Analysis of Nutrient Removal using Membrane Thickening Aerobic Digestion

Bryen Woo, PE
Aeration/Aerobic Digestion Product Manager
OVIVO USA, LLC
2404 Rutland Drive
Austin, Texas 78758
Ph: 512-652-5818
E-Mail: bryen.woo@ovivowater.com

ABSTRACT

There are several long term water quality issues associated with discharging nutrients, specifically nitrogen and phosphorus into receiving water streams that are very difficult to manage. Due to these concerns many environmental regulatory agencies have either established nutrient discharge criteria or in the process of developing nutrient management plans. If a wastewater treatment plant is required to meet nutrient discharge limits the design of a sludge digestion system can be very critical especially for facilities that rely on biological nutrient removal (BNR) processes.

This paper describes the membrane thickening aerobic digestion process technology that features advanced process control, techniques, and optimization that nearly eliminate nitrogen and phosphorus release in wastewater recycled to the head of the plant thereby protecting the effluent quality of a BNR activated sludge process. A membrane thickening aerobic digestion process offers this distinct advantage in contrast to other common biosolids handling processes without the need for chemical addition.

There are up to sixteen operating membrane thickening aerobic digestion processes in the United States with several more in construction. Extensive nutrient data has been collected and evaluated from two existing operating facilities described in this paper then compared against the typical performance of other common biosolids handling processes such as anaerobic digestion, ATAD, aerobic digestion utilizing gravity thickening and decanting. After analyzing and comparing the results of these technologies it can be concluded that membrane thickening aerobic digestion offers the best nutrient management and removal performance in the liquid phase of a biosolids handling process.

KEYWORDS

Membrane, Thickening, Aerobic Digestion, Nutrients, Biological Phosphorus Removal, Nitrogen, Solids Handling, Sludge

INTRODUCTION

Discharge of wastewater containing excessive amounts of nutrients, specifically nitrogen and phosphorus, into lakes, reservoirs, rivers, and streams can result in a surplus of plant growth. This growth causes a depletion of dissolved oxygen in the water, sufficiently harming fishery resources. Excessive algal growth can also create distasteful drinking water. Nutrients can accumulate over time in sediments of lakes and reservoirs and ultimately recycle back, posing a long term water quality problem that is difficult to manage. It has been established that, for controlling excessive algae growth in water bodies, the phosphorus concentration has to be kept lower than 0.03 mg/L (Gachter and Imboden, 1985). Due to these concerns, many regulatory agencies are in the process of or have already adopted nutrient management plans. Some states such as Arkansas, Florida, Illinois, Minnesota, Montana, Michigan, Wisconsin, and Oklahoma have established numeric nutrient discharge limits.

If a wastewater plant is obligated to meet stringent nutrient requirements, it is critical to take a close look at the solids handling process during design. High nutrient concentrations in plant recycles from a solids handling process are widely recognized as a leading cause for high N and P in plant effluents of biological nutrient removal (BNR) facilities. Release of these nutrients in supernatant with subsequent recycling to a plant's head works would defeat the purpose of a BNR activated sludge process.

EVALUATION OF NITROGEN AND PHOSPORUS RELEASE OF VARIOUS COMMON SOLIDS HANDLING PROCESSES

Commonly utilized solids handling technologies following BNR activated sludge processes can release a substantial amount of nitrogen and/or phosphorus into recycle streams. Some of these common solids handling technologies are anaerobic digestion, autothermal thermophilic aerobic digester (ATAD), gravity thickening aerobic digestion, and aerobic digestion with decanting. For example, 60% to 80% of phosphorus removed in the BNR process may be released during anaerobic sludge digestion (Murakami et al., 1987). Furthermore, Table 1 shows characteristics of high-rate two-stage anaerobic digester supernatant listed in the EPA Sludge Treatment and Disposal Process Design Manual.

