

Operator Guidance for Biological Removal of Phosphorus in Municipal Wastewater

January 22, 2018

Brett Ward
Municipal Technical Advisory Service
University of Tennessee

Larry W. Moore
Civil Engineering Department
University of Memphis

The toughest challenge some wastewater operators will face in the next few years is to meet new NPDES phosphorus limits. Removing phosphorus from wastewater is a complex, delicate, and sometimes very expensive process especially when trying to make “old plants do new tricks.” Often NPDES phosphorus limits are being included in permits where the discharge is to small rural streams. In many cases, the 7Q10 (low stream flow condition) is at or near zero cubic feet per second (cfs). Generally these are also small communities with limited resources and where plant operators perform a wide variety of jobs in addition to plant operations.

Fortunately, the Tennessee Department of Environment and Conservation (TDEC) is implementing the limits based on the design flow rate (average daily) of the wastewater treatment plant (WWTP) and applying mass only limits. Moreover, in many cases the mass limits are based on a 6-month or 12-month rolling average. The most stringent limits on Total P are usually based on an effluent phosphorus concentration of 0.5 to 1.0 mg/L. Such a permitting approach gives the WWTP much more flexibility in terms of meeting the new effluent requirements. TDEC should be highly commended for this permitting approach for nutrient limits.

Phosphorus is an essential element for life. Human waste, cleaning products, drinking water anti-corrosion products, and many industrial process water discharges contain small amounts of phosphorus. Normal plant influent can contain 5 to 20 mg/L of total phosphorus with the most common values in the 6 to 7 mg/L range. Phosphorus enters the plant in the influent or within any hauled-in waste and leaves the plant either in the effluent or the sludge/biosolids. So if we want the effluent to be low in Total Phosphorus, the sludge/biosolids must be high in phosphorus. Sometimes this is very difficult to accomplish, especially if the WWTP is trying to achieve the effluent Total Phosphorus limit by biological phosphorus removal.

There are two methods that are generally used to remove wastewater phosphorus: chemical removal and biological removal. Both of these methods lower effluent phosphorus by increasing sludge phosphorus which is ultimately removed from the plant to a landfill or land application.

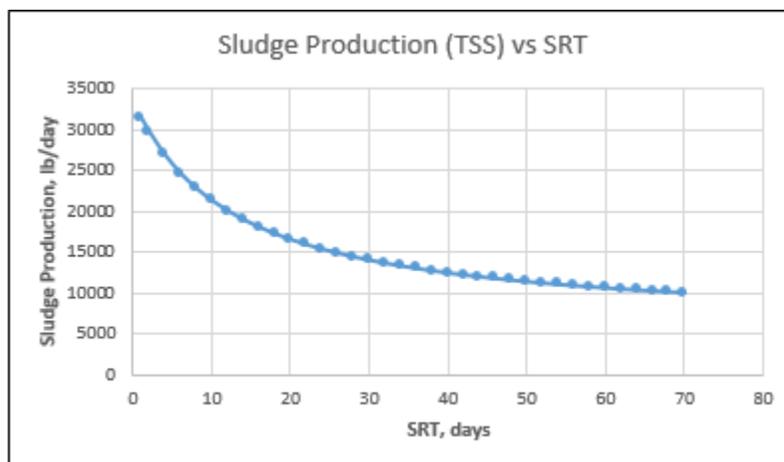
Pass-Through Phosphorus

The first strategy to keep effluent phosphorus low is to keep effluent BOD and TSS low. Most organic compounds that make up BOD will have a small amount of phosphorus within them. Also any TSS that escapes the clarification process into the effluent typically will have 1.5 to 2.0% phosphorus. Plants that are designed to meet low level phosphorus limits should have

effluent filters, but existing facilities may need to have filters added as part of a significant WWTP upgrade.

Assimilative Phosphorus Removal

When BOD (heterotrophic) and ammonia (autotrophic) removal bacteria grow and reproduce, the process is called biological synthesis. All biomass needs a small amount of phosphorus. Normal mixed liquor suspended solids (MLSS) contains about 1.5 to 2.0% phosphorus; so the more MLSS wasted and the more sludge removed from the plant the more phosphorus is removed from the wastewater. See the graph below, taken from the Bio-Tiger (Moore 2017) activated sludge model. At a 10-day solids retention time (SRT or MCRT) this plant is predicted to remove just over 20,000 lbs/day of waste sludge, but at a 70-day SRT the sludge wasted is only 10,000 lbs/day. So at the shorter 10-day MCRT this plant would be removing twice as much phosphorus than it would be if operated at a 70-day MCRT (assuming the P content of the biomass is the same for each MCRT). In an activated sludge process not designed for P removal, Phosphorus removal from biomass growth and wasting can be 10-30% of the influent phosphorus depending on MCRT, waste sludge handling practices, and side stream recycling processes. Thus, one way to keep effluent phosphorus low is to keep MCRT, SRT, or sludge age as low as possible while still getting good BOD and ammonia removal. It should be noted that biological N removal usually is better the longer the MCRT; therefore, trying to achieve bio P and bio N removal requires a careful balancing act by the operator.



