Unique Approach to Inline Fermentation Stabilizes Biological Phosphorus Removal

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Summary (max 500 characters)

Many facilities do not have sufficient volatile fatty acids (VFA) available in the influent wastewater to facilitate consistent biological phosphorus removal. The lack of influent VFA content has driven facilities to modify plant operations. This paper reviews two water resource recovery facilities that upgraded their anaerobic selectors to include inline fermentation with an intermittent mixing strategy to produce VFA for improved biological phosphorus removal.

ABSTRACT (max 150 words)

Many facilities do not have consistent or sufficient volatile fatty acids (VFA) available in the influent wastewater to facilitate efficient and effective biological phosphorus removal. The lack of influent VFA content has driven facilities to modify plant operations, taking advantage of influent carbon to generate their own VFA to ensure consistent biological phosphorus removal to maintain low effluent phosphorus concentrations. An intermittent mixing strategy with gentle pulses of compressed gas allows for VFA generation and transport to facilitate more stable effluent phosphorus. This paper reviews two water resource recovery facilities that recently upgraded their traditional anaerobic selectors to include inline fermentation with an intermittent mixing strategy to produce VFA for improved biological phosphorus removal. One plant increased phosphorus removal efficiency from 85% to 95%, while the other plant saw consistently lower effluent total phosphorus below 0.2 mg/L.

KEYWORDS

Phosphorus, biological phosphorus removal, fermentation, volatile fatty acids, embedded carbon, nutrient removal, compressed gas mixing,

INTRODUCTION | BACKGROUND

Many water resource recovery facilities (WRRFs) are being pushed to meet more and more stringent effluent phosphorus requirements, with pressure to reduce operating budgets and chemical consumption for a more sustainable treatment process. Phosphorus removal has evolved over the years from chemical phosphorus removal to biological phosphorus removal. In more recent iterations, enhanced biological phosphorus removal (EBPR) systems are liberating embedded carbon by fermenting in anaerobic selectors to create robust populations of phosphate accumulating organisms (PAOs).

As shown in **Figure 1**, EBPR is the process by which naturally occurring organisms in the wastewater accumulate phosphorus as they travel through the treatment plant. In activated sludge processes with alternating anaerobic and aerobic environments, PAOs can thrive under the right conditions. In the anaerobic phase, PAOs must have access to and consume carbon in the form of volatile fatty acids (VFA), releasing stored phosphorus as an energy source. PAOs store poly-b-hydroxybutyrate (PHB) under anaerobic conditions in exchange for the release of stored phosphorus and then process the stored PHB under aerobic conditions. After passing through the anaerobic selector, the activated sludge enters an aerobic zone where PAOs use the PHB consumed as an energy source for phosphorus uptake. Phosphorus uptake in the aerobic environment is significantly greater than phosphorus release in the anaerobic zone, resulting in lower effluent levels.

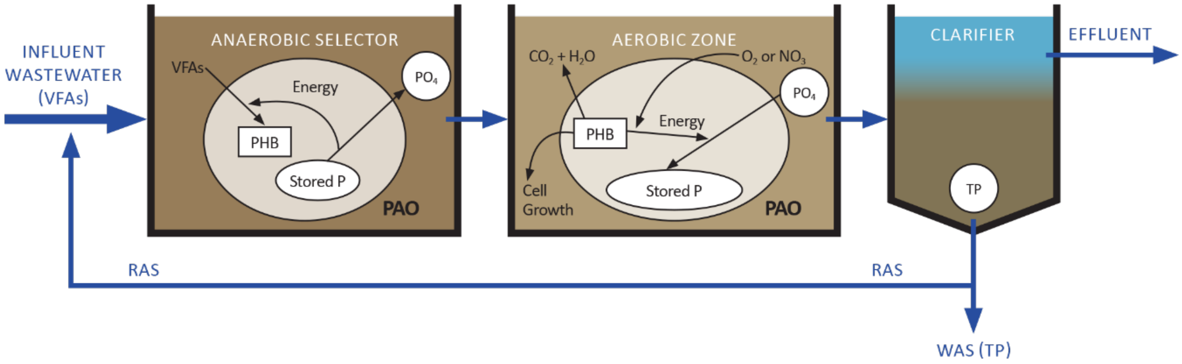


Figure 1: Biological Phosphorus Removal

Conventional activated sludge configurations targeting biological phosphorus removal include an influent anaerobic zone to select for PAOs and an abundance of VFA to facilitate the biological phosphorus removal process. Innovative thinking coupled with experimentation revealed the importance of VFA to maintain consistent EBPR maximizing biological phosphorus uptake.

Many WRRFs do not have consistent or sufficient VFA content available in the influent wastewater because of a low organic content or seasonal variability of influent characteristics. The lack of influent VFA content has driven facilities to modify plant operations, taking advantage of influent carbon to generate their own VFA to ensure consistent EBPR to maintain low effluent phosphorus concentrations.

Recent developments have focused on inline and side stream fermentation of mixed liquor suspended solids (MLSS) and return activated sludge (RAS) to boost VFA production and elevate the readily biodegradable chemical oxygen demand to phosphorus ratio (rbCOD:P). Utilizing organic content within the influent stream and MLSS is a sustainable approach to EBPR as it eliminates chemical addition while leveraging efficient carbon management practices.

This paper reviews two WRRFs that recently upgraded their traditional anaerobic selectors to include inline fermentation to produce VFA for improved EBPR.