Table 1: Anaerobic Digester Supernatant Characteristics (EPA Sludge Treatment and Disposal Design Manual, 1979)

Parameter*	**Range of Plant Averages (mg/L)**
Suspended Solids	143 – 2,205
Total Kjeldahl Nitrogen	306 – 1,144
NH_3-N	253 – 853
Total PO_4-P	63 – 143

*pH range 7.0 – 7.8

Boulanger studied nitrogen and phosphorus levels in supernatant produced from an ATAD process and discovered supernatant from an ATAD digestion process could contain ammonia concentrations between 580 mg/L to 870 mg/L, and TKN concentrations between 610 mg/L to

940 mg/L, depending on air flow range and supernatant solids content, which is close to that of anaerobic digesters. Total Phosphorus in ATAD supernatant could range from 300 mg/L to 390 mg/L. These ranges are higher than concentrations reported for anaerobic and aerobic digesters treating conventional waste secondary sludge (Boulanger, 1994).

Although aerobic digestion processes exhibit much lower nitrogen and phosphorus levels in its supernatant in comparison to ATAD and anaerobic digestion processes, there can still be a substantial release of these constituents that can compromise the performance of a BNR activated sludge process when recycled to the head of the plant. Characteristics of supernatant from several full scale aerobic digesters treating mixed primary and secondary sludge containing 2% to 3% total solids are summarized in Table 2 below from a study by Ahlberg and Boyko (1972).

Table 2: Aerobic Digester Supernatant Characteristics (Ahlberg and Boyko, 1972)

Parameter*	**Range of Plant Averages (mg/L)**
Suspended Solids	46 – 11,500
Total Kjeldahl Nitrogen	10 – 400
Total Phosphorus	19 – 241
Total Dissolved Phosphorus	2.5 - 64

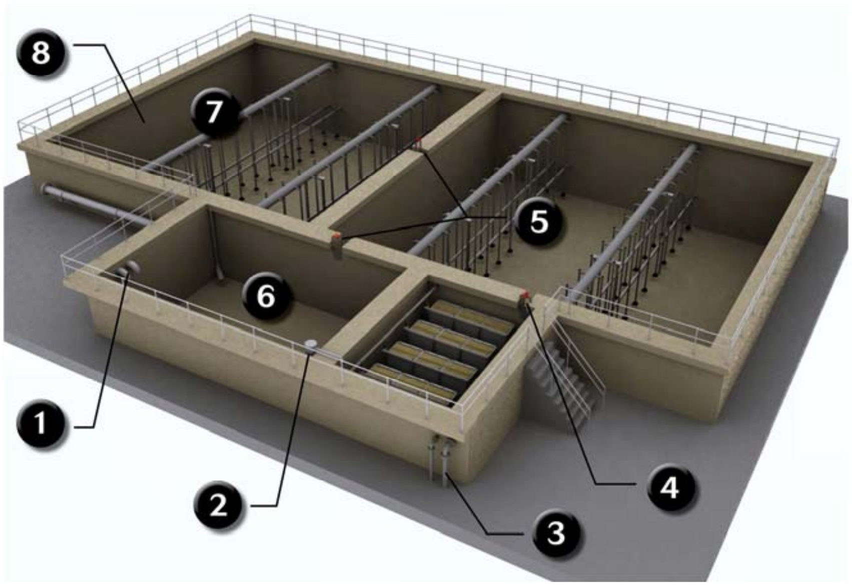
*pH range 5.9 – 7.7

For biosolids handling systems with high phosphorus in their supernatant, ferric chloride, alum, and ferrous sulphate are chemicals commonly added to remove phosphorus by precipitation. These chemicals can be expensive and cause an increase of sludge volume by 40% (Lenntech, 2009).

