Preliminary Investigation of an Installed Pilot-Scale Biological Nutrient Removal Technology (BNRT) for Sewage Treatment

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Abstract Water utilities, commercial and industrial establishments are required to upgrade or install new treatment systems to comply with the revised effluent standards issued by the Department of Environment and Natural Resources – Environment Management Bureau (DENR – EMB) which now includes removal and monitoring of nutrients (nitrogen and phosphorus components). One solution is to utilize a biological nutrient removal technology (BNRT) system capable of removing nutrients from sewage. The on-going study aims to investigate the performance of the pilot-scale system in the removal of nutrients from sewage. The designed pilot-scale anaerobic-anoxic-oxic (A2O) process with a total hydraulic retention time of 8.37 hrs. was operated in an existing sewage treatment plant (STP). System modification was adapted to ensure continuous operation. Dissolved oxygen (DO) and temperature of each compartment were evaluated after 45 days of system modification. The DO of the anaerobic and oxic compartment remained within the required range, while the internal recycling flowrate and/or aeration must be adjusted to achieve a DO concentration of 0.20 – 0.50 mg/L in the anoxic compartment. The research is financially supported by the Philippine Council for Industry, Energy and Emerging Technology Research and Development of the Department of Science and Technology (PCIEERD Project No. 04176).

1 Introduction

Rapid urbanization has contributed to deteriorating water quality. It was reported that about millions of cubic meters of untreated wastewater are discharged to water bodies such as Manila Bay and Laguna Lake (The International Water Association, 2018). Untreated wastewater contains high concentration of nutrients such as nitrogen and phosphorus, resulting to several environmental issues such as eutrophication and fish kill (Falahti-Marvast and Karimi-Jashni, 2015; Majdi Nasab et al., 2016; Simeon, 2019)

Last 2016, the Department of Environment and Natural Resources – Environmental Management Bureau (DENR-EMB) released the Department Administrative Order (DAO) 2016 – 08 which limits nitrogen and phosphorus concentrations on effluent wastewater. (DENR, 2016) as shown in Table 1. All establishments are given a 5-year grace period to install or upgrade their wastewater treatment facilities to comply with the revised standards.

| Parameters | DAO 1990-35 OEI | DAO 2016-08 |
|------------|-----------------|-------------|
| BOD (mg/L) | 80              | 50          |
| COD (mg/L) | 50              | 100         |
| NH₃-N (mg/L) | -              | 0.5         |
| NO₃-N (mg/L) | -              | 14          |
| PO₄³⁻ (mg/L) | -              | 1           |
| TSS (mg/L) | 90              | 70          |

Biological nutrient removal (BNR) systems are widely accepted in other countries. Examples of BNR systems are anoxic-oxic (AO), anaerobic-anoxic-oxic (A³O), University Cape Town (UCT), and 5-stage Bardenpho (5-BP) (Tchobanoglous et al., 2003; von Sperling, 2007; Xiang et al., 2014). The utilization of these systems has been studied extensively in several countries, especially in developing countries, for different wastewater characteristics, operating parameters, and system configuration. Fan et al. (2009) evaluated the performance of a modified
anaerobic/anoxic/oxic (A²O) process for low strength wastewater treatment. 90% of the wastewater was fed to the anaerobic tank while the remaining 10% was fed to the pre-anoxic tank installed prior to the anaerobic tank. Return sludge was recycled back to the pre-anoxic tank instead of the anaerobic tank. At low strength wastewater, low total nitrogen removal was attained due to low nitrate recirculation rate and higher total phosphorus removal was attained when influent total phosphorus is above 1 mg/L. Results of the study is to evaluate the performance of a designed pilot-scale BNR system in the removal of phosphates (PO₄³⁻), ammonia as nitrogen (NH₃-N), and nitrates as nitrogen (NO₃⁻N) for sewage treatment in the Philippines.

2 Methodology

2.1 Design parameters for A²O design

A pilot-scale anaerobic-anoxic-oxic (A²O) process was designed for an influent flowrate of 1 m³/day. The influent and effluent wastewater characteristics used for the design was based on the medium-strength wastewater characteristics from Tchobanoglous et al., (2003) and Class C DAO 2016-08 Standards, respectively.