South Granville Water and Sewer Authority (SGWASA)

The South Granville Water and Sewer Authority (SGWASA) operates a permitted 5.5 MGD (867.5 m^3/hr) flow wastewater treatment plant (WWTP), originally constructed in the 1940s, that serves Granville County, the Town of Butner, the Town of Stem and the City of Creedmoor. The wastewater collection system consists of over 150 miles (241 km) of force mains and gravity flow pipe ranging from 8 inches to 30 inches (20.3 cm to76.2 cm) in diameter. There are 48 pumping stations in the system, which lift wastewater from lower areas up to the main outfall lines to the WWTP. The SGWASA mission is to provide quality water and sanitary sewer services to the community, in an efficient, sustainable, and environmentally conscious manner. The facility consists of dual bar screening, extended aeration, biological nutrient removal, clarification, denitrification filtration, chlorination, dichlorination, two-stage digestion, sludge dewatering and disposal of sludge by land application. A process flow diagram is illustrated in **Figure 2.**

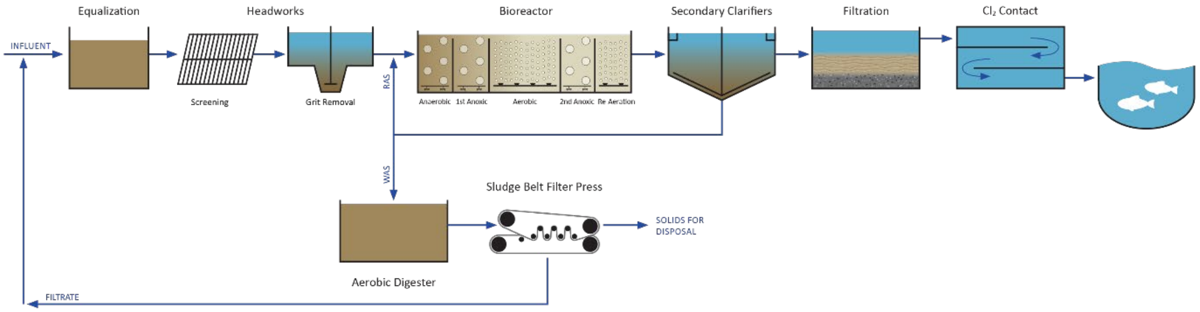


Figure 2: SGWASA Process Flow Diagram

SGWASA was upgraded in 2015 to replace infrastructure that had reached the end of its design life and enable the facility to meet more stringent nitrogen and phosphorus effluent limits by upgrading to a 5-stage Bardenpho nutrient removal process. The NPDES permit through June 2023 requires the facility to operate under the following permit limitations: biochemical oxygen demand (BOD): 5 mg/L summer and 10 mg/L winter; total suspended residue/solids (TSS): 30 mg/L; ammonia (NH4): 1 mg/L summer and 2 mg/L winter; Total Nitrogen (TN): 22,420 lbs/year (10,170 kg/year) and Total Phosphorus 2,486 lbs/year (1128 kg/year), among other parameters.

Warren, MI Water Recovery Facility (Warren)

The Warren, MI Water Recovery Facility (WRF), a 50 MGD (7886 m^3/hr) design flow treatment plant originally built in 1959, has been performing biological phosphorus removal since 2014 when the facility modified their conventional activated sludge process to an anaerobic/oxic (A/O) process, adding a biological phosphorous removal process by installing anaerobic selectors to meet a permitted effluent total phosphorus requirement of 1.0 mg/L, while reducing their dependency on chemical addition

Warren serves an area of 34 square miles (88 square kilometers) with a single lift station in the collection system consisting of 497 miles (800 km) of sewer pipe varying in size from 42 to 84 inches (106.7 to 213.4 cm). The advanced treatment facility preliminary treatment consists of mechanically cleaned coarse bar screens followed by eight raw sewage pumps which lift screened sewage 65 feet (19.8 m) to the fine screen and grit removal structure. After fine screening the raw flow enters three covered grit channels, with grit and screenings disposed of in a sanitary landfill. The last step of preliminary treatment consists of eight rectangular primary clarifiers which remove approximately 60% of the suspended solids and 40% of the BOD_5.

The secondary process consists of six parallel activated sludge trains, each with anaerobic zones followed by aerated zones. The primary effluent and RAS are split between the six parallel secondary activated sludge trains in a splitter structure prior to entering the anaerobic zones. The flow from the aeration zones is split amongst eight secondary clarifiers. Secondary effluent is fed to the tertiary treatment section of the facility with four vertical turbine pumps.

Twelve mixed media filters with a total filter bed area of 8,640 ft^2 (802.7 m^2)are utilized for polishing with backwash water returned to the secondary activated sludge trains. Disinfection is the final step of the tertiary treatment process, utilizing two ultraviolet (UV) channels consisting of four banks of UV bulbs prior to discharging final effluent to the Clinton River. A process flow diagram is illustrated in **Figure 3**.

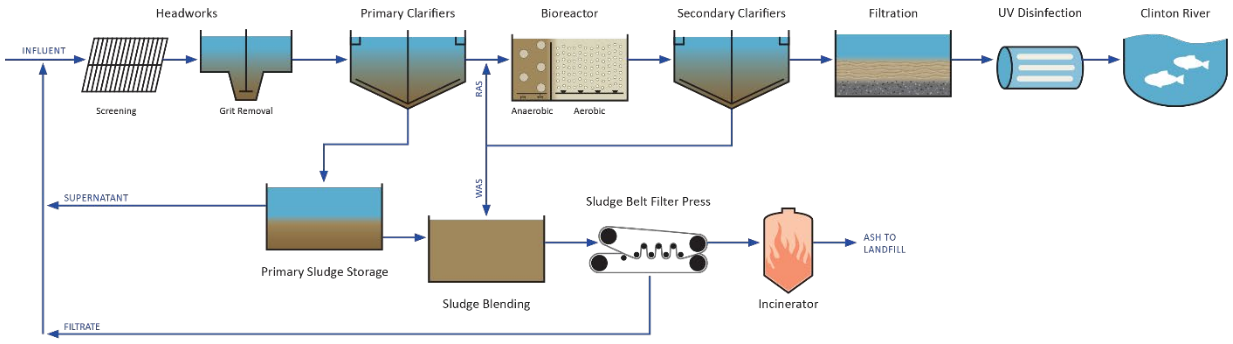


Figure 3: Warren Process Flow Diagram

Compressed Gas Mixing

During the SGWSA 2015 upgrade to a 5-stage Bardenpho nutrient removal process, $BioMix^{TM}$ Compressed Gas Mixing from EnviroMix (Charleston, SC, USA) was selected to replace the jet mixing system in the plant's anaerobic and anoxic selectors. BioMix nozzles were also integrated with fine bubble aeration in the post-anoxic zones to provide additional operation flexibility with independent aeration and mixing equipment.