ANALYSIS OF NUTRIENT REMOVAL AND CONTROL USING MEMBRANE THICKENING AEROBIC DIGESTION

In contrast to the other solids handling processes mentioned above, an advanced aerobic digestion process featuring membrane thickening produces a reuse quality permeate that contains very minimal amounts of total nitrogen and phosphorus. The permeate is biologically treated wastewater that is filtered through the membrane units. The low nutrients in the effluent can then be sent directly to disinfection or back to the head of the plant, safeguarding a BNR activated sludge process from excess nutrients. It is important to note that since nutrient levels in the permeate are extremely low, the addition of chemicals for phosphorus precipitation is not required. The standard membrane aerobic digestion process consists of an anoxic tank, membrane thickening tank (MBT), in-loop digester, and isolation digester. The process is shown in Figure 1 and is described in more detail below.

Figure 1: General Aerobic Digestion Process with Membrane Thickening



The following are the steps of the membrane thickening aerobic digestion process shown above:

1. Waste Activated Sludge (WAS) is wasted from the activated sludge process and enters the Anoxic Tank at a rate of 1Q.

2. As the liquid level in the Anoxic Tank rises, sludge is pumped into the MBT tank at a recycle rate of 4Q, ensuring the solids remain at the optimum thickness.

3. As WAS is pumped into the MBT from the Anoxic Tank, permeate is extracted through the membranes and either goes to the head of the plant or to disinfection.

4. When the maximum liquid level in the MBT is reached, the addition of sludge to this tank causes a corresponding overflow into the In-Loop Digester for first stage digestion.

5. When the maximum liquid level in the In-Loop Digester is reached, the addition of sludge to this tank will cause a corresponding overflow of sludge to either the Isolation-Digester or to the Anoxic Tank, completing a continuous process loop.

6. Nitrified sludge transferred from the In-Loop Digester to the Anoxic Tank is mixed with the incoming WAS, which serves as a fresh carbon source allowing for denitrification and anaerobic conditioning of the polyphosphorus accumulating organisms (PAOs) without having to cycle the air on and off in the digester tanks.

7. The small portion of sludge that is transferred from the In-Loop Digester to the Isolation Digester is aerated and mixed for second stage digestion for further pathogen removal.

8. Sludge is transferred out of the Isolation Digester tank for final disposal.

As described above an aerobic digestion process with membrane thickening utilizes a nitrification and denitrification process to remove nitrogen in both the solid and liquid phase. In order to facilitate the explanation of the process, nitrification and denitrification chemistry equations are presented in Table 3 below.

Table 3. Aerobic Digestion Chemistry Equations (Operation of Municipal Wastewater Treatment Plants, Manual of Practice No. 11, Volume III Solids Processes, Sixth Edition)

Process	Equation
Biomass Destruction in Aerobic Digestion	$C_5H_7NO_2 + 5O_2 = 4CO_2 + H_2O + NH_4HCO_3$
Nitrification	$NH_4 + 2O_2 = H_2O + 2H^+ + NO_3$
Biomass Destruction with Nitrification	$C_5H_7NO_2 + 7O_2 = 5CO_2 + 3H_2O + H^+ + NO_3$
Denitrification	$C_5H_7NO_2 + 4NO_3 + H_2O = + NH_{4\,+}\, 5HCO_3 + 2N_2$
Complete Nitrification-Denitrification	$C_5H_7NO_2 + 5.75O_2 = 5CO_2 + 3.5H_2O + 0.5N_2$

In the initial phases of aerobic digestion the oxidation of biomass produces carbon dioxide, water, and ammonium bicarbonate, a form of alkalinity. If additional oxygen is provided beyond what is required for biomass destruction the nitrification process will occur. In the nitrification process ammonia is converted into nitrate while two moles of acidity (H^+) are produced and a loss of two moles of alkalinity. If oxygen is continues to be provided after the nitrification process has occurred acid production will continue which can kill the biomass and destroy alkalinity to neutralize the acid. In order to prevent excessive acid accumulation the denitrification process must occur. Denitrification in an aerobic digestion process can be achieved by cycling the air off resulting in the absence of oxygen thus oxidizing the biomass with nitrates as an electron acceptor. When denitrification is accomplished in an aerobic digestion process nitrate is converted into nitrogen gas and in a complete nitrification – denitrification process carbon dioxide, alkalinity, and water are produced. As described above, the continuous looping cycle of the membrane thickening aerobic digestion system provides continuous nitrification and denitrification sequencing, which virtually eliminates nitrate and ammonia in the permeate and solids.

