Achieving Enhanced Biological P Removal: Have we forgotten how to design a bioP plant?

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ABSTRACT

Enhanced biological phosphorus removal (EBPR) is an attractive means for achieving effluent phosphorus (P) limits in municipal wastewater treatment plants. However, there is an industry perception that EBPR plants often do not achieve consistent and reliable performance. Several factors have been proposed as reasons for poor biological P removal performance: low organic strength wastewater, long solids residence time (SRT), insufficient anaerobic contact time, and nitrate recycles to the anaerobic zone. This paper proposes that a common reason for poor biological P performance in many cases is that plants have been designed with anaerobic zones that are too small. This contention is supported by the many examples of improved performance through interventions such as switching off mixers in the anaerobic zone or adding an additional fermentation zone (*e.g.* RAS fermentation). Data from research indicates that reliable and successful EBPR performance can be attained in plants with a mainstream anaerobic zone provided the anaerobic mass fraction is sufficiently large, probably in the range of at least 15% to say 25%. The paper recaps the role of the anaerobic zone in EBPR, and discusses the relevance of RAS fermentation and modeling of side-stream EBPR.

Keywords: Enhanced biological phosphorus removal (EBPR); anaerobic mass fraction; RAS fermentation

INTRODUCTION

Enhanced biological phosphorus removal (EBPR) is an attractive means for achieving effluent phosphorus (P) limits in municipal wastewater treatment plants. The alternative of P removal through chemical addition (*e.g.* ferric) has several drawbacks; these include increased excess sludge for disposal, dependence on availability of metal salts, and difficulties for P recovery. There is a perception in the industry that EBPR plants often do not achieve consistent and reliable performance. There are many examples where chemical polishing is needed to achieve effluent P limits, and therefore the advantages of EBPR often are lost. The performance of biological P systems is dependent on several factors including: influent wastewater characteristics, solids residence time (SRT) of the EPBR system, anaerobic mass fraction and contact time, nitrate load to the unaerated zones, and temperature.

A dominant factor in EPBR is the amount of readily biodegradable COD (RBCOD) and volatile fatty acids (VFA) available in the influent. As a result, it is difficult to achieve low effluent P in

EPBR systems when the organic strength of wastewaters is low, specifically when the influent COD to total phosphorus (TP) (COD:TP) and COD to Total Kjeldahl Nitrogen (TKN) (COD:TKN) ratios are low. Barnard *et al*. (2006) suggest that an influent COD:P ratio below 40:1 is a guideline for when P removal becomes difficult. This is particularly true for nitrifying systems – usually the case - because denitrification of nitrate recycled to anaerobic zones reduces the amount of RBCOD available for biological P removal. Several systems have been configured to help shield the anaerobic zone from recycled nitrate. These include the University of Cape Town (UCT) and Modified-UCT processes, the Modified Bardenpho process, and the Johannesburg process.

The impact of influent characteristics, SRT, nitrate recycles to the unaerated zone, and temperature are widely reported in the literature. However, there is little information on sizing of the anaerobic zone, and this remains empirical and experienced-based. A WRC (1984) manual is one of the few published guidelines for anaerobic sludge mass fraction based on raw COD strength in typical municipal wastewater. Based on the limited anaerobic zone sizing guidelines and the pressures to design smaller plants, it is not surprising that many systems in North America are designed with very small anaerobic mass fractions (*i.e.* < 10%).

The contention in this paper is that a major factor in the poor performance of many EBPR plants is a consequence of designing plants with anaerobic zones that are too small. As a result, very often interventions to increase the anaerobic mass fraction are sought after the plant is already designed; for example, switching off mixers in the anaerobic zone. This acts to retain mixed liquor solids in the anaerobic zone, thereby increasing the anaerobic mass fraction. Another partly-related idea on how to design for reliable EBPR is the concept of side-stream mixed liquor or RAS fermentation. Much of the recent literature, particularly in North America, has promoted this practice strongly. This paper discusses the role of RAS fermentation, and considers whether this is a robust technological approach.

In general, the intent of this paper is to review the role of anaerobic conditions in EBPR and discuss what considerations should be made for design of a sufficient anaerobic zone.

ROLE OF THE ANAEROBIC ZONE

Biological P removal is mediated by phosphorus accumulating organisms (PAOs) and is driven by the availability of volatile fatty acid (VFA) (preferably acetate). In the anaerobic zone VFA are sequestered by PAOs (and stored as PHA); this is linked directly to release of soluble phosphate from stored polyphosphate in the PAOs. In the subsequent aerobic (and anoxic) zone PAOs grow on stored PHA, with uptake of soluble phosphate to replenish the polyphosphate pool. The greater the anaerobic VFA uptake, the larger the PAO population. Figure 1 illustrates this traditional understanding of PAO interactions under anaerobic, anoxic and aerobic conditions. Figure 1 also illustrates the interactions and symbiotic behaviour of ordinary heterotrophic organisms (OHOs) where the OHOs produce VFA through fermentation of influent RBCOD and RBCOD derived from hydrolysis of particulate biodegradable COD (from the influent and from biomass decay). In this regard it should be recognized that the PAO population in a well-performing EBPR system likely is only 10 – 15 % of the total heterotroph mass.