During the 2014 A/O process upgrade at Warren, BioMix was selected for installation in the new anaerobic selectors targeting biological phosphorus removal. The City of Warren WWTP was the first ever cold weather installation of the BioMix technology in secondary process tanks.

Implementing the A/O configuration resulted in more than $150,000 annual operational savings through reduced ferric chloride addition for phosphorus precipitation.

Compressed gas mixing has gained popularity over the past decade due to the benefits of reduced energy, ease of maintenance, and the ability to integrate with diffused aeration to provide process flexibility without sacrificing mixing. Compressed gas mixing systems provide significant power savings compared to mechanical mixers by uniformly delivering mixing energy across the basin floor rather than distributing mixing energy from a point source mixing device equally throughout a reactor. Multiple studies have documented a 60% or greater reduction in power usage versus mechanical mixers and even more versus diffused air mixing.

Compressed gas mixing provides uniform mixing of tank contents by firing programmed, short-duration, high-intensity bursts of compressed air through engineered nozzles located near the tank floor. Mixing parameters — including pressure, sequence, duration, and frequency — may be adjusted, either through operator input or automatic process feedback, to optimize power utilization and deliver ideally mixed conditions.

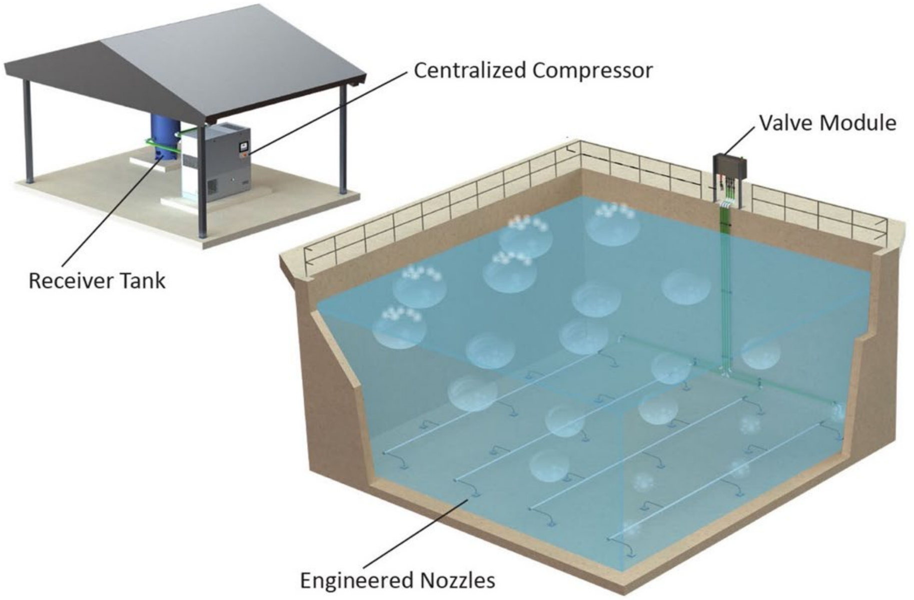


Figure 4: BioMix Compressed Gas Mixing System

BioMix (see **Figure 4**) starts with a centralized compressor system that can be used for multiple applications, regardless of treatment process, liquid depth, or solids concentration. The compressor, which uses ambient air, modulates output to maintain system pressure while conserving energy when demand is low. Charged by the compressor, the receiver tank supplies compressed air to the valve module. The valve module controls the mixing intensity and releases the bottled-up air in high-pressure, high-velocity timed bursts through groups of nozzles across the floor of the tank. Large volumes of gas generate an upwelling motion and create circulatory currents, suspending solids and maintaining a completely mixed environment.

Extensive amounts of oxidation-reduction potential (ORP) data have been collected from multiple treatment facilities utilizing compressed gas mixing and practicing EBPR. Installing online instrumentation in continuously mixed anaerobic zones, data sets have been established by collecting months of ORP data points at 30 second intervals using ORP sensors. The data demonstrates the integrity of anaerobic and anoxic zones with ORP values representative of anaerobic and anoxic environments. Two such data sets are presented in **Figure 5**, including data from Warren, labeled as "Michigan Plant". The consistently low ORP data from both the Kansas and Michigan treatment facilities demonstrate a deep anaerobic environment with average ORP values of -442 mV and -471 mV respectively.

