilizing raw wastewater instead of ethanol as the carbon source and saves energy by rearranging the sequence of reactors. Consequently, this novel process saves more energy than other methods because it utilizes a wisestep feeding strategy that introduces raw wastewater into the anaerobic and anoxic units by varying the influent ratios. The operational parameters and characteristics of the AOAO (Anaerobic/Oxide/Anoxic/Oxide) process can be derived using a process similar to that adopted to remove the nutrients.

**Material and methods**

The A2O process was traditionally used to simultaneously remove nitrogen and phosphorus from wastewater. The AOAO process rearranges the reactor sequence into anaerobic, oxide, anoxic and oxide reactors. The phosphorus will be released from the biomass in the anaerobic reactor and it will consume the carbon source in the anaerobic reactor. The ammonia oxide is reduced to nitrate and nitrite in the oxide reactor and reduced to nitrogen gas in the anoxic reactor. Figure 1 schematically depicts the AOAO pilot plant. The net volume of the reactor and settlement tanks are 28 litres (anaerobic zone), 70 litres (oxide zone), 35 litres (anoxic zone), 7 litres (oxide zone), and 21 litres (settlement zone), respectively. The anaerobic zone was divided into two sections, the oxide zone into four sections, and the anoxic zone into two sections. Moreover, a mixer was applied in each reactor to prevent the activated sludge from settling.

The first initial flow rate Q1 leads into the anaerobic zone while the second flow rates Q2 leads into the anoxic zone, with a variety of ratios Q1 / Q2 ratios were 9/1, 8/2 and 7/3, respectively. In addition, the total flow rate was maintained at a constant Q1+Q2=Q=230 ml/min and the pilot plant operated at a fixed recycling sludge ratio of r = 0.5 under the same influent wastewater concentrations. No returning nitrified supernatant liquid was applied for saving energy in this research.

The hydraulic retention time (HRT) was fixed at ten hours, the constant sludge retention time (SRT) was ten days, and temperature was maintained at 20 °C. The dissolved oxygen in the mixed liquid in the oxide reactor was maintained above 2.0 mg/l. Meanwhile, the final oxide reactor was maintained above 4.0mg/l to confirm that no phosphorus would be released from the settling tank. Synthetic municipal wastewater that simulated the settled influent wastewater concentration of the Min-Sheng Municipal Wastewater Treatment Plant in Taipei City was the influent substrate applied herein. The substrate was formulated.
using full-fat dry milk power and some laboratory grade compounds including: COD$_T$=300mg/l, COD$_S$=215mg/l, BOD$_T$=210mg/l, BOD$_S$=160mg/l, total nitrogen (T-N)=40mg/l, NH$_4^+$-N=20mg/l, organic nitrogen (org-N)=20mg/l, total phosphorus (T-P)=5.5mg/l, ortho-phosphorus (PO$_4^{3-}$)=4mg/l, and alkalinity as CaCO$_3$=60mg/l.

Results and discussion

COD Removal

The wastewater was influenced by Wisestep feeding at two points: anaerobic-1 zone (as Q$_1$) and anoxic-1 zone (as Q$_2$). The substrate CODs (soluble CODs) were led into anoxic-1 to facilitate denitrification. Figure 2 demonstrates that CODs were primarily consumed (92%~87%) during the anaerobic stages (anaerobic-1&2) in all testing runs. There was no significant change in the effluent CODs throughout the runs, while Q$_1$/Q$_2$ ratios varied from 9/1 to 7/3. The soluble CODs removal efficiency was 98%~95%.

Phosphorus Removal

The Q$_1$/Q$_2$ ratio influenced the concentration of PO$_4^{3-}$-P at each stage while the PO$_4^{3-}$-P consumed the DO that originated from aerobic 5 and the PO$_4^{3-}$-P slightly rose in effluence as a result. In addition, increasing the DO concentration in the settling zone would decrease the phosphorus in the effluent. Phosphorus was rapidly released in the anaerobic zone when the C/P ratio was between 75~100 and an appropriate environment was maintained: ORP was maintained below - 400. The released phosphorus increased from 21mg/l to 29.5mg/l as the Q$_1$/Q$_2$ ratios moved from 9/1 to 7/3. However, adding Q$_2$ reduced the Q$_1$, which implies the

![Figure 2](https://iwaponline.com/wst/article-pdf/42/3-4/89/428422/89.pdf)

Figure 2 CODs concentration (mg/l) in each reaction stage with different Q$_1$:Q$_2$ ratio

![Figure 3](https://iwaponline.com/wst/article-pdf/42/3-4/89/428422/89.pdf)

Figure 3 The concentration of PO$_4^{3-}$-P (mg/l) in each reaction stage with different Q$_1$:Q$_2$ ratio
carbon source was also be simultaneously reduced in both the anaerobic and oxide reactors. Meanwhile, a secondary release occurred under these conditions since the oxide zones had insufficient energy to absorb the phosphorus released from the anaerobic reactors. Nevertheless, the anoxic zone can slightly influence phosphorus absorption. The AOAO process can efficiently remove phosphorus and the PO₄-P release/absorption profile are detailed in Figure 3.