Phosphorus removal presents a much more challenging, complex, and sophisticated concept in the aerobic digestion with membrane thickening process than nitrogen removal. In order to understand these concepts it is important to note that phosphorus is comprised of the following three forms: inorganic phosphorus, polyphosphorus, and organic phosphorus. An aerobic digestion process with membrane thickening is capable of minimizing the release of these three forms of phosphorus.

The continuous nitrification and denitrification looping cycle also provides excellent pH control, preventing the dissolution of inorganic phosphorus. Dissolution of inorganic phosphorus precipitates is controlled by physical and chemical conditions, with pH being the most important. Lowering the pH between 4 and 6 clearly promotes the release of inorganic phosphorus (Ju, 2005).

Polyphosphorus accumulating organisms (PAOs) are able to store carbon compounds as a source of energy in the absence of oxygen or nitrate, which are common energy sources in biological processes. The storage of carbon compounds by the PAOs results in a polyphosphorus release. The incoming WAS into the Anoxic Tank provides a fresh carbon source for the PAOs to release polyphosphate following the exhaustion of nitrate, which also occurs in this tank. The aerated MBT tank, where permeate is collected, allows for the PAOs to grow and uptake the released polyphosphorus while burning their stored carbon reserves. The growth rate of biomass under anoxic conditions is about 40% lower as compared to the growth rate of biomass under aerobic conditions (Van Haandel & Van der Lubbe, 2007), so PAOs are capable of facilitating the removal of large amounts of phosphorus in the liquid phase because growth rate is significantly increased under aerobic conditions. This uptake of the polyphosphate by PAO bacteria under aerobic conditions in the MBT results in the polyphosphorus to remain in the solids, resulting in substantially reduced phosphorus levels in permeate from an aerobic digestion process with membrane thickening. Sludge shows clear cycles of significant phosphorus release under no aeration and subsequent phosphorus uptake when aeration is turned back on, consistent with the commonly accepted metabolism of PAO microorganisms (Ju, 2005).

Due to substantial biomass destruction in a membrane thickening aerobic digestion process, PAO decay will occur making organic phosphorus release unavoidable. When the PAO decay the organic phosphorus is released into the liquid phase. Table 4 below summarizes the values of some key characteristics of PAO as compared to those of conventional micro-organisms in activated sludge systems.

Table 4: Parameters of PAO compared to regular heterotrophic organisms at 20°C, (Van Haandel and Van der Lubbe, 2007)

Parameter	PAO	Non-PAO	U of M
Polyphosphorus Content	0.38	0.025	mg P .mg^{-1} VSS
Decay Constant	0.04	0.24	d^{-1}
Endogenous Residue	0.25	0.20	(-)
P-fraction end..residue	0.025	0.025	mg P .mg^{-1} X_e
Ratio VSS/TSS	0.46	0.80	mg VSS .mg^{-1} TSS
Denitrifying fraction	0.6 – 1.0	1.0	(-)
Denitrification rate	0.10/0.08	0.10/0.08	mg N .mg^{-1} X_a.d^{-1}
Anaer. Phosphate release	0.5	---	mg P .mg^{-1} COD

Analyzing T able 4, it illustrates that the decay rate of a PAO is approximately six times slower than non-PAO bacteria, and there are approximately twice as many non-PAO bacteria than PAO in a typical biomass. Although non-PAO bacteria are more common in a biomass and have a faster decay rate they contain approximately fifteen times less polyphosphorus than PAO bacteria. These observations show that the PAO in biomass does not decay at a fast enough rate and there is not a sufficient amount of polyphosphorus content in non-PAO bacteria for a significant amount of organic phosphorus release to occur in the liquid phase. It can be concluded that organic phosphorus release in permeate produced from an aerobic digestion process with membrane thickening will be very minimal even though it is unavoidable due to PAO decay from substantial volatile solids destruction in this process.