Several parameters are considered in designing a BNR process. For the tank design, parameters such as sludge age, sludge yield, endogeneous coefficient, mixed liquor suspended solids (MLSS) concentration, mixed liquor volatile suspended solids (MLVSS) concentration, hydraulic retention times, and size fraction of the anoxic and oxic tanks are determined. Sludge age should be between 5 – 10 days, and the MLSS and MLVSS concentration should be between 2000 – 4000 mg/L.

The total oxygen requirement is computed by determining the oxygen demand during nitrification and denitrification. Parameters values of specific growth rate (μmax), saturation coefficients, temperature and yield coefficients, denitrification rate, oxygen production, and fraction of ammonia in the sludge used in the design are based from von Sperling (2007).

Oxygen in the oxic compartment can be supplied either by mechanical aeration or by diffused air. Energy requirement is typically calculated in order to determine the more suitable and cost-effective. However, in the study, aeration by diffused air was utilized (Chen et al., 2011; Falahiti-Marvast and Karimi-Jashni, 2015).

Lastly, the hydraulic retention time, diameter/sidewater depth, and bottom cone slope should be considered in the design of a final clarifier (or secondary sedimentation tank) (von Sperling, 2007).

The summary of the parameter values is provided in Table 1.
2.2 Influent wastewater characteristics and seed sludge

The fabricated system was installed in an existing sewage treatment plant (STP) in Metro Manila. The influent wastewater of the system came from the effluent of the fine screening process. The inoculated activated sludge (MLSS = 2000 mg/L) was collected from the aeration tank of the STP.

2.3 Analytical measurements

Meter devices will be utilized to measure in-situ parameters such as pH (Hanna Instruments, HI 98129), dissolved oxygen (DO) and temperature (Horiba Instruments DO120-K, Japan). Hach TNTplus vials will be used for parameters such as COD, ammonia as nitrogen, nitrate as nitrogen, and phosphates (HACH, Germany) and its concentrations will be measured using HACH DR 1900 Portable Spectrophotometer. HACH DRB 200 Digital Reactor Block will be used for digestion of samples for COD and phosphate analysis.

3 Methodology

3.1 A2O design

The parameter values in Table 2 were used to compute for tank dimensions. However, the dimensions and hydraulic retention times changed after fabrication. After fabrication, the pilot-scale BNR system, with a total volume of 348.6 L at tap water level, was divided into three compartments: anaerobic (62.6 L), anoxic (79.2 L), and oxic (206.8 L). The hydraulic retention times are 1.50 hours, 1.90 hours, and 4.97 hours, respectively. All HRT values, except for HRT\textsubscript{anoxic}, are within the range as shown in Table 2. The calculated height of the tank is 40 cm, including the freeboard of 10 cm to prevent wastewater from overflowing. The width is 58 cm, and each compartment has a length of 30 cm, 39 cm, and 115 cm.

Vertical flow mixers are installed in the anaerobic and anoxic compartments. The calculated power requirement for the mixer in the anaerobic and anoxic compartments are 95 W and 125 W. However, supplied mixers have a power of 400 W and speed of 180 rpm. Since these mixers are too fast, intermittent mixing is carried out twice a week for 5 – 15 minutes.

Aeration by diffused air was chosen for oxygen supply in the oxic compartment. Air was supplied by compressor passes through the perforated stainless-steel rods installed at the bottom surface.

The total calculated volume of the final clarifier is 87.5 L. It has an outer diameter of 83 cm and a height of 25.02 cm. A freeboard of 10 cm was added to prevent overflowing from the outer perimeter. Its hydraulic residence time was calculated to be 2.10 hours. Peristaltic pumps were supplied to deliver influent wastewater and sludge to the anaerobic compartment, and to recycle wastewater from the oxic to anoxic compartment. Figure 1 above illustrates the schematic diagram of an A2O process.