Enhanced Biological Phosphorus Removal - EBPR

Enhancing biological phosphorus removal within a wastewater treatment plant can be quite complex and challenges the abilities and skills of even the most experienced operators. Even after 50 years of trials and research enhanced biological phosphorus removal is often best characterized by its “process instability.” (Gebremariam 2011) To get better phosphorus

removal, plant operations may need to be dramatically adjusted and the “way we have always done it” most likely will not work for phosphorus removal. There will be more testing, process control monitoring, and more attention to details. Slight adjustments to improve phosphorus removal may negatively impact other processes, and slight adjustments to other processes may significantly impact phosphorus removal. Running a plant for EBPR can be like walking a tightrope in a hurricane. Nevertheless, many operators are meeting low Total P limits and have learned what operating adjustments are required in their plants. It is a major learning process that continues indefinitely.

Biological wastewater treatment makes use of naturally occurring soil and aquatic microorganisms to purify the water. For enhanced phosphorus removal, a group of bacteria generally called phosphorus accumulating organisms (PAOs) are the “bugs” we desire to be present. All plants have PAOs, perhaps 10% of the biomass of a conventional activated sludge is made up of PAOs. (Gebremariam 2011) They are heterotrophic (feed on organic matter or CBOD) and obligate aerobes (must have oxygen). But, unlike most treatment plant bacteria, PAOs have a very unique metabolic cycle. When they are circulated through alternating anaerobic/aerobic conditions, they demonstrate the capability to remove from the water huge amounts of dissolved phosphorus, commonly called luxury uptake. This luxury uptake of phosphorus is much greater than that which is needed for simple growth and reproduction that is seen in assimilative uptake by typical heterotrophic bacteria.

During the aerobic phase, PAOs will take up and store phosphorus in the form of Polyphosphate (PO_4). This uptake and storage of PO_4 within the bacterial cells will result in the MLSS being high in phosphorus and the clarified effluent being low in phosphorus. Biomass phosphorus levels will change from the normal 1.5 to 2% phosphorus to 3 to 6% phosphorus, sometimes to 16% (Miklos, Mulkerrins 2004) and effluent can be as low as 0.1 mg/L total phosphorus. When this 3 to 6% phosphorus MLSS is wasted from the system, greater phosphorus removal is accomplished. It should be noted that PAOs will be about 20% or so of the biomass inventory in a bio P removal activated sludge process. PAOs are 15% to 30% by weight phosphorus.

When the settled biomass is returned to the head of the activated sludge process, all or part of the return goes into an anaerobic zone or fermenter. The purpose of this anaerobic unit is twofold. The first purpose is the fermentation of incoming wastewater organics to increase the amounts of readily biodegradable organic matter (rbBOD) generally measured as volatile fatty acids (VFAs); the second purpose is to select for PAO bacteria. This means the anaerobic zone is created to enhance the growth of PAOs at the expense of all other types of treatment plant bacteria. It should be noted that it may be more desirable to have a side-stream fermenter which provides a relatively high concentration of VFAs to the anaerobic reactor.

VFAs are readily biodegradable and all heterotrophs will use them quickly but the anaerobic conditions in the fermenter prevent VFA usage by all but the PAO's. In other words, the fermenter selects for the PAO's. In the anaerobic zone, PAOs use the available VFAs and store this organic matter as Polyhydroxyalkanoates (PHA) while releasing significant amounts of

phosphorus into solution. In fact, the P concentration in the anaerobic zone may be 30 to 50 mg/L compared to influent P of 5 to 8 mg/L. Expect the fermenter effluent to be 3-4 times higher in ortho phosphorus than the plant influent. (Wisconsin) It is very important that dissolved oxygen (DO) is absent and nitrate-N is at very low concentration to ensure that anaerobic conditions occur. If oxygen is present, the heterotrophs will undergo aerobic metabolism; if oxygen is absent but nitrate-N is present, the heterotrophs will undergo anoxic metabolism; this will interfere with bio P removal. When the PAOs reach the subsequent aerobic reactor, they begin oxidizing all this stored PHA using the available oxygen and take up phosphorus (luxury uptake) to give a low phosphorus effluent. See the diagrams of phosphorus release and uptake below. (EPA 1987)

Figure 3-1. Biological phosphorus and BOD removal due to anaerobic-aerobic contacting.