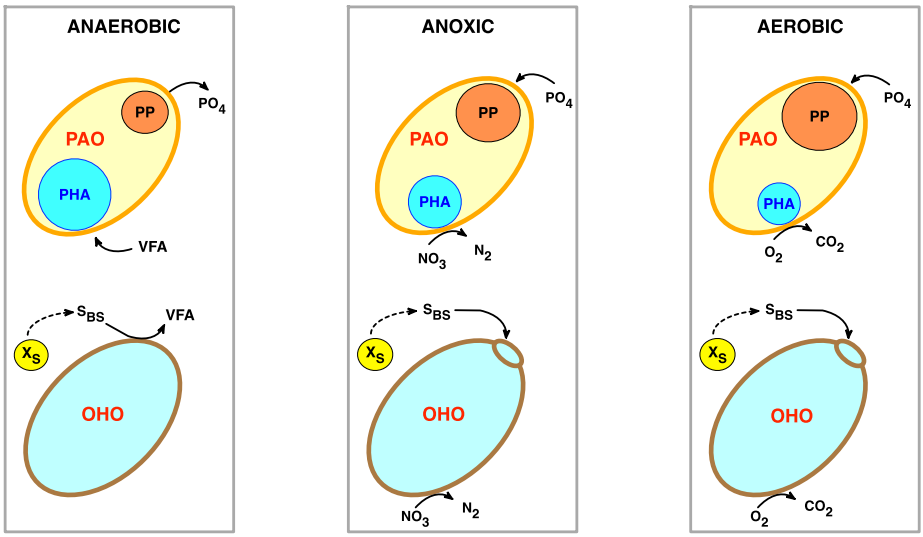

Figure 1: PAO and OHO interactions in anaerobic, anoxic and aerobic zones.

Rules-of-thumb indicate that removal of 1 mg P/L requires (i) 8 mg COD/L of acetate, or (ii) approximately 15 mg/L of RBCOD - substantially more than the 8 mg/L of acetate. This difference can be explained by recognizing that fermentation is a growth process. The yield (Y) of biomass in the anaerobic process is low compared to Y for aerobic growth; typically, Y = 0.10 mg biomass COD/mg COD utilized (*versus* 0.66 for aerobic growth). The stoichiometry of fermentation and the distribution of fermentation products depend on many factors, including dissolved hydrogen partial pressure. For low hydrogen partial pressure (typical for an anaerobic zone in a bio P system) fermentation pathways for 'typical' RBCOD components such as glucose indicate yields (all as COD fractions for 1 unit of RBCOD consumed) of:

- $Y_{BIOMASS} = 0.10$
- $Y_{H2} = 0.35$
- $Y_{ACETATE} = 0.55$

For 15 mg/L of RBCOD utilized in fermentation, the acetate production based on this stoichiometry would be 15 x 0.55 = 8.25 mg/L; hence the rules-of-thumb suggesting 8 mg/L of acetate or 15 mg/L of RBCOD for removal of 1 mg P/L.

Traditionally the anaerobic zone is at "the front end" of the process configuration. VFAs either enter with the influent (usually limited), or are generated within the anaerobic zone through fermentation of influent RBCOD mediated by OHOs. The amount of acetate from the influent and fermentation of influent RBCOD often is still insufficient for good P removal performance. A third and fourth source of VFAs within the anaerobic zone is through fermentation of RBCOD generated from hydrolysis of slowly biodegradable particulate COD (X_{SP}). The X_{SP} comes from the influent wastewater and from decay of active biomass.

In assessing particulate substrate hydrolysis as a source of RBCOD for fermentation and VFA production, several factors should be recognized:

- Hydrolysis of X_{SP} should not be regarded as a process that suddenly "switches on" as a source for generating VFAs. Hydrolysis of X_{SP} is occurring in the anaerobic zone in conjunction with other processes such as fermentation and VFA sequestration.

- X_{SP} from the influent is immediately available for hydrolysis, particularly in the anaerobic zone at the "front" of the process.
- The amount of influent X_{SP} remaining in the RAS is limited because the major portion has been utilized before the downstream end of the process.
- Organism decay is a slow process, so X_{SP} from this source is only available at a slow rate.
- Hydrolysis is mediated by heterotrophic organisms, so rates of hydrolysis increase with increasing mixed liquor concentration.
- Irrespective of where the VFAs are generated, to promote growth of PAOs and improve P removal, the VFAs must be combined with mixed liquor where the PAOs have internal stored polyphosphate. That situation enables VFA uptake with P release. [If 'excess' VFAs are produced, this may promote growth of undesirable organisms such as GAOs].

Two important factors regarding the sizing of the anaerobic zone in EBPR are:

- If the anaerobic zone is too small then fermentation of influent RBCOD may not be complete; and
- If the amount of influent VFA and RBCOD is limited, this supports the case for a larger anaerobic zone to promote hydrolysis of X_{SP} at a location where VFA production can enhance PAO growth.