The HRT is a major operating parameter at an appropriate C/P ratio. Q₁ decreased from 207ml/min to 161ml/min when the Q₁/Q₂ ratio was raised from 9/1 to 7/3, which subsequently caused the hydraulic retention time to increase from 135 to 174 minutes. A longer HRT stimulates more phosphorus to be released as the oxide zones completely absorbed all of the released phosphorus.

Nitrogen Removal
The raw wastewater that possessed ammonia nitrogen had nearly half the total amount of nitrogen. The ammonia nitrogen removal rate was decreased slightly from 100% to 89.81% while the Q₁/Q₂ ratio increased from 9/1 to 7/3, as displayed in Figure 4. Although, the ammonia nitrogen removal rate decreased slightly and the NOx-N removal rate increased quite obviously and made effluent concentration from 11.83mg/l decrease to 5.65mg/l. Total nitrogen removal was the chief concern considering that nitrogen removal must include the organic nitrogen content in the wastewater. Although raising Q₂ would lead towards extra ammonia nitrogen entering the anoxic zones, only a slight amount of NH₄-N remains in the anoxic zone after adding Q₂ since the organisms will immediately absorb the ammonia nitrogen. However, the NH₄-N removal rate decreases because absorption occurs so rapidly. The NH₄-N removal rate decreased from 85% to 55.4% as the Q₁/Q₂ ratio
increased from 9/1 to 7/3 as displayed, in Figure. 4 Table 1 reveals denitrification was encouraged when Q₂ was increased and the carbon source was brought into the anoxic zone. NOx-N was moved away from the reactor and the NOx-N concentration decreased from 11.83mg/l to 5.65mg/l. The organic nitrogen and ammonia nitrogen did not have enough time to oxidize into NO₂⁻N, NO₃⁻N, and subsequently be reduced to nitrogen gas when Q₂ was added to the wastewater in the anoxic zone. Meanwhile, the removal efficiency decreased and a large quantity of NH₄⁺N and Org-N were still present in the effluent when the Q₁/Q₂ ratio was raised to 7/3. However, the NOx-N removal efficiency continued to rise with an increased Q₁/Q₂ ratio suggesting that denitrification was favorable when Q₂ brought a carbon source into the anoxic reactor.

Furthermore, the organic nitrogen and ammonia nitrogen removal efficiency must be sacrificed when employing a carbon source in denitrification to reduce the NOx-N concentration. The T-N remained nearly constant (65% ~ 70%) while the Q₁/Q₂ ratio increased from 9/1 to 7/3. Thus, when the carbon source was brought by Q₂ to encourage denitrification in the anoxic zone, it also compensated the T-N removal efficiency by leading the NH₄⁺N and Org-N into the anoxic zone and keeping them constant, as displayed in Figure 5. The NOx-N removal rate will vary with the CODs/NOx-N ratio and can be displayed as CODs/NOx-N = 5.429(NOx-N removal rate)-0.346. The NOx-N removal efficiency increases with the CODs/NOx-N ratio. Indeed, the NOx-N removal rate approached 90% as the CODs/NOx-N ratio neared 4.5, which can be expressed as CODs = 5.43(NOx-N) –0.346. Meanwhile, the denitrification bacteria in the anoxic zone utilized the carbon source from Q₂. The utilization rate was expressed as a consumption of CODs per MLSS that varied with the CODs/NOx-N ratio: CODs/NOx-N =182.37(CODs₁-CODs₂)/MLSS+ 1.022. Two hours for detention are adequate for nitrification in the oxide zone, meanwhile the TKN removal would cease and nitrification would stop. The nitrification rate was 6.61mg N/l/h. The Wise step feed substrate strategy improved the biomass washout problem in the plug-flow type aerobic reactor as it maintained at 2500mg/l MLSS average value and at 2.64mg N/g MLSS/h specific nitrification rate in the aerobic zone.

Conclusion
The proposed A0AO process for nutrient removal demonstrated that wastewater can be used as a carbon source for denitrification in the anoxic zone. The organic nitrogen pro-
duced in wastewater conversion to ammonia did not have enough time to reduce into nitrogen gas, which resulted in decreased T-N removal efficiency (65%~70%). The experimental results confirm that the AOAO process efficiently removed TKN (81.81% ~93.96%), COD (93%~98%), and PO4-P (93%~100%). NOx-N removal with carbon consumption can be expressed as CODs/NOx-N = 182.37*(CODs1-CODs2)/MLSS + 1.022 as sufficient carbon increases NOx-N removal efficiency. Indeed, the NOx-N removal rate approached 90% when the CODs/NOx-N ratio equals 4.5.

References