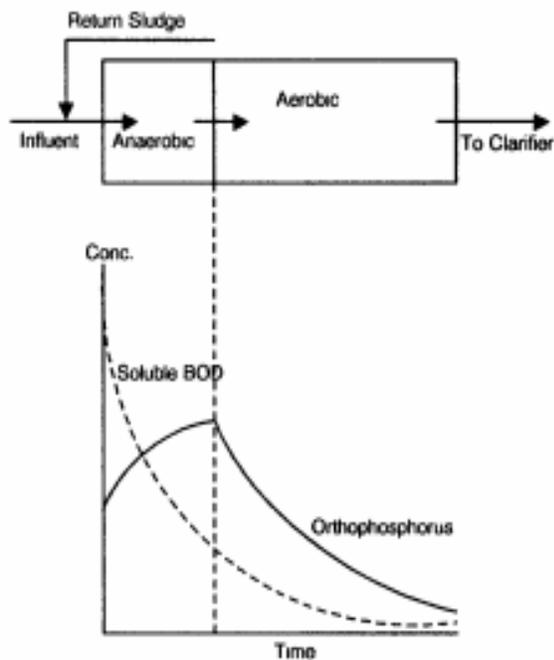
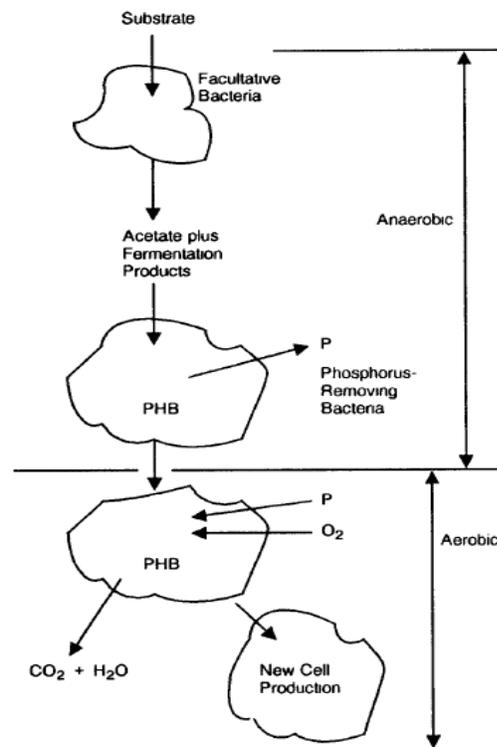


Figure 3-3. Schematic of biological phosphorus removal mechanism.



Plant Influent

Plant influent has a significant impact on EBPR. Key factors are phosphorus level, BOD-COD-VFA levels, oxygen or nitrate levels, collection system design, flow variations, and preliminary and primary treatment within the plant.

Common influent phosphorus levels are 6 to 7 mg/L. Numerous references state it takes about 7.5 mg VFA to remove one mg of phosphorus. A normal range of influent VFAs is 5-80 mg/L so influent may not have enough VFAs for good removal; so additional fermentation is needed. Generally recommended operational ratios are: $BOD_5/TP \geq 20$ mg BOD_5 /mg P removed (WEF 2010), Minnesota reports that a ration between 30:1 to 40:1 is better (2006), $sBOD_5/TP \geq 15$ mg

sBOD₅/mg P removed (EPA 1987, WEF 2010), VFA/TP = 7.5 mg VFAs/mg P removed (Mulkerrins 2004), or a range of 5-10 mg VFA/ mg P removed (Damesh 1997). It is reported that > 25 mg/L VFAs are needed in the anaerobic zone to achieve significant EBPR (EPA 2010), but rarely are there enough VFAs entering the plant (Barnard 2017, deBarbadillo 2015, Jeyanayagam 2004).

The influent dissolved oxygen and nitrate levels depend on the collection system and will impact the anaerobic zone environment. From the construction of the first sewer collection system, efforts have been made to keep aerobic conditions within the flowing sewage, but if EBPR is the goal, having oxygen and nitrate in the influent hinders those operations. Surges of rainwater will also complicate EBPR because of the volume of flow, the oxygen level, and the lowering of BOD concentrations which occurs when there is a surge of inflow and infiltration. Typically, raw municipal wastewater will have little to no nitrate-N because sewer systems are predominantly anaerobic (chemical reducing) environments.

Preliminary and primary treatment units can also have an impact on EBPR. Any actions to aerate the raw wastewater will add oxygen and hinder EBPR. Screw-lift pumps, aerated grit and grease removal units, and pre-aeration units can be sources of unwanted oxygen (Keller 2010). On the other hand, primary clarifiers can be used as fermenters to raise the levels of VFAs. Maintaining deeper sludge blankets and reducing primary clarifier effluent aeration are steps to enhance biological phosphorus removal.

Influent Testing

Knowing what is entering the plant is very important. The following list of parameters can be a guide to help operators develop that knowledge. Some tests are required by regulations and/or NPDES permits. Some test procedures are conducted less frequently than others, but all will provide insight about the characteristics of wastewater entering the facility and how the various processes may be impacted.