BACKGROUND ON SIZING THE ANAEROBIC ZONE

One of the few published guidelines for sizing an anaerobic zone are those provided by the WRC (1984) based on raw COD strength in typical municipal wastewater. The guidelines are said to provide an initial estimate of anaerobic sludge mass fraction (F_{ana}) which should be checked and modified based on actual influent P, COD, and RBCOD concentrations:

- Influent COD strength < 400 mg COD/L, F_{ana} = 0.20 - 0.25
- 400 < Influent COD strength < 700, F_{ana} = 0.15 – 0.20
- influent COD strength > 700 mg COD/L, F_{ana} = 0.10-0.15.

For a given influent COD load, the size of the system essentially depends on the SRT. Most EBPR systems require nitrification and often nitrogen removal. Nitrification requires a certain aerobic SRT which depends on the maximum specific nitrifier growth and decay rates. Incorporating unaerated zones [anaerobic zones for P removal systems, and anoxic zones if N removal is also an objective] means that the total SRT for the system must be increased beyond the nitrification aerobic SRT. Design to achieve nitrification should be based on the kinetic parameters at the minimum operating temperature. The following simplified equation for estimating the SRT incorporates the effect of having an unaerated fraction (f_{UA}) of the mixed liquor (anaerobic plus anoxic); nitrifier growth takes place only in the aerated part of the process ($1 - f_{UA}$) but decay occurs in all zones. The equation should include a safety factor (S.F.) to make allowance for design uncertainties and diurnal loading variations.

$$SRT = \frac{1}{(1-f_{UA}).\mu_{T,min}-b_{T,min}}.(S.F.) \qquad [1]$$

The symbols $\mu_{T,min}$ and $b_{T,min}$ are the respective growth rate and aerobic decay rate of nitrifiers at the minimum plant operating temperature. [Note that the term "unaerated fraction" refers to the "unaerated **mass** fraction" and not the volume fraction. This distinction becomes important in systems where the MLSS concentration differs significantly from reactor to reactor. Examples of the latter are UCT-type configurations and MBR systems].

The nitrifiers are comprised of ammonia oxidizing bacteria (AOB) and nitrite oxidizing bacteria (NOB). The overall ammonia removal rate in nitrification essentially is determined by the AOB. Hence it is probably appropriate to apply the AOB parameters in the calculation of SRT. The values of $\mu_{T,min}$ and $b_{T,min}$ depend on temperature according to the following equations where θ is the Arrhenius value (θ = 1.072 for $\mu_{T,}$; θ = 1.029 for b_T):

$$\mu_{AOB,T} = \mu_{AOB,20°C}\theta^{(T-20)} \quad [2]$$

$$b_{AOB,T} = b_{AOB,20°C}\theta^{(T-20)} \quad [3]$$

Taking typical values, if $\mu_{AOB,20°C}$ is 0.9 d^{-1} and $b_{AOB,20°C}$ is 0.17 d^{-1}, then at 12°C, $\mu_{AOB,12°C}$ is 0.516 d^{-1} and $b_{AOB,12°C}$ is 0.135 d^{-1}. Assuming an unaerated fraction (f_{UA}) of 0.45 and S.F. of 2.5, the overall process SRT is calculated as follows:

$$\boldsymbol{SRT = \frac{1}{(1-0.45).(0.516)-0.135}.(2.5) \approx 16.8\ d} \quad [4]$$

Increased SRT translates into increased plant size (for a given operating MLSS). For that reason, designers would prefer a smaller unaerated zone. In design there are trade-offs between the size of the total unaerated zone and the SRT (which sets plant size), and the size of the anoxic *versus* anaerobic zone. A danger is that the anaerobic zone may be undersized to meet the biological requirements for sustaining strong PAO growth.

RESEARCH INSIGHTS ON SIZING THE ANAEROBIC ZONE

Possibly the most extensive compendium of research on EBPR performance is from data accumulated over many years at the University of Cape Town (UCT) [summarized in Wentzel *et al.*, 1990]. The work on systems treating municipal wastewater was conducted on a range of: (1) process configurations [Phoredox (A/O), 3-stage Bardenpho, UCT, Modified UCT, Johannesburg]; (2) SRTs (3 to 30 days); (3) anaerobic zone mass fractions from 9 to 50%; and (4) influent wastewater characteristics (COD, TKN/COD, RBCOD). An important feature of all this research was that influent was supplemented with extra phosphate so there was residual P in the effluent; that way the actual potential for P removal in each system could be assessed. Too often research on EBPR processes achieving low effluent P concentrations, perhaps is a result of low influent P, but has been reported as successful performance. Unless there is residual P in the effluent there is not an assessment of process capability.

Figures 2 and 3 show a broad-brush overview of the UCT data (*i.e.* TP removed *per unit influent COD versus* anaerobic mass fraction, and TP removed *per unit influent COD versus* SRT) with two clear outcomes:

- Long SRTs should be avoided. With long SRTs less of the influent P load is removed as synthesis P in the waste activated sludge (WAS), and therefore the amount of P to be removed through EBPR in the mainstream is increased.
- The synthesis P content of WAS is in the approximate range of 0.06 to 0.10 mgP/mg influent COD depending on SRT. The data in Figure 2 essentially demonstrate a linear increase in excess P removal with increasing anaerobic mass fraction, starting from an intercept in the range of 0.06 to 0.10 mgP/mgCOD.
- With typical municipal influent wastewater, an anaerobic mass fraction of less than approximately 12% likely is too small. In fact, an anaerobic sludge mass fraction of 20 - 25% is desirable to attain effective P removal of approximately 0.02 mgP/mgCOD in the influent.