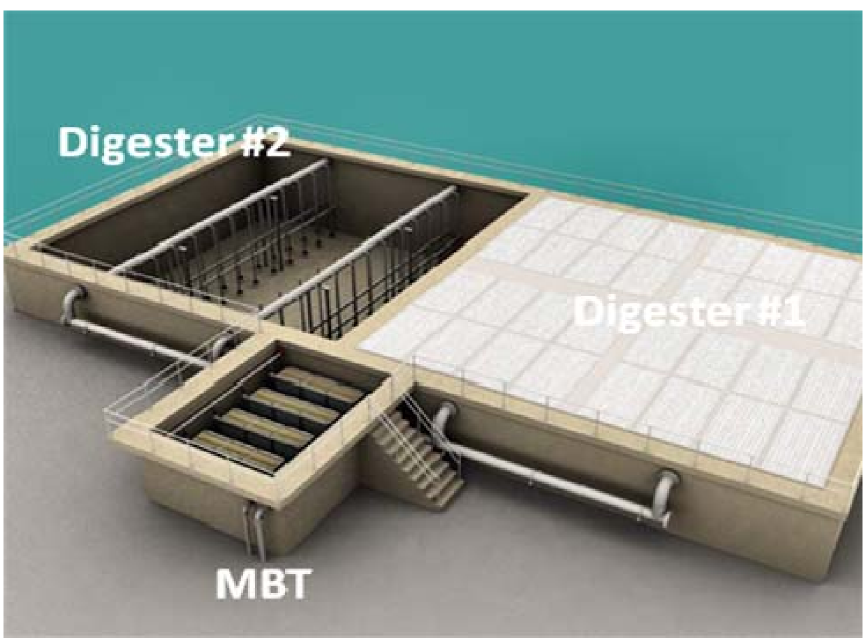
NUTRIENT REMOVAL RESULTS FROM OPERATING MEMBRANE THICKENING AEROBIC DIGESTION PROCESSES

Extensive nutrient data was collected from permeate of two operating membrane thickening aerobic digestion systems. The facilities that have been evaluated are Dundee WWTP and Union Rome WWTP. A brief background and results from the operations are described below.

Membrane Thickening Aerobic Digestion Case Study: Dundee Wastewater Treatment Plant, Dundee, Michigan

Dundee Wastewater Treatment Plant (WWTP) in Dundee, Michigan currently operates a Membrane Bioreactor (MBR) activated sludge system followed by a membrane thickening aerobic digestion process. The membrane thickening aerobic digestion process at Dundee WWTP currently consists of a membrane thickening tank, an in-loop digester (Digester 1), and an isolation digester (Digester 2). A layout of this process is shown in Figure 2 below.

Figure 2. Dundee WWTP Membrane Aerobic Digestion Facility



Permeate Quality Results

Aerobic/Anoxic conditions critical to biological nutrient removal is achieved at this facility by cycling the air on and off in Digester 1. Permeate produced from the membrane thickening aerobic digestion process is sent to the head of the plant. As shown in Figure 3, the permeate produced by the membrane thickener has excellent nutrient quality and will not compromise the performance of the upstream MBR activated sludge process. Table 5 demonstrates that this type of permeate quality has been sustainable throughout the entire course of the operation of the Dundee membrane thickening aerobic digestion process.

Table 5. Dundee WWTP Membrane Thickener Permeate Results (September 2005 to June 2008)

Parameter	Results (mg/L)
BOD	1.12
TSS	2.00
Total Phosphorus	1.09
NH_3-N	0.22
NO_3-N	0.03

Membrane Thickening Aerobic Digestion Case Study: Union Rome Wastewater Treatment Plant, Union Rome, Ohio

Union Rome Wastewater Treatment Plant (WWTP) in Union Rome, Ohio currently operates a Membrane Bioreactor (MBR) activated sludge system followed by a membrane thickening aerobic digestion process which was commissioned on December 2009. The Union Rome WWTP membrane thickening aerobic digestion process consists of a membrane thickening tank operating in-loop with an anoxic and a aerobic digester tank. A layout of the Union Rome membrane thickening aerobic digestion process is shown in Figure 3 below.