Total Phosphorus

Ortho Phosphorus

VFA- individual acids by gas chromatography. A major Tennessee lab has a method (AM 21G) that reports 5 individual acids. HACH now has a TNT method for VFA.

Dissolved Oxygen (DO)

Nitrate-N

Oxidation Reduction Potential

pH

CBOD₅, or better sCBOD₅ (soluble CBOD₅)

Anaerobic Zone or Fermenter

This is the treatment unit that is unique to EBPR and one that is the center of most operational testing and attention. The purpose of this unit is twofold, generation of VFAs and the uptake of the VFAs by PAOs. The common hydraulic detention time in this unit is 1 to 2 hours, but this all depends on the incoming level of VFAs. Dr. Barnard prefers a series of basins that can “swing” as needed. If the incoming VFAs are adequate, a smaller unit works; but if the VFAs are totally depleted by the end of the unit, the tank is too large (Barnard 2017). This tank needs a small amount of mixing; Dr. Barnard recommends only 0.13 hp/ 10,000 gallons. A heavy layer of solids on the bottom of the fermenter can enhance VFA production (deBarbadillo 2014).

The desired operating conditions are zero oxygen and zero nitrate-N. Both inhibit PAO performance. Each mg of O₂ enables the other heterotrophic bacteria to use VFAs and reduce phosphorus release by 0.3 mg and each mg of nitrate-N enables the other heterotrophic bacteria to use VFAs and reduce phosphorus release by 0.7 mg (WEF 2010). Clearly nitrate-N is the most inhibiting of the two. ORP values of < -250 mV are desired, and others recommend < -300 mV (Danesh 1997, Barnard 2017, WEF 2010). If plant influent has an abundance of VFAs and lots of rbBOD, low levels of oxygen and nitrate-N are of less concern.

Other recommendation by Dr. Barnard (2017):

- No bubble mixers

- Limit oxygen from storm water

- Plug flow works better than a completely mixed reactor

- Recycle 10% of RAS through the fermenter

Some plants will supplement the VFAs by adding acetate or propionate. deBarbadillo and Barnard report (deBarbadillo 2014) on a variety of fermentation strategies (both in-line and side-stream) using plant influent, MLSS, and RAS as well as using external sources of readily biodegradable BOD such as glycerol, whey, and sugar waste and the use of VFAs generated in solids processing such as an ATAD unit. Several of these strategies separate the fermentation stage (where VFAs are generated) from the anaerobic zone (where VFAs are taken up and phosphorus release occurs). The hydraulic detention time (HDT) and MCRT of fermenters are often different from plant to plant and are adjusted to enhance VFA production and avoid methane generation. Most fermenters are allowed to develop a settled blanket of sludge which is often mixed only once per day or with very low horsepower mixers that provide a mixing intensity of 0.13 hp/ 10,000 gallons. Danesh suggests that a mixing time of 15 minutes/ 8 hour is optimal (1996)

EPA (2010) suggests a SRT in the fermenter/anaerobic zone of ≤ 4 days to prevent methane formation, and a HDT of 1 to 2 hours. Coats' research concludes that even a 3 hour hydraulic detention time is acceptable. (2011) Skalsky and Daigger (1995) suggest a 5 day SRT is the optimum for VFA production. Where there is a separate fermenter, the anaerobic zone could have a HDT of ≤ 1 hour. Recommended anaerobic zone testing is shown below:

Internal: DO, ORP, pH, temperature, MLSS

Effluent: VFAs, Ortho Phosphorus

Many utilities have retrofitted existing plants to enhance phosphorus removal. Traditional plug-flow basins are often changed to make the first 1/3 an anaerobic zone. In some SBR plants the cycles can be adjusted to make the initial fill cycle anaerobic. Other plants have used “sidestream” type anaerobic zones. It depends on plant design, existing piping and controls, availability of unused basins, and, of course, the money available for making changes.

Aerobic Zone

The aerobic zone is where phosphorus uptake occurs. PAOs will use free oxygen to metabolize the stored PHA and to take up phosphorus and store more PO₄ for the next trip through the anaerobic zone. Also ammonia-N will be oxidized and the remaining CBOD will be removed via aerobic metabolism. There are a variety of approaches to denitrify the contents of the aerobic zone. This may be achieved by an off/on aeration strategy or a recycle process through an anoxic zone. If an anoxic reactor is used, it typically will immediately follow the anaerobic zone in a process designed for biological N and P removal.