3.2 System modification

Weekly inspection of the system was conducted to ensure continuous operation. During the operation (Days 0 – 45), several adjustments were done such as relocation of influent wastewater source, replacement of the mesh attached at the hose that draws influent wastewater to the system, and removal of floating sludge. After steady-state conditions, internal recycling pump was operated at a flowrate of 1.12 m\textsuperscript{3}/day (780 mL/min).
Table 2. Parameter Values Used in the Design of the A²O System (Tchobanoglous *et al.*, 2003; von Sperling, 2007; Michigan Department of Environmental Quality Operator Training and Certification Unit, n.d.)

| Parameter                          | Unit | Range        | Value  |
|------------------------------------|------|--------------|--------|
| **Tank Design**                    |      |              |        |
| Sludge Age                         | d    | 5 – 10       | 14     |
| Sludge Yield                       | g VSS/g BOD₅ | 0.40 – 0.80  | 0.6    |
| Endogeneous Coefficient, K₀        | g VSS/g VSS-d | 0.06 – 0.10  | 0.137  |
| Temperature Coefficient for K₀     | -    | 1.05 – 1.09  | 1.07   |
| MLSS                              | mg/L | 2000 - 4000  | 3750   |
| MLVSS                             | mg/L | 2000 - 4000  | 3000   |
| Fraction of Anoxic Tank           | -    | 0.25         | 0.25   |
| Fraction of Oxic Tank             | -    | 0.75         | 0.75   |
| **Hydraulic Retention Time (HRT)**|      |              |        |
| Anaerobic                         | hr   | 0.50 – 1.50  | 1.20   |
| Anoxic                            | hr   | 0.50 – 1.00  | 1.58   |
| Oxic                              | hr   | 3.50 – 6.00  | 4.73   |
| **Oxygen Requirements**            |      |              |        |
| Nitrification                     |      |              |        |
| μ<sub>max</sub> at 20°C            | d⁻¹  | 0.30 – 0.70  | 0.50   |
| Temperature Coefficient           | -    |              | 1.10   |
| Ammonia Half-Saturation Coefficient, Kₐ | g NH₄+/m³ | 0.50 – 1.00 | 0.70 |
| Oxygen Half-Saturation Coefficient (K₀) | g O₂/m³ | 0.40 – 1.00 | 0.80 |
| Yield Coefficient for Nitrifiers (Yₐ) | g cells/g NH₄⁺ oxidized | 0.05 – 0.10 | 0.08 |
| Oxygen Demand                     | g O₂/g NH₄⁺ oxidized | 4.57 |
| **Denitrification**               |      |              |        |
| Denitrification Rate              | kg NO₃⁻/kg VSS-d | 0.03 – 0.11 | 0.08 |
| Temperature Coefficient           | -    | 1.08 – 1.09  | 1.09   |
| Fraction of Ammonia in the Sludge | kg NH₄⁺/kg VSS | 0.12 |
| O₂ Savings                        | g O₂/g NO₃⁻ reduced | 2.86 |
| **Parameters**                    |      |              |        |
| α                                 | -    | 0.85         |        |
| β                                 | -    | 0.90         |        |
| θ                                 | -    | 1.024        |        |
| Specific Gravity of Air           | kg/m³ |              | 1.20   |
| Fraction of O₂ in Air             | g O₂/g air | 0.23 |
| **Aeration by Diffused Air**      |      |              |        |
| O₂ Transfer Efficiency            | -    | 0.15         |        |
| Motor and Blower Efficiency       | -    | 0.60         |        |
| **Final Clarifier**               |      |              |        |
| Hydraulic Retention Time          | hr   | 2.00 – 3.00  | 2.10   |
3.3 Dissolved Oxygen (DO) and Temperature measurement

After flow stabilization and system adjustment, dissolved oxygen (DO) and temperature measurement started by day 45. Figure 2 illustrates the decrease in temperature per compartment through time. This is attributed to the change in the weather in the Philippines as the rainy season usually starts by June.

It is critical to measure the dissolved oxygen (DO) concentration per compartment for effective nitrogen and phosphorus removal. von Sperling (2007) states that effective denitrification process occurs when DO is 0.20 mg/L and nitrification process occurs when DO is from 0.50 – 4 mg/L. Studies such as Falahi-Marvast and Karimi-Jashni (2015) and Majdi Nasab et al. (2016) maintained the DO concentration less than 0.50 mg/L for anaerobic and anoxic compartments of their BNRT systems.