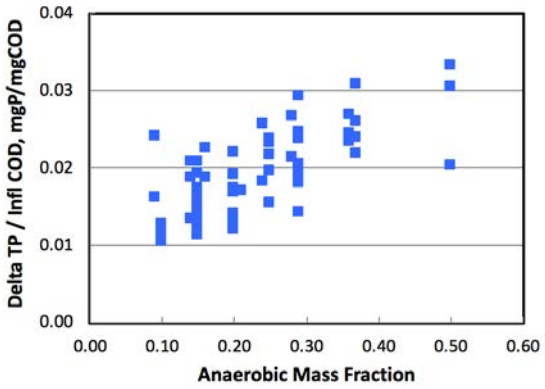

Figure 2: Effect of anaerobic mass fraction on P removed (delta P per unit influent COD) (from data of Wentzel *et al.*, 1990).

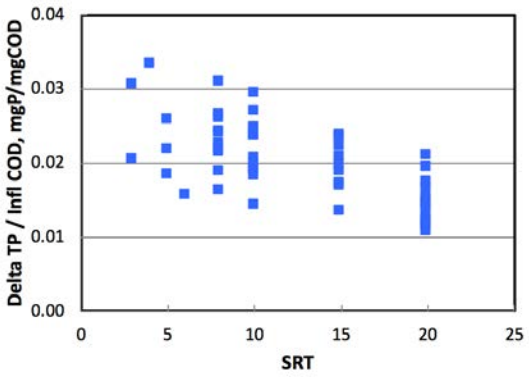

Figure 3: Effect of SRT (days) on P removed (delta P per unit influent COD) (from data of Wentzel *et al.*, 1990).

Many systems in North America have been designed with small anaerobic mass fractions (*i.e.* < 10%). For the case of typical influent wastewaters, it is not surprising that EBPR performance often has been disappointing. As a result, in many cases reported in the literature, interventions to improve EBPR by increasing the anaerobic mass fraction are sought after the plant is already in operation. An example is the Pinery treatment plant (Clark and Neethling, 2009). It was found that cyclic mixing of the anaerobic zone (mixed once daily for 30 minutes) improved VFA production

and P removal. Without mixing, the mixed liquor solids settled to the base of the anaerobic zone and thickened to a concentration greater than 10,000 mg/L compared to 2,500 mg/L in the anoxic and aerobic zone.

Several recent papers suggest that the reason for the improved performance from switching off mixers [or other approaches such as RAS fermentation] is to provide "*deep anaerobic*" conditions with low ORP (*e.g.* Barnard *et al.*, 2017). Avoiding ingress of oxygen through the liquid surface as a result of turbulence from too-intense mixing or oxygen entrainment should improve fermentation conditions. In this regard, two factors should be considered:

- For the case of on/off mixing, with settlement of biomass, a great proportion of the influent RBCOD will "pass over the top" of the settled sludge, and will not be exposed to fermentation.
- In all of the research at UCT the lab-scale anaerobic reactors were well-mixed. Liquid depths were approximately 20 - 30 cm. That implies an average liquid surface area to volume (SA:V) ratio of 20-fold the SA:V ratio in a full-scale anaerobic reactor 5 m deep. Obviously the propensity for surface oxygen transfer was far greater in the laboratory reactors compared to full-scale plants. However, the lab-scale systems achieved good EBPR provided the anaerobic mass fraction was sufficient.

It is agreed that any input of oxygen will have a negative impact on EBPR perhaps through impeding anaerobic fermentation, but more importantly as a result of consuming RBCOD and reducing the amount available for fermentation.

COMMENTS ON RAS FERMENTATION

Currently there is a push in the industry to make mixed liquor fermentation or RAS fermentation [given the acronym S2EBPR – side-stream EBPR] standard in design. Barnard and Kobylinski (2018) contend that "*… the evidence that side-stream fermentation is an essential part of creating the selective forces for more reliable EBPR is overwhelming"*.

RAS fermentation to improve EBPR apparently has been applied quite widely in parts of Europe. Vollertsen *et al.* (2006) reported that "*…nearly 30 Danish plants have since 1996 implemented anaerobic hydrolysis of RAS…*". To incorporate RAS fermentation, the anaerobic zone is moved from the main stream into the RAS stream, perhaps with only a portion of the RAS passing through the anaerobic zone. Initially approximately 4-7% of RAS was directed to a fermentation reactor with an HRT of 30-40 hours. More recent applications report 15-30% of RAS passing through the fermentation reactor with 5-16 hours HRT.

Figure 4 depicts the conversion of a standard 3-stage Bardenpho system (left) to a RAS fermentation mode (right). Each plant has the same reactor volumes, and a 50% RAS recycle. Each system has the same influent TKN/COD ratio of 0.07 mgN/mgCOD, and the SRTs are both 16 days. In the RAS fermentation mode, only 15% of the RAS is diverted to the RAS anaerobic zone (HRT ~ 40 hours) and the anaerobic mass fraction is essentially double that in the Bardenpho system. Simulating the two systems in BioWin 6.0 indicates the same P removal performance. The

main difference is the high concentration of soluble phosphate in the anaerobic zone of the RAS fermentation system.