Figure 3. Union Rome WWTP Membrane Thickening Aerobic Digestion Process Layout

(Membrane Thickening Tank shown on the left, Aerobic Digester shown on the right)

The aerobic zones (the membrane thickener and digester) provide nitrification with the anoxic basin provides built-in time for denitrification and stabilizes the pH. This continuous nitrification and denitrification sequencing eliminates nitrate and ammonia in the permeate which is critical in allowing the facility to comply with their ammonia effluent discharge limit of 1.0 mg/L and 0.3 mg/L for summer and winter operations respectively. Table 6 below shows the permeate results from the Union Rome membrane thickening aerobic digestion process.

Table 6. Union Rome WWTP Permeate Results (October 2010 to November 2011)

Parameter	**Result (mg/L)**
BOD	< 1.0
TSS	< 1.0
Total Phosphorus	< 5.0*
NH3-N	< 0.1

*No biological phosphorus removal in MBR process upstream

CONCLUSIONS

Nutrients specifically nitrogen and phosphorus if discharged to receiving waters can cause a long term water quality issues such as excessive algal growth causing depletion of dissolved oxygen of water, distasteful drinking water, and sufficient harm to fishery resources and aquatic life that are difficult to manage. Due to these water quality concerns environmental agencies have established discharge limit criteria or establishing nutrient management plants.

Release of these nutrients is often overlooked in the design of sludge digestion systems. This issue is especially important for facilities relying on BNR activated sludge processes because if nitrogen and phosphorus are released during digestion and returned to the head of the plant this significantly compromises the effectiveness and performance of a BNR activated sludge system. An aerobic digestion process with membrane thickening produces a high quality permeate with very low amounts of nitrogen and phosphorus that can be sent to the head of the plant to protect the effluent quality of a BNR activated sludge system without requiring chemical addition. When compared with other common sludge digestion technologies an aerobic digestion process featuring membrane thickening offers outstanding nutrient removal and management capabilities.

REFERENCES

Alhberg, N. and Boyko, B. (1972) Evaluation and Design of Aerobic Digesters, Journal of Water Pollution Control Federation 44., 634-643.

Boulanger, M. L. (1994) The Effect of Varying Air Supply Upon Supernatant Quality in Autoheated Thermophilic Aerobic Digesters Treating Waste Sludge from a Biological Phosphorus Removal Process, The University of British Columbia Department of Civil Engineering Thesis., 153.

EPA. (1979) Process Design Manual, Sludge Treatment and Disposal, Cincinnati, Ohio EPA.

Gachler, R.; Imboden, D.M. (1985) Lake Restoration. In Chemical Processes in Lakes. John Wiley and Sons: New York, 365-388.

Ju, L. – K; Shah, H.K., Porteous, J (2005) Phosphorus Release in Aerobic Sludge Digestion, Red Orbit News, Water Environment Federation.

Lenntech (2009) Phosphorus Removal in Wastewater, Lenntech Water Treatment & Purification Holding B.V.

Murakami, T.; Koike, N.; Taniguchi, N.; Esumi, H. (1987) Influence of Return Flow Phosphorus Load on Performance of the Biological Phosphorus Removal Process. Adv. Water Pollut. Control, 237-245; IAWPRC Conference Series, Pergamon Press: London.

Van Haandel, A. and Van der Lubbe, J. (2007) Wastewater Treatment Design and Optimization of Activated Sludge Systems, Model of Biological Phosphorus Removal 5.1.3., 197-198.

Water Environment Federation (2008) Operation of Municipal Wastewater Treatment Plants, Manual of Practice No. 11, Volume III: Solids Processes, Sixth Edition, Chapter 31 Aerobic Digestion, 31-23