![Image of Temperature (°C) versus time (days) of anaerobic, anoxic, and oxic compartments from day 46 onwards. The system is operated at Q_influent = 1 m³/day and Q_R = 780 mL/min.](image)

Figure 2. Temperature (°C) versus time (days) of anaerobic, anoxic, and oxic compartments from day 46 onwards. The system is operated at Q_influent = 1 m³/day and Q_R = 780 mL/min.

The typical DO value in the oxic compartment is 2 mg/L, but some studies use DO concentrations of 3 – 4 mg/L (von Sperling, 2007; Falahi-Marvast and Karimi-Jashni, 2015; Majdi Nasab et al., 2016). Figure 3 illustrates DO concentration per compartment through time. Based from the data, the DO in the anaerobic and oxic chambers are within the recommended range. The DO concentration at the anaerobic compartment was maintained below 0.40 mg/L, except in day 76 where the mixer was operated continuously for two days. The DO in the anoxic compartment, however, was not maintained within the recommended range. The lowest concentration recorded was 0.53 mg/L and the highest was 2.74 mg/L. The DO of the wastewater recycled from the oxic compartment increases the DO in the anoxic compartment.

![Image of Dissolved oxygen concentration versus time (days) of anaerobic, anoxic, and oxic compartments from day 46 onwards. The system is operated at Q_influent = 1 m³/day and Q_R = 780 mL/min.](image)

Figure 3. Dissolved oxygen concentration versus time (days) of anaerobic, anoxic, and oxic compartments from day 46 onwards. The system is operated at Q_influent = 1 m³/day and Q_R = 780 mL/min.

implied poor denitrification process in the anoxic compartment. Hence, modification should be done to adjust the DO to below 0.50 mg/L. NH₃-N and PO₄³⁻ concentrations did not reach the required standards but decreased by a maximum of 59.5% and 69.4%, respectively. The removal efficiencies for NH₃-N and PO₄³⁻ are low compared to other studies (Fan et al., 2009; Tran and Tran, 2011; Xiang et al., 2014). Fan et al. (2009), Tran and Tran (2011) and Xiang et al. (2014) achieved > 95% removal of NH₃-N for low strength wastewater. The low NH₃-N removal efficiency may imply that there are insufficient nitrifiers in the system. On the other hand, the low phosphorus removal can be an indication that there is not enough carbon source for the PAOs. According to Xiang et al. (2014), the addition of an external carbon source can increase the phosphorus removal. However, some authors such as Fan et al. (2009) and Yuan et al. (2012), who did not add any external carbon source, mentioned that high phosphorus removal depends on the influent COD/P ratio.

The performance of the system will be further investigated upon the installation and operation of the pump for return activated sludge.

3.4 Evaluation of nutrient removal

The performance of the system was evaluated for 150 days BOD, COD, and TSS reached the required effluent standards and were reduced by a maximum of 94.3%, 73.9%, and 99.3%, respectively. The effluent NO₃-N concentration increased from its initial average concentration of 0.62 mg/L. Although the effluent concentration below the limit, the increase of NO₃-N concentration in the anoxic zone.

4 Conclusion

The pilot-scale A²O system was designed based on several parameter values in the book of von Sperling (2007) and was installed at an existing sewage treatment plant to investigate its performance. Several modifications were required to ensure continuous system operation. The DO concentration in each compartment was measured and it was found out that DO concentration in the anoxic chamber did not fall within the required range. Adjustments can be done by lowering the recycling flowrate or decrease the aeration can be done. The removal efficiencies for BOD, COD, TSS, NH₃-N, and PO₄³⁻ were 94.3%, 73.9%, 99.3%, 59.5% and 69.4%, respectively. The effluent NO₃-N concentration increased, implying the need to promote denitrification in the anoxic zone. Effluent NH₃-N and
PO₄⁻ decreased, however, it did not meet the current effluent standards. The low nutrient removal efficiency can be attributed to insufficient microorganisms and/or insufficient food source for the microorganisms. Phosphate removal of the system will be further investigated upon the operation of the return activated sludge (RAS) pump. Mixers should be replaced with lower speed to ensure homogeneous mixing of the solids in the anaerobic and anoxic zone. Finally, chemical precipitation for phosphorus removal may be conducted in future studies to compare the performance of chemical and biological phosphorus removal.

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