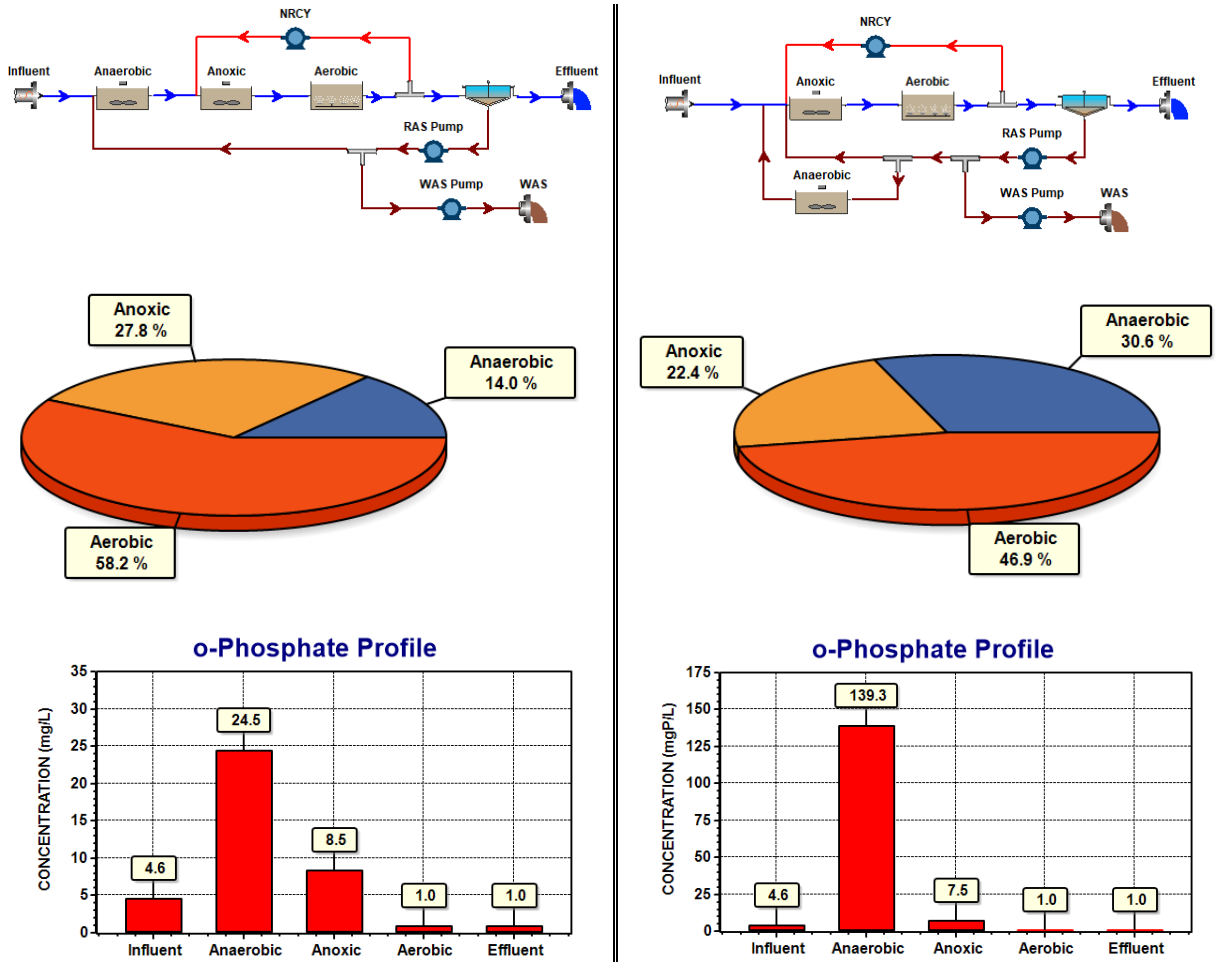

Figure 4: Converting 3-stage Bardenpho system (left) to RAS fermentation system (right)

Halving the anaerobic volumes in each system in Fig. 4 results in poorer effluent P for the Bardenpho plant, but this is the consequence of a too-small 7% anaerobic zone; the RAS fermentation zone is still 15% after halving the volume. It is interesting to note that in the side-by-side comparison of the Rock Creek plant reported in the WRF study (Gu *et al.*, 2019) the conventional A2O process only had a 7.5% anaerobic mass fraction *versus* an approximate fraction of 22% in the RAS fermentation system. In the first phase of that study (both anaerobic zones continuously mixed) the performance of the two parallel trains was very similar [effluent: 0.7 mgP/L for A2O; 0.6 mgP/L for RAS fermentation]. When intermittent once-per-week mixing was introduced in the RAS fermenter, that system performed slightly better than the conventional A2O plant [effluent: 0.7 mgP/L for A2O; 0.3 mgP/L for RAS fermentation]. It is suggested here that if the anaerobic zone in the conventional system had been sized appropriately at say 15%, then the performance of the conventional A2O system would have been far better than the RAS fermentation system for both phases. In fact, it appears that in all the studies comparing RAS

fermentation to conventional EBPR configurations, the conventional anaerobic fraction has never been sized appropriately for a proper comparison.