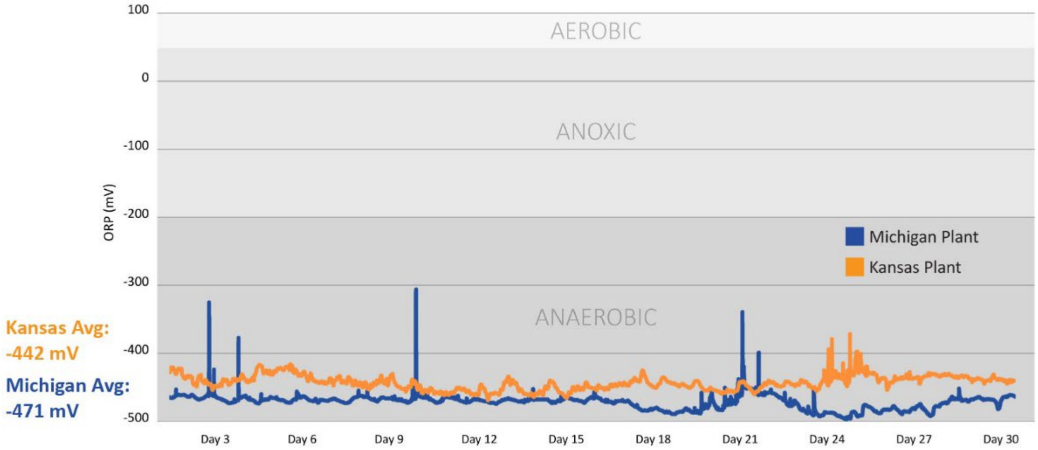


Figure 5: Consistently Low ORP Data in Anaerobic Selectors

METHODOLOGY

While both plants achieved biological phosphorus removal and reduced chemical consumption with their process upgrades, Warren was specifically interested in exploring ways to elevate their process to EBPR, resulting in more consistent phosphorus removal and further reduce chemical usage, while simultaneously preparing for future reductions in their phosphorus permit. With a new anaerobic selector, Warren saw an improvement in biological phosphorus removal, but the performance was not consistent enough to eliminate the need for periodic chemical addition. Warren discovered that their low influent rbCOD:P ratio combined with limited influent VFA was putting them at a disadvantage to achieve consistent biological phosphorus removal.

Plant staff partnered with EnviroMix to implement an intermittent mixing solution with the compressed gas mixing system already installed to enhance the anaerobic zone VFA production and elevate biological phosphorus removal. In April 2021, Warren upgraded the anaerobic selector in a single process train to include an inline fermentation process which utilized embedded carbon to increase VFA production and subsequent delivery of VFA to the PAOs to maximize phosphorus uptake. The testing and development completed at Warren resulted in a product solution that EnviroMix (Charleston, SC) named BioMix-DC Enhanced Anaerobic Mixing which was launched in June 2021. In November 2021 – after hearing of the success at Warren – the anaerobic selector at SGWASA was upgraded to an intensified fermentation tank by alternating a short mixing cycle with a long non-mixed deep anaerobic cycle. This increased the anaerobic solids retention time while creating a fermentation blanket in the anaerobic selector to ferment readily and slowly biodegradable COD to VFA.

BioMix-DC optimizes EBPR by transforming a traditional anaerobic selector into an intensified fermentation tank by alternating a short mixing cycle with a long deep cycle – see **Figure 6**. During the mixing cycle of BioMix-DC, the fermentation blanket is uniformly suspended to discourage methanogenic activity and recharge the blanket with organic matter for more VFA production. Utilizing BioMix, large bubbles are released through engineered nozzles near the floor of the tank, creating an upwelling motion and circulatory currents to completely mix the reactor. During the non-mixed, deep cycle, the fermentation blanket forms and VFA production resumes. Transporting surplus VFA from the blanket to the PAOs in the upper layers is accomplished through short, gentle pulses of compressed gas. These pulses transport the VFA upward without resuspending the blanket.

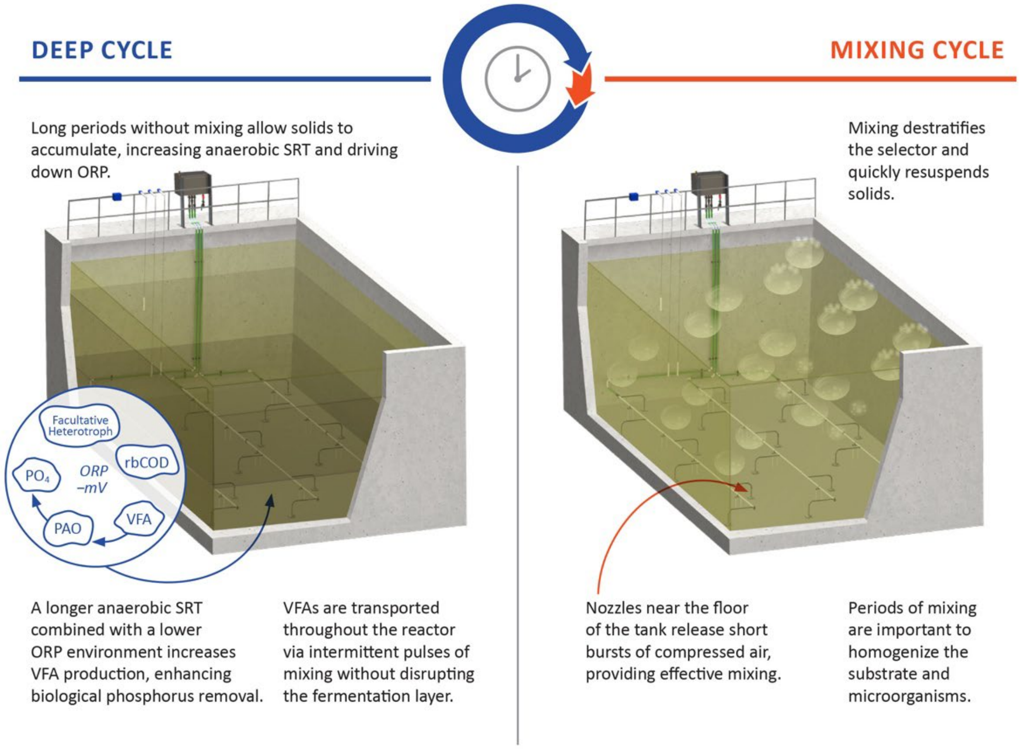


Figure 6: Illustration of How a Novel Intermittent Mixing Strategy Works

The unique approach used by both plants included an update to the control logic for the mixing system in the anaerobic selector, switching from continuous mixing to intermittent mixing. The new approach operates compressed gas mixing cyclically, with complete mixing events occurring every 8-12 hours, and intermittent low-energy compressed gas pulses occurring every 30-60 minutes during the unmixed phases.

When mixing is discontinued, solids accumulate and a sludge blanket forms at the bottom of the tank – this is the fermentation blanket. To confirm the presence of a fermentation blanket, TSS readings were collected from a variety of locations and depths within the reactor. A portable, handheld TSS analyzer, Cerlic model C83C5EN11 was used.