The aerobic reactor will have oxygen, but the next question is just how much oxygen. Most recommendations are presented in ranges that vary from 1.0 to 6.0 mg/L. Several of the recommended ranges overlap at 3.0 mg/L. Higher values may be due to the need to nitrify within the same basin or in high-rate activated sludge systems (EPA 2010). Dr. Barnard’s recommended range is 1.0 to 3.0 mg/L. Several references made recommendations for tapered aeration, high initial aeration where the demand is highest, followed by less aeration and a lower DO (0.5 to 1.0 mg/L) at the effluent end of aeration (Jeyanayagam 2005). This is consistent with the document (WEF 2010) which states phosphorus uptake is quite rapid --- occurring within the first 50% of the aeration zone. EPA (2010) reports low oxygen values from 0.25 to 0.5 mg/L in extended aeration systems that operated successfully. Recommended aerobic zone testing is given below:

Internal: DO profile of the basin; ortho phosphorus profile of the basin when working well and when not working well

Effluent: Total phosphorus and filtered ortho phosphorus.

MLSS Levels

There is a very consistent message on MCRT or Sludge Age; the shorter the better (Barnard 2003, Keller 2010, Strom 2006, WEF 2010) for bio P removal. The recommended range was 8 to 15 days, but all recommendations included 10 days. There appear to be three reasons for this MCRT recommendation. The first is just the simple assimilative removal. The more sludge wasted the more phosphorus that is removed. Another researcher stated that a longer MCRT would mean higher MLSS phosphorus percentages and a higher risk of secondary phosphorus

release from endogenous respiration of the MLSS. Operators in Ann Arbor, MI, keep MLSS values between 1500 and 1700 mg/L and stated higher levels resulted in too many PAOs and poor performance (Mulkerrins 2006).

Generally there are not enough VFAs or sBOD entering the plant for complete phosphorus removal. Operating at a lower MCRT is a way to improve removal when influent sBOD is limited. The amount of influent sBOD needed per pound of phosphorus removed is lower at a lower MCRT (EPA 1987).

EBPR plant operators report sludge volume index (SVI) values lower than what would be found in a conventional plant without phosphorus removal. PAO cells are denser and settle faster than normal heterotrophs (EPA 2010).

MLSS Phosphorus testing. As mentioned above, MLSS phosphorus levels can vary from 1.5-16%. Normal MLSS in the 1.5-2% range where MLSS with a high population of PAOs may go as high as 16%. Knowing the value of the MLSS phosphorus can be very useful in managing the EBPR process. There are two ways to determine this value. A simple way is to send a sample to your favorite commercial lab and request a phosphorus test using a Solid Waste SW-846 method. The results will be reported in mg/Kg generally as “Dry” results.

$$\begin{aligned} & \text{mg/Kg (Dry)} * 100/1,000,000 = \text{percent TP} \\ & \text{mg/Kg (wet)/ percent total solids(as a decimal)} * 100/1000,000 = \text{percent TP} \end{aligned}$$

A second way of determining MLSS percent phosphorus can be performed in the plant lab (or sent to a commercial lab) if the analyst has access to a sample digester to perform the Total Phosphorus test. Two samples are collected. The first is analyzed for Total Phosphorus using the normal procedures. The second sample is first filtered through a 0.45um filter (e-coli membrane) then the Total Phosphorus test is performed on the water that went through the filter. Caution, make sure the filter flask is clean and phosphorus free. This value is the Total Dissolved Phosphorus.

MLSS phosphorus calculations. The second value, Total Dissolved Phosphorus is subtracted from the Total Phosphorus giving Total Suspended Phosphorus. See Standard Methods, Figure 4500-P:1.

$$\begin{aligned} & \text{Total Phosphorus} - \text{Total Dissolved Phosphorus} = \text{Total Suspended Phosphorus} \\ & \text{Standard Methods Formula: } C - G = \text{Total Suspended Phosphorus} \end{aligned}$$

The resulting value will be in mg/L and is converted to percent using the following formula.

$$\text{TSP mg/L} / 1,000,000 * 100 = \text{percent Total Suspended Phosphorus, or MLSS-TP}$$

Filaments

EBPR plants are known to be more susceptible to infestation of the filament *Microthrix Parvicella* (Mulkerrins 2006). *M. Parvicella* is a foaming/scum forming filament known to feed on fat-oil-grease (FOG), and may actually be a PAO (Gebremariam 2011). The first control measure is to remove the FOG. Chlorination of the return sludge is also an effective way to control *M. Parvicella*.

Wasting MLSS

Wasting MLSS is the number one operator control method for activated sludge. Wasting the phosphorus-rich mixed liquor suspended solids (MLSS) is how phosphorus is removed from the wastewater. It is recommended that wasting occur when the mixed liquor is fully aerobic (Mulkerrins 2006, WEF 2010). Wasting when the mixed liquor is in an anoxic or anaerobic condition could mean removing solids during a release cycle that would leave more phosphorus in the effluent. The wasted solids would be lower in phosphorus, and final effluent would be higher in dissolved phosphorus.

pH

Most researchers recommend a pH range of 6.5 to 8, with higher values in that range being better. A range of 7.0 to 7.5 is cited as best for PAOs (EPA 2010, Oehman 2007, WEF 2010), yielding greater VFA uptake and phosphorus release in the anaerobic zone.