Several claims on the benefits of RAS fermentation have been proposed; for example:

- Protection from wet weather (*i.e.* temperature shocks, dilution, and reduced anaerobic retention time);
- Creation of a large anaerobic mass fraction without increasing reactor volume;
- Favoring the growth of a different PAO which can ferment (*Tetrasphaera* – discussed briefly later);
- Possible GAO suppression (Nielsen *et al.*, 2016);
- Barnard *et al.* (2017) and Barnard and Kobylinski (2018) claim that by removing the fermentation step out of the main plant flow, the need for favourable influent RBCOD/P concentration is removed from the equation. In fact, the claim is that side-stream fermentation arrangements make EBPR performance independent of influent wastewater characteristics.

Of these claims, the last one is the most interesting and controversial, because this would essentially mean that all prior EBPR process configurations should be discarded. However, this paper contends that availability of VFA still drives EBPR. Therefore, it is important to examine the sources for VFA generation in mainstream *versus* side-stream fermentation. Influent VFA and RBCOD, and most of the influent slowly biodegradable particulate COD (Xsp) essentially are not available in a RAS fermentation zone. All that is available to ferment in this zone is COD from biomass decay; that is, the RBCOD for fermentation comes from hydrolysis of slowly biodegradable COD derived from decay of biomass (of mainly ordinary heterotrophs). Figure 5 illustrates the concept of substrate uptake for biomass synthesis and the subsequent decay of biomass.

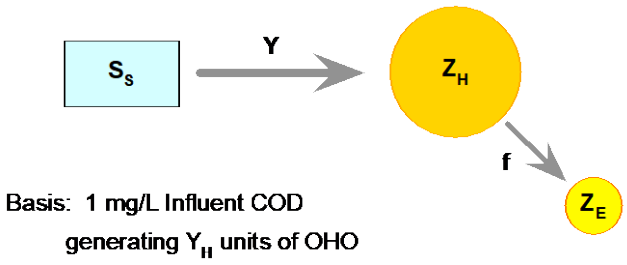

Figure 5: Substrate uptake for synthesis and the subsequent decay of biomass.

Assuming 1 mg/L of influent COD generates Y_H units of OHOs, the residual amount of active biomass remaining for a given SRT in COD units is [where b_H is the net endogenous decay rate, and R_S is the SRT]:

$$Z_{H,SRT} = \frac{Y_H}{(1+b_H.R_S)} \qquad [5]$$

The net amount of biomass removed through decay is:

$$\Delta Z_H = Y_H - \frac{Y_H}{(1+b_H.R_S)} = \frac{Y_H.b_H.R_S}{(1+b_H.R_S)} \quad [6]$$

A portion (f) remains as endogenous residue, and the net amount of substrate available from decay is given by:

$$\Delta S = (1-f)\frac{Y_H.b_H.R_S}{(1+b_H.R_S)} \quad [7]$$

Assuming an SRT of 10 days, the substrate available in RAS fermentation per unit influent COD is:

$$R_S\ 10\ days: \quad \Delta S = (1-0.2)\frac{0.67\ .0.24\ .10}{(1+0.24\ .10)} = 0.38\ mg/L \quad [8]$$

That is, only 0.38 mg/L of COD from the 1 mg/L of influent COD is available to ferment in the RAS fermentation system. Discarding the possibility to ferment the other 62% of the influent COD surely should bring into question the merits of RAS fermentation over a properly designed mainstream EBPR system.

Perhaps the claim that EBPR performance in systems with RAS fermentation is independent of influent wastewater characteristics appeared reasonable for a few cases. However, a full review of the potential impact of all influent wastewater characteristics has yet to be conducted. For example, the influent TKN/COD ratio has yet to be considered. Figure 6 shows the predicted effect of an increased influent TKN/COD ratio on EBPR in the RAS fermentation system of Figure 4. Increasing the influent TKN/COD ratio from 0.07 mg N/mgCOD to 0.10 mgN/mgCOD essentially results in a complete loss of biological P removal. This is a consequence of increased nitrate load to the RAS fermentation zone. The 3-stage Phoredox system is also impacted but not as severely since the mainstream anaerobic zone is able to take advantage of the influent RBCOD.

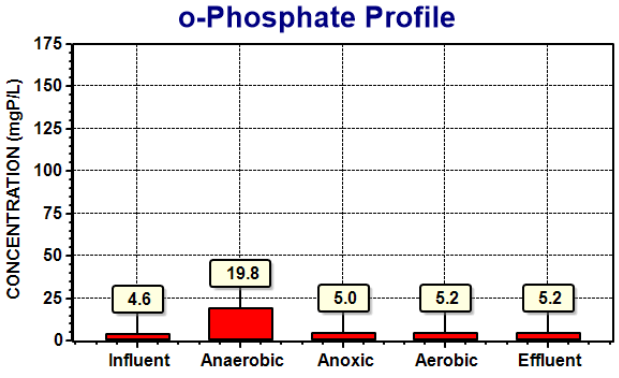

Figure 6: Predicted soluble phosphate profile in the RAS fermentation system with an influent TKN/COD ratio of 0.10 mgN/mgCOD

RAS FERMENTATION AND THE ROLE OF *TETRASPHAERA*

In recent EBPR research significant attention has been directed at the role of *Tetrasphaera* organisms; these are distinct from the "traditional" PAO - *Candidatus* Accumulibacter. This paper does not address this topic in detail, but at least recognizes the discussion of *Tetrasphaera* and points out a few potential conflicts in the information that has been presented.