The periodic gentle pulses of low energy compressed gas mixing transport VFA from the fermentation blanket into the upper volume of the reactor. The pulses are gentle enough to transport and distribute VFA while maintaining the structure of the sludge blanket, allowing the fermentation process to continue producing VFA. VFA production was confirmed by collecting samples from the reactor at depths within the fermentation blanket and depths considered within the bulk liquid (or remainder of the tank). VFA transport was confirmed by measuring VFA in the fermentation layer before and after a periodic pulsing event. VFA samples were analyzed using a Hach TNT 872 Volatile Acids test kit, measured as acetic acid (CH_3COOH). In other instances, VFA was approximated using a filtered COD test kit, Hach Method 8000, combined with a vacuum filter and 0.45 μm filter paper.

Elevated levels of VFA suggest that the PAOs have released all their internally stored phosphate and are no longer able to uptake VFA. However, a more direct measurement of phosphorus release by PAOs is to measure orthophosphate in the fermentation blanket. To collect samples from the fermentation blanket, two methodologies were utilized. At Warren, a sludge judge was used to grab a sample from within the fermentation blanket. At SGWASA, a Conbar 500 mL sampler was utilized. At both facilities, the sample collected was filtered immediately at the tanks using a coffee filter and then quickly brought into the lab for vacuum filtration with 0.45 μm filter paper. Hach test kits 844 and 845 were used for orthophosphate and total phosphorus analyses.

Analyses performed by the plant for influent and effluent phosphorus were performed using lab approved processes and procedures at each facility. Deoxyribonucleic acid (DNA) analyses were performed by Microbe Detectives to compare the microbial community and PAO population at Warren.

RESULTS

Performance data from both Warren and SGWASA was collected and analyzed over multiple site visits by EnviroMix and is combined with data collected and analyzed by staff from both facilities before and after implementation of the anaerobic intermittent mixing solution.

Establish a Fermentation Blanket

The TSS concentrations before the pulsing events show stratification of solids between the surface and the bottom of the tank (**Figure 7**). The highest concentration of solids is found at the bottom 2-4 ft (61-122 cm) of the tank – the fermentation blanket. The lowest solids concentrations are found at the surface of the tank. The solids profile during a non-mixing period is unique for each facility and largely dependent on the settling characteristics of the activated sludge. The settled solids data collected from intermittently mixed anaerobic zones at sites in Michigan and North Carolina show a fermenting layer with a TSS concentrations greater than

10,000 mg/L and a bulk layer above the settled blanket with a solids concentration range of 3,000 – 5,000 mg/L.

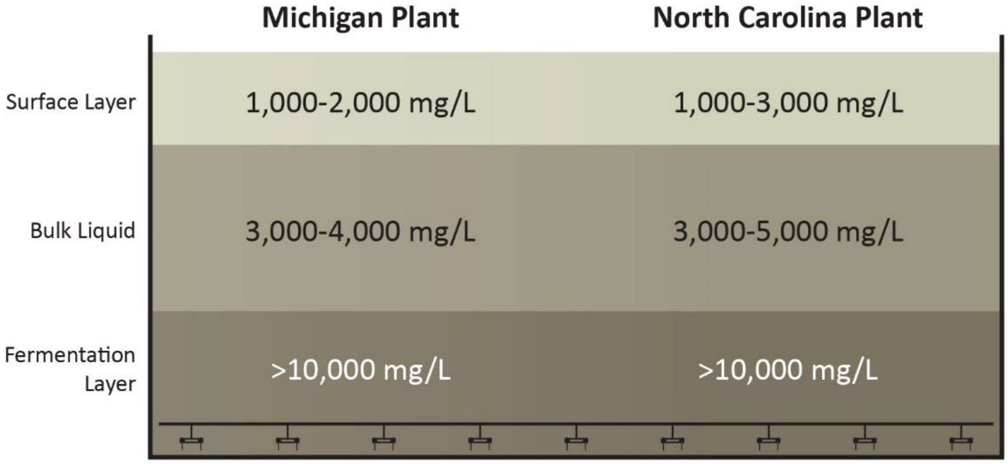


Figure 7: Stratified TSS Levels Confirm Fermentation Layer

The TSS measurements were also repeated after a pulse, creating a solids concentration profile comparison to confirm two things: (1) that the tank is not completely mixed and (2) that the blanket is not disrupted. A slightly lower TSS concentration found at the same depths after a pulse indicates that the blanket has slightly expanded; the stratified layers of solids demonstrate that the reactor was not completely mixed. The presence of a 2-4 ft (61-122 cm) layer of highly concentrated solids remaining in the tank and a low ORP indicates that the fermentation blanket and VFA production was not disrupted.

VFA Generation

Creating a deep anaerobic environment coupled with readily available carbon, such as VFA leads to PAO selection and consistent EBPR. **Figure 8** presents the differences in VFA concentrations between a fermenting anaerobic blanket and the bulk liquid within an intermittently mixed anaerobic zone. To confirm VFA production in the fermentation blanket, samples were collected from both the fermentation blanket and volume above the blanket during periods of unmixed operation. The samples routinely showed that the VFA in the fermentation blanket were, on average, five to ten times higher than the values measured in the bulk liquid above the blanket. The presence of elevated VFA in the fermentation layer indicates an abundance of carbon. Accumulation of VFA in the fermentation layer indicates that the PAO population in the fermentation layer have depleted all stored phosphate and therefore will no longer utilize VFA in exchange for phosphorus release.