Temperature

The generally accepted wisdom for biological treatment is that warmer ambient temperatures mean better pollutant removal, but with phosphorus removal it appears cooler temperatures are better. Lower temperatures appear to favor PAOs (Oehmel 2007, EPA 2010, WEF 2010). But in sBOD limited systems, cooler temperatures limit fermentation and the production of VFAs (WEF 2010). Lower temperatures also give some advantage to *M. Parvicella* filaments.

Cations

Three cations that impact the EBPR process are potassium, magnesium and calcium (Mulkerrins 2003). Generally the levels in raw municipal wastewater are adequate (WEF 2010). Just like phosphorus, magnesium and potassium are released in the anaerobic zone and taken up in the aerobic zone (Jeyanayagam 2015). The amount of cations needed when influent soluble P = 10 mg/L is:

Mg	=	5.6 mg/L
K	=	6.3 mg/L
Ca	=	3.2 mg/L

Sludge Digestion

A key principle for EBPR plants is to not let the sludge processing side of the treatment plant negatively impact effluent quality. Great effort has been made to “train” (Miklos) PAOs to release and then take up phosphorus. If basins within the solids processing train become anaerobic or perhaps even anoxic, there could be phosphorus release. If release occurs, digester decant water, dewatering underflows, and drying bed underflows can return a significant amount of phosphorus to the liquid side of the facility and thereby elevate effluent phosphorus levels.

Many aerobic digesters are operated using an off/on aeration strategy. For years this has been an effective and economical strategy, but it may need to be modified. Closer monitoring of redox conditions in the decanted water is required. If the air-off cycles are too long, secondary phosphorus release is possible; so careful monitoring of the digester is warranted. Check the ORP, DO, and nitrate-N levels before and after “off” cycles, and also monitor ortho phosphorus of any decanted water or dewatering system return flows. If there are elevated levels, a secondary release has occurred. An east Tennessee operator has reported Ortho Phosphorus in decant water as high as 200 mg/L.

Aerobic digesters may need to be operated with longer air “on” cycles and shorter air “off” cycles. A bench-scale study conducted by the engineering firm JJ&G concluded an off/on cycle of 6 hours anoxic/2 hours aerobic produced the smallest release when compared to 24 hours on, 24 hours off; 2 hours anoxic/ 6 hours aerobic; and 4 hours anoxic/4 hours aerobic. The 6 hour anoxic/2 hour aerobic cycle also had the highest phosphorus level in the digested sludge and generally the lowest TSS destruction rate (Lan). Normal VSS destruction within an aerobic digester will also release phosphorus (Strom 2006) in proportion to solids destruction (EPA 1987). As MLSS solids are digested, cells die and lyse (break apart), releasing phosphorus back into solution. With the elevated phosphorus levels in PAO bacterial cells, this release is greater than normal. So just as the aeration basin MCRT should be kept as low as possible, digester MCRT should also be as short as possible. If landfill disposal is used, waste MLSS to a fully aerobic tank; dewater and haul as quickly as possible. If land application is used, digest the waste mixed liquor until regulations are met and move it out of the plant as quickly as possible. High phosphorus biosolids should be of more value to farmers because phosphorus is generally the most expensive fertilizer nutrient.

Secondary Phosphorus Release

Secondary release of phosphorus is a common factor contributing to poor phosphorus removal (Barnard 2003). When phosphorus-rich MLSS is allowed to become anaerobic outside of the influent anaerobic zone, secondary release can occur (Barnard 2003, Mulkerrins 2004, WEF 2010). Locations for potential secondary release include final clarifier blankets, RAS wet wells and pipelines, aerobic or anaerobic digesters, and oversized influent anaerobic zones where VFAs are depleted long before the hydraulic detention time is completed (WEF 2010). Any

location where phosphorus-rich MLSS or sludge is allowed to become anaerobic, or where there is no free dissolved oxygen and no nitrate-N present could be a location for secondary release.

Glycogen Accumulating Organisms (GAOs)

Competing with PAOs within the anaerobic zone for the available VFAs are a group of bacteria called GAOs. There are several factors that favor GAOs over PAOs and reduce phosphorus removal. GAOs out-compete PAOs at higher temperatures, lower pH, and longer MCRTs (Barnard 2003, Oehman 2007, Strom 2006, WEF 2010). Also contributing to GAO dominance can be very high organic loading relative to the amount of phosphorus. WEF, MOP 34 reports carbon/phosphorus ratios $\geq 50/1$ favor GAOs.

Process Control

A plant operator’s most important job is to effectively control the various processes within the treatment plant. Some of these processes are easy to control. Disinfection, for example, is generally easy to control, but EBPR is a difficult process to control. Jeyanayagam (2015) states, “The EBPR process is complex and entails several competing and complementing sub-processes.” The Table below from the Canadian Water Network reports some of process conflicts (Oleszkiewicz 2015).