Kristiansen *et al*. (2013) proposed mechanisms for the behavior of *Tetrasphaera* for anaerobic and aerobic conditions in EBPR systems:

- Anaerobic: Fermentation of glucose and synthesis of glycogen using energy generated from substrate fermentation and degradation of polyphosphate (*i.e.* phosphate release).
- Aerobic: Consumption of glycogen for biomass growth and accumulation of polyphosphate (*i.e.* phosphate uptake).

Barnard *et al.* (2017) imply that the so-called "deep anaerobic" conditions [with on/off mixing or RAS fermentation] will favour the growth of *Tetrasphaera*. Several sources have reported on the relative abundances of *Ca.* Accumulibacter and *Tetrasphaera* in full-scale plants. Although there is no consensus on the difference in populations, certain cases have reported that *Tetrasphaera* have been more abundant (Nguyen *et al*., 2011) and play a bigger role in EBPR than *Ca.* Accumulibacter. In the side-by-side studies of Gu *et al.* (2019) at Rock Creek there was no significant difference in the measured relative abundance of *Tetrasphaera versus Ca*. Accumulibacter in the conventional A2O and RAS fermentation processes.

There still appears to be a great deal of uncertainty over the specific role of *Tetrasphaera* in EBPR systems. Further research is needed to clarify a number of apparent conflicts; these include:

- Regarding the abundance of *Tetrasphaera* relative to Accumulibacter, at least one recent reference (Rubio-Rincon *et al*., 2019) has identified conflicts in the different quantification procedures.
- Regarding the implied importance of *Tetrasphaera* specifically in RAS fermentation systems, Lanham *et al.* (2013) conducted side-by-side anaerobic-aerobic batch tests on sludge from two A2O plants and two plants with RAS fermentation. All four tests showed similar phosphate release and uptake patterns. Also, the glycogen responses in all four tests showed the same decrease in concentration during the anaerobic phase followed by an increase during the subsequent aerobic phase. That glycogen response corresponds to the expected profile with Accumulibacter, and is the reverse of the response expected with *Tetrasphaerea*. In all four of these systems it seems to indicate that the polyphosphate storage was related to Accumulibacter.
- Significant attention has been directed at the ability of *Tetrasphaera* to denitrify with simultaneous phosphate uptake under anoxic conditions. The information is presented seemingly to imply that Accumulibacter cannot denitrify with simultaneous P uptake. However, it is well established that Accumulibacter can denitrify with simultaneous polyphosphate storage. For example, Kuba *et al.* (1993) operated two acetate-fed SBRs, one with an anaerobic-aerobic sequence and one with an anaerobic-anoxic sequence where nitrate was added in place of oxygen. The anaerobic-anoxic SBR exhibited stable P removal and performed essentially the same as the anaerobic-aerobic SBR. Vlekke *et al.* (1988) demonstrated the same behavior in side-by-side SBRs, but with municipal

wastewater influent. Barker and Dold (1996) reviewed data demonstrating denitrification behavior in many EBPR systems and concluded that a significant portion of Accumulibacter PAOs can use nitrate as an electron acceptor with simultaneous uptake of phosphate.

- Significant attention has also been directed at the importance of *Tetrasphaera* being able to ferment. However, in full-scale EBPR systems the PAOs comprise only 10 – 15 % of the total heterotroph mass. The bulk of the fermentation is performed by the OHOs, and whether or not PAOs contribute to fermentation probably is not significant.

IMPLICATIONS FOR MODELING

The EBPR modeling approach based on Accumulibacter behavior (*e.g.* BioWin) has been widely criticized as deficient for modeling side-stream systems. If a different PAO species such as *Tetrasphaera* is shown to be important in certain EBPR configurations, then it will be necessary to modify and extend the single-PAO models. Also, if it is shown that the behavior in "deep anaerobic" conditions of S2EBPR systems differs from that in conventional system anaerobic zones, then it may also be necessary to adjust the existing models. In fact, currently in BioWin the hydrolysis rate in anaerobic digesters is higher than in activated sludge anaerobic zones. Perhaps this indicates a need to adjust hydrolysis rate for different intensities of anaerobiosis.

Models and model development are data-driven. For example, the extensive data set on EBPR developed at UCT provided a good basis for developing models for conventional EBPR systems. Those systems were operated under closely controlled conditions (temperature, SRT, recycle rates, DO concentrations, *etc*.) and were monitored very extensively (nitrate, phosphate, COD concentrations in all reactors; oxygen uptake rates, influent wastewater characteristics, *etc.*). Many systems were operated at constant flow and load (steady state) and others were operated under carefully controlled dynamic loading. To develop and test models for S2EBPR systems requires far more extensive data than that which has been provided in the literature to date.