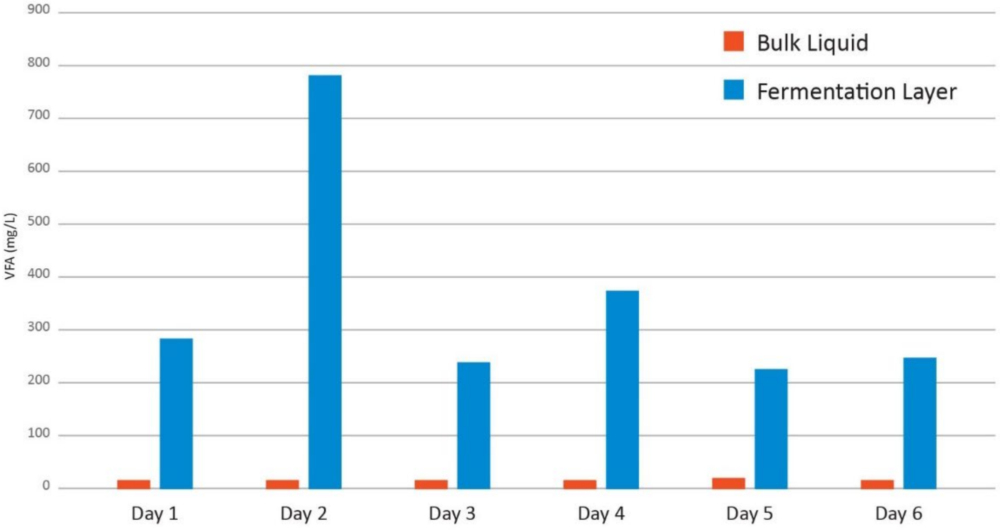


Figure 8: VFA in Bulk Liquid v.s. Fermentation Layer, Michigan Plan

The VFA data from the two distinct locations within the anaerobic reactor suggests that the elevated VFA in the blanket is a result of PAOs releasing all internally stored phosphate which results in the buildup of VFA. The presence of excess VFA in the blanket, with values measuring between 200 – 800 mg/L as acetic acid, reinforces the need to actively transport the substrate out of the blanket, into the bulk liquid giving PAOs outside of the fermentation blanket access to VFA.

VFA Transport

Transporting excess VFA throughout the reactor is critical to providing sufficient VFA to the entire PAO community within the anaerobic zone. The data presented in **Figure 9** validates the conveyance of accumulated VFA from the blanket with short, compressed gas burst originating from the bottom of the reactor within the settled fermenting blanket. Samples taken within the settled blanket, before and after the pulsing compressed gas burst were analyzed for VFA. The results show a steep decline in VFA within the blanket after a pulsing event, giving PAOs access to VFA outside of the blanket.

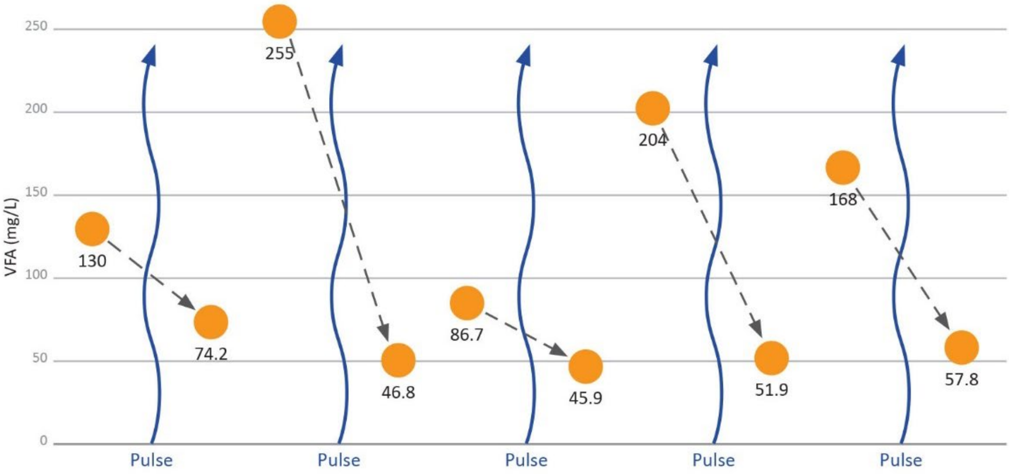
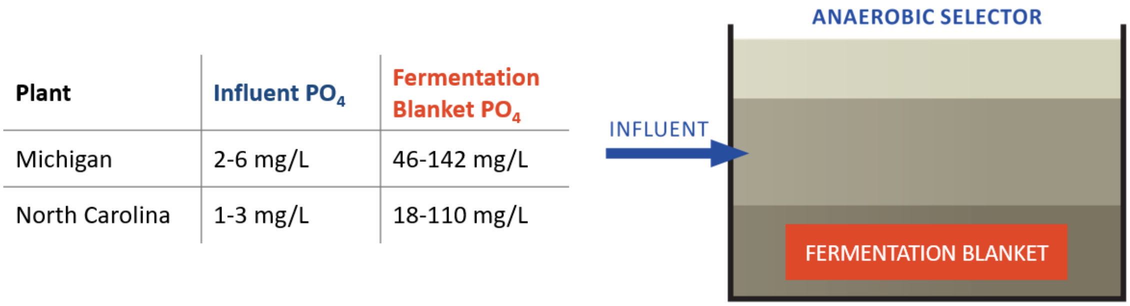


Figure 9: VFA in Fermentation Layer, Before and After Pulse - Michigan Plant

While it is important to generate VFA from readily biodegradable material in the fermentation blanket, it is equally as important to transport excess VFA to the PAOs throughout the reactor. The periodic gentle pulses of low energy compressed gas mixing from the fermentation blanket are used to transport excess carbon to the bulk liquid providing availability to PAOs throughout the anaerobic reactor.

Phosphorus Release

While generating and transporting VFA is imperative to fermentation, to get biological phosphorus removal, there must first be PAOs present to release stored phosphorus prior to luxury uptake in downstream aerobic zones. When PAOs consume VFA, they release phosphorus. To measure and confirm phosphorus release, the influent orthophosphate was compared to the orthophosphate concentration found in the fermentation blanket. **Figure 10** presents the results from orthophosphate measurements taken from influent and fermenting blanket locations.