Parameter	Nitrifiers	Denitrifiers	PAO
Preferred SRT	Long	Short	Short
F/M	Low	High	High
ORP (DO)	High	Low	Very low → High
rbCOD	No	Yes	Yes: VFA
NO _x -N	Ok	Must	No ¹
Temperature sensitivity	Very high	Moderate	Low

1 – When conditions for secondary release are not present.

Developed after Metcalf and Eddy (2014); EPA (2010); Downing et al. (2009); Kang et al. (2008); Brown et al. (2007); Oleszkiewicz and Barnard (2006).

A first step in controlling the EBPR process is to fully understand the biological process and the various treatment units that impact phosphorous removal. There are two main sources for this information, EPA and WEF. EPA’s 2010 design manual is available online and is relatively easy to understand. The WEF MOP-34 is a second good reference book. Additionally, the latest

research or summaries of worldwide phosphorus research can be reviewed by doing on-line searches or using the Water Environment Federation's publication [Water Environment Research](#).

Secondly, a plant operator needs to understand the plant and the nature of the influent. Some analytical guidance was included in previous sections. A more extensive guide (below) is taken from the 2010 EPA Design Manual.

Thirdly, Operators must act. Below is a list of possible operational changes that can be made to improve the EBPR process (EPA 2010).

Adjust MCRT - lower or raise MLSS concentrations; use or bypass "swing" fermentation zones.

Adjust Dissolved Oxygen (DO) - use tapered aeration, off/on aeration, or variable frequency drives (VFDs) on aerators or blowers where appropriate.

Add baffles – plug-flow movement of the wastewater generally works better. Multiple small anaerobic zones that can be used or bypassed improves flexibility; prevent backflow from adjacent units with elevated dissolved oxygen levels.

Adjust anaerobic zone mixing- several authors reported improved performance when anaerobic zones were only minimally mixed. This may mean only mixing 10 to 15 minutes per day, or using very low mixing intensity (0.13 hp/ 10,000 gallons).

Lower the impact of internal recycle flows; keep aerobic digesters aerobic; digester supernatant, for example, can be very high in phosphorus because of secondary release within the digester unit; and reduce intermittent loading from solids processing actions.

Raise VFA levels; monitor influent; track collection system odor control methods; make use of other treatment units such as primary clarifiers and solids processing units; and devise a side-stream fermenter to supply VFAs to the anaerobic reactor where possible.

Table 12-1. Recommended Parameters for Data Evaluation

Parameter ¹	Location(s)	Rationale
Flow	Influent, effluent, flow splits, recycles	Essential for developing mass balances, which are essential for a complete understanding of the treatment system.
Total BOD/COD Soluble ¹ BOD/COD	Influent, primary effluent, effluent, anaerobic & anoxic zone effluents	Can be used to evaluate substrate availability for biological processes. High effluent BOD could indicate activated sludge performance problem.
TSS, VSS	Primary effluent, secondary effluent, final effluent	Important if phosphorus is removed chemically. Used to calculate ISS, determine clarification efficiency, and determine an accurate solids residence time (SRT) for the bacteria.
DO	Aerobic, anaerobic, and anoxic zones (multiple locations recommended)	Minimum DO of 2.0 is usually needed to minimize oxygen limitation of nitrification rates, which is important for low SRT/HRT systems. DO should not be present in anoxic or anaerobic zones.
pH	Influent, mixed liquors, effluent	Should be above 6.5 and below 9.0 for biological nitrogen removal. Low pH or wide swings in pH could mean significant industrial component. Could affect BPR and nitrification.
Alkalinity	Influent, primary effluent, mixed liquor supernatants, effluent	If effluent is below 50, there is probable nitrification inhibition, and process is susceptible to large pH drops as a result of nitrification or chemical addition for phosphorus removal.
Temperature	Influent, mixed liquors of reactors, effluent	Low temperatures can significantly reduce nitrification rate. For the typical range between 10 and 25 °C, the rate will drop by half for every 8 to 10 °C reduction in mixed liquor temperature. Reactor temperatures are likely to be significantly different from influent temperature because of aeration.
NH ₃ -N or TKN	Influent, primary effluent, reactor mixed liquors, secondary effluent, effluent	Can be used to evaluate load to and performance of biological nitrification kinetics.
Nitrate	Influent, reactor mixed liquors, secondary effluent, effluent	A check on nitrification, and can be used with TKN to calculate denitrification.
Total Phosphorus	Influent, primary & secondary WAS, plant effluent	Used to calculate phosphorus removal efficiency by treatment processes.
Phosphate	Reactor mixed liquors, primary & secondary effluents, effluent	Used to determine release and uptake in reactors, release in secondary clarifier, and phosphorus removal efficiency.
ORP	Anaerobic & anoxic reactor mixed liquors	Measures the balance between oxidized and reduced compounds present in solution. Will detect presence of significant concentrations of oxidized compounds. Can be used for automatic detection of excess electron acceptors (DO, nitrate, and nitrite) in reactors.
VFA or rbCOD	Influent, primary effluent	Can be used to evaluate substrate availability for enhanced biological phosphorus removal.
MLSS & MLVSS test and WAS test	MLSS & MLVSS: well-mixed location in aeration basin WAS: well-mixed and representative sample from the WAS pipe (may need composite sample)	MLSS and WAS tests provide suspended solids concentrations and can be used to determine percent phosphorus in sludge. This information, in conjunction with aeration basin volume and WAS flow, can be used to calculate SRT. Maintaining SRT is critical for nitrification and, sometimes, for enhanced biological phosphorus removal.