AN EBPR SUCCESS STORY

One example of a well-functioning EPBR plant is the Southwest Water Reclamation Facility in the City of St. Petersburg (Florida). The Southwest WRF achieves effluent total inorganic nitrogen (TIN) and (TP) concentrations of approximately 2.0 mg N/L and 0.5 mg P/L, respectively, at an average influent TKN/COD of 0.14 and with mixed liquor summer temperatures reaching 30°C (Jimenez *et al.*, 2014). The Southwest WRF facility incorporates a very simple anaerobic – aerobic (A/O) design with no dedicated anoxic zones, a single recycle (RAS) and operates at low DO (*i.e.* between 0.1 – 0.4 mg/L), with a 24% anaerobic mass fraction, and at short SRT (total and aerobic SRT of 5 days and 3.5 days, respectively). A flow diagram of the Southwest WRF is illustrated in Figure 7. Figure 8 illustrates the final effluent TP concentration and mixed liquor temperature over a ten-month period in 2013.

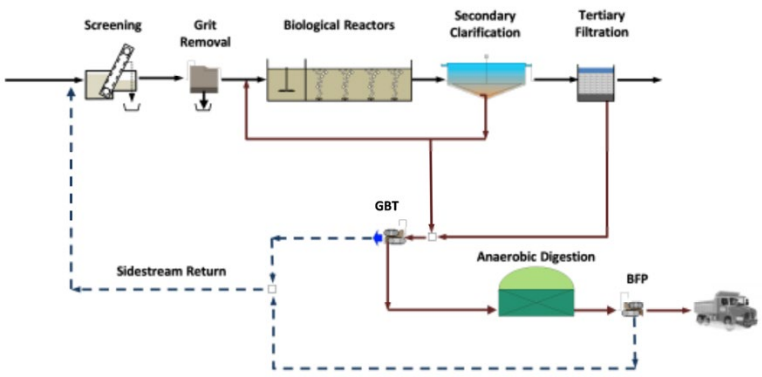

Figure 7: Flow diagram of St. Petersburgh Southwest WRF (from Jimenez *et al.*, 2014).

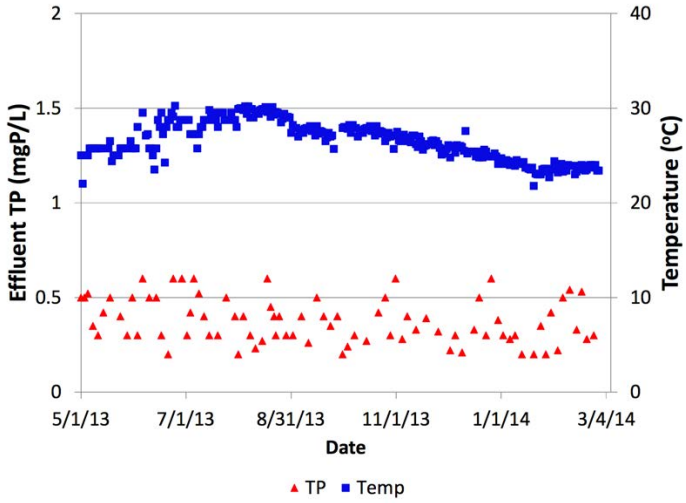

Figure 8: Southwest WRF final effluent TP and mixed liquor temperature (from Jimenez *et al.*, 2014). [Effluent TSS = 5-12 mg/L].

CONCLUSIONS

The paper concludes that reliable and successful EBPR performance can be attained in plants with a mainstream anaerobic zone provided the anaerobic mass fraction is sufficiently large, probably in the range of at least 15% to say 25%. There are many examples where EBPR systems treating typical municipal wastewater in North America are being designed with anaerobic zones that are too small. An effective option for modifying poorly performing systems may be as simple as increasing the anaerobic reactor size rather than making extensive process changes.

Currently there is a push in the industry to make mixed liquor fermentation or RAS fermentation [given the acronym S2EBPR – side-stream EBPR] standard in design. RAS fermentation may offer certain advantages including (a) protection from wet weather (temperature shocks, dilution and reduced anaerobic retention time), (b) increasing anaerobic mass fraction; (c) and possible GAO suppression. However, the paper identifies potential issues with RAS fermentation. Most

importantly, that it relies on only one source of fermentable substrate - from hydrolysis of biomass decay products. Biodegradable influent COD is largely not used to facilitate EBPR.

The paper notes that S2EBPR has only be tested for a limited range of conditions, often under poorly controlled situations. As a consequence, there is only limited information for checking, verifying, and/or developing process simulation models. It is suggested that substantially more data for systems operated under closely controlled conditions is needed for this task. Such data will also provide important insights into whether S2EBPR is essential for stable EBPR. Additionally, such data will identify possible difficulties with S2EBPR. Modeling results presented in the paper, albeit with the existing one-PAO model in BioWin, indicate complete loss of EBPR in a particular side-stream configuration if influent TKN/COD is greater than 0.1 mgN/mgCOD. The impact of factors such as influent TKN/COD ratio have not been evaluated rigorously in practice.

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