Plant	Influent PO_4	Fermentation Blanket PO_4
Michigan	2-6 mg/L	46-142 mg/L
North Carolina	1-3 mg/L	18-110 mg/L

Figure 10: Phosphorus Release in Fermentation Blanket

The data demonstrate that the measurements in the blanket were 10 to 100 times higher than the concentrations found in the influent, confirming high levels of VFA consumption – and subsequent phosphorus release.

Proliferation of PAOs

The Michigan plant used DNA analyses to compare the microbial population in the treatment train with intermittent mixing for fermentation to that of another parallel treatment train using a traditional continuously mixed anaerobic selector. The two parallel treatment trains operate with completely separate sludge streams, including separate clarifiers and RAS flow. The data shown in **Figure 11** presents the results from the DNA analysis, with the intermittently mixed anaerobic zone identified with the "fermentation" label and the trains using continuously mixed anaerobic zones labeled as "traditional anaerobic". The parallel trains were operated with separate sludge streams throughout the testing. The results indicated a relative abundance of over 12% PAOs in the train practicing fermentation with intermittent mixing in the anaerobic zone, whereas the relative abundance of PAOs in the train using traditional anaerobic zones with continuous mixing was less than 4%.

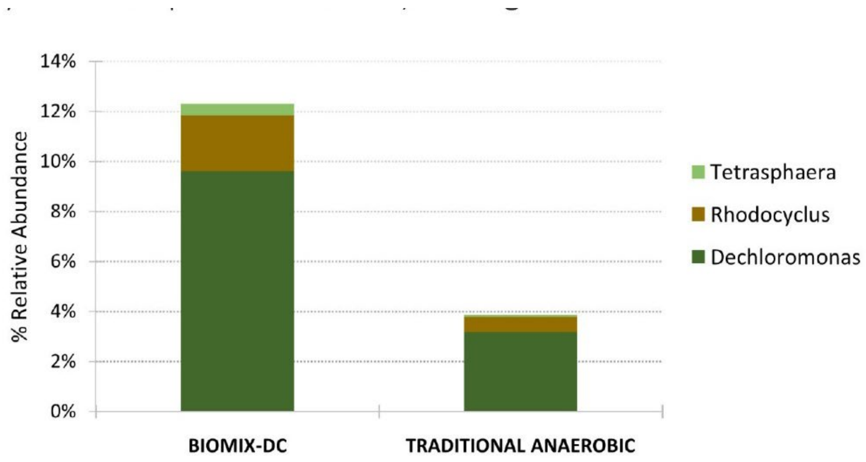


Figure 11: Side-by-Side Comparison of PAOs, Michigan Plant

DISCUSSION

While the results discussed so far are important for understanding how fermentation leads to PAO proliferation and subsequent phosphorus release and uptake, for many WRRFs the most important end result is consistent effluent quality and meeting permit. With the intermittent compressed gas mixing strategy in place, EBPR performance responded quickly with consistently low effluent phosphorus at both facilities.

Warren Effluent Quality

Like many WRRFs, Warren experiences fluctuations in influent phosphorus and historically this often resulted in effluent phosphorus variation as well. To compare performance before and after the intermittent mixing strategy was introduced, influent total phosphorus data using a 24-hour composite sampler was compared to effluent orthophosphate data collected using a 24-hour composite sampler. Samples were collected by plant staff and analyzed an average of 5 days per week. The results are shown in **Figure 12** spanning a period of approximately 50 days before and after implementation.

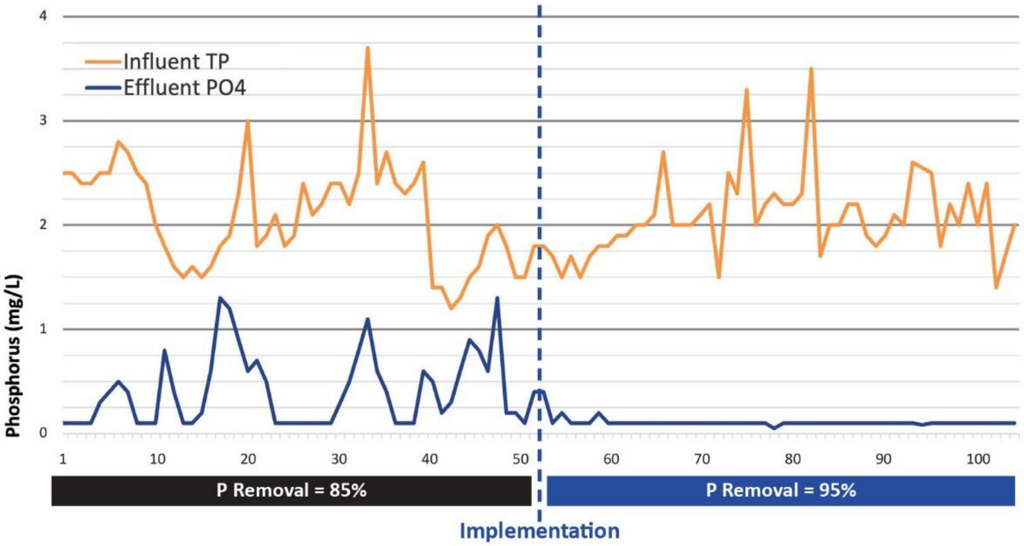
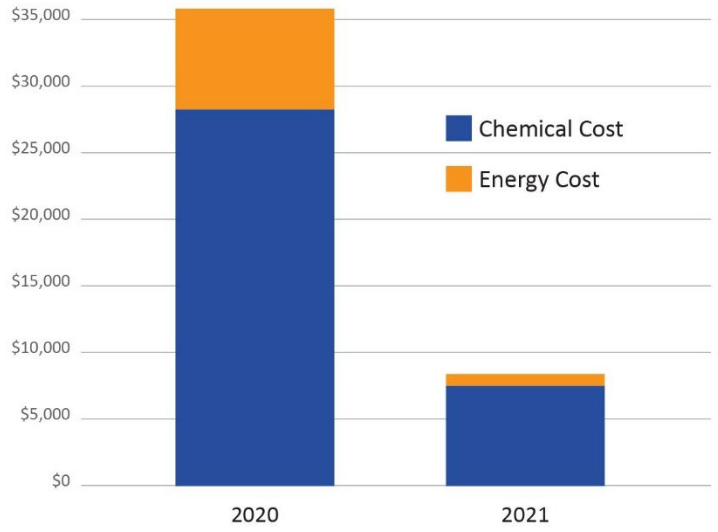