¹ BOD = biochemical oxygen demand (5-day unless otherwise noted)

COD = chemical oxygen demand

TSS = total suspended solids

DO = dissolved oxygen

TKN = total Kjeldahl Nitrogen

VFA = volatile fatty acids

MLSS = mixed liquor suspended solids

MLVSS = mixed liquor volatile suspended solids; Inorganic suspended solids (ISS) = MLSS - MLVSS

Total BOD/COD = unfiltered BOD/COD

Soluble BOD/COD = BOD/COD of filtrate from 0.45 µm pore size filter

VSS = volatile suspended solids

ORP = oxidation reduction potential

NH₃-N = ammonia Nitrogen

rbCOD = readily biodegradable COD

WAS = waste activated sludge

References:

Barnard, James L., Caroline E. Scruggs, “Biological Phosphorus Removal,” Water Environment & Technology, February 2003.

Barnard, James L. et.al., “Rethinking the Mechanisms of Biological Phosphorus Removal,” Water Environment Research, November 2017.

Cashman, Linda, Environmental Science Corporation, Mt. Juliet, Tennessee

Coats, Eric R., et.al., Effect of Anaerobic HRT on Biological Phosphorus Removal and the Enrichment of Phosphorus Accumulating Organisms, Water Environment Research, May 2011.

Danesh, Shahnaz, and Jan A. Oleszkiewicz, Volatile fatty acid production and uptake in biological nutrient removal systems with process separation. Water Environment Research, Sept/Oct 1997.

deBarbadillo, Christine, James L. Barnard, “Mixed Liquor Fermentation and Other Alternatives for Providing VFA to EBPR Processes,” WEFTEC 2014.

EPA, Nutrient Design Manual, August 2010.

EPA, Design Manual, Phosphorus Removal, 1987.

Gebremariam, Seyoum Yami, et.al., Research Advances and Challenges in the Microbiology of Enhanced Biological Phosphorus Removal-A Critical Review, Water Environment Research, March 2011.

Jeyanayagam, Sam, “True Confessions of the Biological Nutrient Removal Process,” Florida Water Resources Journal, January 2005.

Jeyanayagam, Samuel, Leon Downing, “More efficient enhanced biological phosphorus removal,” Water Environment & Technology, November 2015.

Keller, Jeff, “Phosphorus Removal How To’s,” KY/TN Water Environment Association, Water Professionals Conference 2010.

Lan, J.C., “Phosphorus Release During Anoxic-Aerobic Digestion Process,” Jordan, Jones & Goulding, Inc, Atlanta, GA.

Miklos, Dan, W. James Gellner, Hazen & Sawyer, “BNR: An Operators Perspective,” Ohio Water Environment Association.

Minnesota Pollution Control Agency, Phosphorus Treatment and Removal Technologies, June 2006.

Moore, Larry, University of Memphis, Department of Civil Engineering.

Mulkerrins, D., et.al., “Parameters affecting biological phosphate removal from wastewaters,” Environment International, Volume 30, Issue 2, April 2004.

Oehmen, Adrian, et.al., “Advances in enhanced biological phosphorus removal: From micro to macro,” Water Research 41 (2007) 2271-2300.

Oleszkiewicz, Jan, et.al., “Options for Improved Nutrient Removal and Recovery from Municipal Wastewater in the Canadian Context,” Canadian Municipal Water Consortium, Canadian Water Network, March 2015.

Skalsky, D. S., Daigger, G. T., Wastewater solids fermentation for volatile acid production and enhanced biological phosphorus removal. Water Environment Research, 67 (2) 230-237, (1995)

Standard Methods for the Examination of Water and Wastewater, APHA, AWWA, WEF, 22nd Edition, 2012

Strom, Peter F., “Technologies to Remove Phosphorus from Wastewater,” Rutgers University, 2006.

Water Environment Federation, Nutrient Removal- MOP No. 34, 2010.

Wisconsin Department of Natural Resources, Study Guide-Phosphorus Removal.