Figure 12: Total Phosphorus Before and After, Michigan Plant

Prior to the implementation of the new mixing strategy, Warren was achieving a P-removal efficiency of approximately 85%. After the upgrade, the phosphorus removal efficiency increased to 95% and Warren did not experience any effluent peaks above 1 mg/L.

In addition to achieving consistently low phosphorus effluent, Warren also appreciated a reduction in both energy and chemical consumption. **Figure 13** summarizes the operating cost reduction in percentage and dollars when comparing operation of year 2020 to 2021.



Reduced Chemical Consumption

- 73% reduction in ferric consumption
- $20,800 annual chemical savings

Reduced Power Consumption

- 89% reduction in power consumption
- $6,700 annual power savings

Figure 13: Operating Costs, Michigan Plant

Intermittent mixing inherently reduces energy consumption when the mixing device is operating less than 10% of the time, so the savings comes as little surprise. In comparison of 2020 vs. 2021 operating costs at Warren the new mixing strategy resulted in 89% reduction of power consumption, or $6,700 USD.

With the higher phosphor removal efficiency, Warren found themselves needing less and less ferric chloride addition to trim the effluent phosphorus to ensure they were compliant with permit. When comparing 2020 vs. 2021 chemical usage, Warren reduced ferric consumption by 73%, saving $20,800 USD year over year.

SGWASA Effluent Quality

Similar data was collected at SGWASA with 24-hour composite samples being collected and analyzed by plant staff. The influent and effluent TP data presented in **Figure 14** illustrates the variability of the influent TP load along with an unstable effluent TP. After implementation, the positive impact of the intermittently mixed anaerobic zone provides a more consistently low effluent TP, reducing the number of spikes. Fermenting embedded carbon with intermittent mixing created VFA and the proliferation of PAOs, which stabilized the EBPR process, resulting in lower and more consistent effluent total phosphorus.

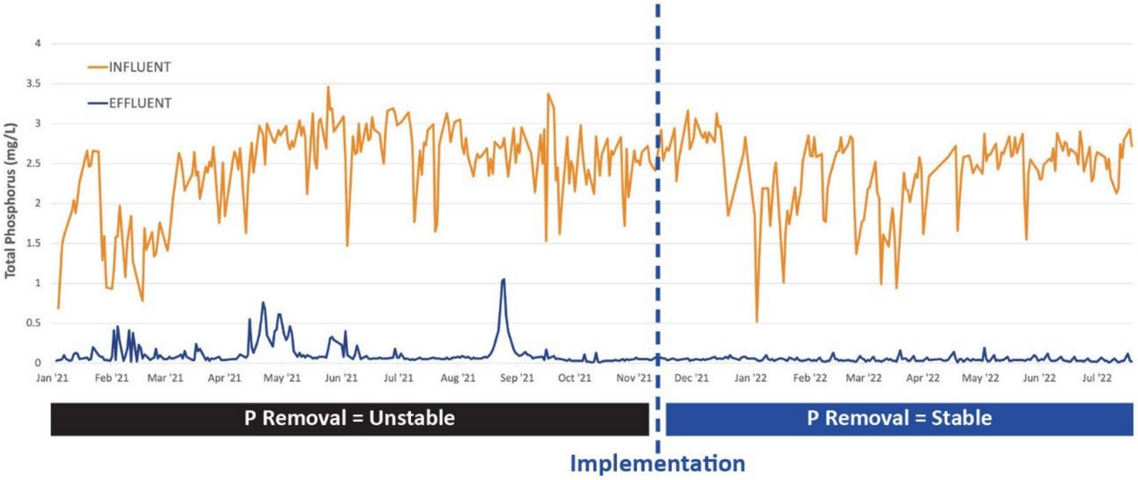


Figure 14: Total Phosphorus Before and After, North Carolina Plant

Prior to implementing intermittent mixing, the effluent TP experienced peaks between 0.5 and 1.0 mg/L, after implementation the effluent TP was consistently below 0.2 mg/L. In addition, the plant realized a 90% reduction in mixing energy demand for the anaerobic reactors. In November 2022, having gained confidence in EBPR process, the plant initiated a plan to lower the alum feed rate 10% each week, and continues to monitor performance and lower the chemical feed to further optimize savings.

CONCLUSION AND LESSONS LEARNED

This paper demonstrates how plants can adjust mixing in anerobic selectors to benefit from the fermentation of embedded carbon while providing more consistent performance and lower effluent phosphorus values. Providing an environment for fermentation, recognizes the value of embedded carbon as a resource, enhancing biological phosphorus removal while reducing mixing energy and chemical consumption. The intermittent mixing solution maintained exceptionally low ORP, generated excess VFA, and utilized a unique mixing regime to transport VFA throughout the reactor without disturbing the fermentation process. The results included reduced mixing energy, VFA production, decreased chemical consumption, and lower and more stable effluent P.

In summary, it is important for plants to consider the following when looking to modify their anaerobic selectors with intermittent mixing strategies:

- When VFA in the influent is inadequate for EBPR, an intermittent mixing strategy can be employed to produce more VFA.
- Short, gentle pulses of compressed gas mixing transport VFA throughout the anaerobic zone to be utilized by PAOs in exchange for phosphorus release and the proliferation of a PAO population.
- In addition to the process benefits, intermittent mixing substantially reduces power consumption.