

Factors Affecting Enhanced Biological Phosphorus Removal

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Abstract

Process upsets and the deterioration of P removal in enhanced biological phosphorus removal (EBPR) plants has occurred in the laboratory as well as in full-scale wastewater treatment plants. Successful operation of the EBPR depends on numerous process operational factors such as carbon source, COD/P ratio, temperature, pH, cations, dissolved oxygen, solid retention time, secondary phosphorus release. To optimize the EBPR effective and robust, it should be focused factors influencing the competition polyphosphate accumulating organisms (PAO) and glycogen accumulating organisms (GAO) in EBPR systems. In this review, factors influencing EBPR are discussed.

Key words: Enhanced Biological Phosphorus Removal (EBPR), carbon source, temperature, pH.

1. Introduction

Enhanced biological phosphorus removal (EBPR) is accepted as one of the most economical and environmentally sustainable processes to remove phosphorus (P) from wastewater. EBPR can be achieved through an activated sludge process by re-circulating sludge through anaerobic and aerobic conditions and when all of the influent is directed to the anaerobic portion. The group of microorganisms that is largely responsible for phosphorus removal, i.e. polyphosphate accumulating organisms (PAOs), are enriched in wastewater treatment systems. In the anaerobic phase, carbon substrates such as acetate are taken up and converted to polyhydroxyalkanoic acids (PHA). Concurrently, internally stored polyphosphate and glycogen are degraded to provide required adenosine triphosphate (ATP) and reducing power, which results in an increase of orthophosphate concentration in bulk solution. In the subsequent aerobic phase, where no external carbon source is present, the internally stored PHA is oxidized and used for cell growth, polyphosphate production from orthophosphate, and glycogen synthesis from PHA. The net phosphorus removal can be achieved by wasting excess sludge of high P content because the aerobic phosphorus uptake is greater than the anaerobic phosphorus release.

When operated successfully, the EBPR process can be an inexpensive option to reach relatively high phosphorus removal efficiency (effluent phosphorus concentrations less than 1 mg/L). However, the stability and reliability of EBPR can be a problem. It is widely known that EBPR plants may experience process upsets, deterioration in performance. Certain environmental and operational factors have been identified to influence EBPR, which include carbon source, COD/P ratio, temperature, pH, cations, dissolved oxygen, solid retention time, secondary phosphorus release. Thus, it becomes extremely important to evaluate factors that influence the stability and reliability of the EBPR systems. The objective of this paper is to review factors affecting EBPR.

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2. Factors Affecting Enhanced Biological Phosphorus Removal

2.1. Carbon source

The success of activated sludge plants for EBPR depends on carbon availability in the form of readily biodegradable COD or VFAs. Choice of substrate or carbon source is critical to the EBPR process economics as influenced by the cost of the carbon source and the selective use of the carbon source of PAOs against GAOs [1].

Most previous studies focused on EBPR systems have used acetate as the sole carbon source. Recently, however, there has been an increased interest in the impact of propionate and other substrates on EBPR performance [2].

While the use of acetate as a carbon source in EBPR systems has been often documented to yield robust and stable P removal performance, there are also many reported occasions where the P removal deteriorated due to what is believed to be microbial competition of GAOs with PAOs [2]. Recent studies have suggested that propionate may be a more favourable substrate than acetate for successful EBPR performance [3,4,5,6,7,8].

VFAs other than acetate and propionate (such as butyrate, lactate, valerate and isovalerate) can also be taken up by PAOs and/or GAOs [9,10,11,12,13]. The effect of these substrates on the PAO–GAO competition is currently unclear.

The most widely studied carbon substrate other than VFAs, has been glucose. Successful EBPR operation has been achieved in some studies fed with glucose as the carbon source [14,15,16,17]. However, the deterioration of EBPR systems has frequently been observed when glucose is fed as the carbon source [14,18,19,20].

2.2. COD/P ratio

The influent COD or BOD to total phosphorus ratio (influent COD:P or influent C:P) is crucial for proper design and operation of the phosphorus removal systems. For the removal of each P unit, there is a stoichiometric requirement of COD. Whether a system is limited by COD (or BOD) or phosphorus determines the extent to which PAOs can function, and the amount of excess phosphorus can be taken up from the solution. Oehmen et al [2] stated that PAOs tend to dominate at COD:P ratios of 10-20 mg-COD/mg-P whereas GAOs tend to dominate at COD:P ratios >50 mg-COD/mg-P. Thus, maintenance of optimum COD:P ratio, as well as good control over the operational conditions, is required to utilize the competition for substrate between PAOs and GAOs provide a positive outcome. On the other hand, a sufficient amount of VFAs has to be provided in order to achieve good P removal.

2.3. Temperature

In EBPR systems, a lower temperature has been observed to decrease the rates of biochemical

transformations (e.g. P release/uptake, acetate uptake, PHA oxidation, growth), as is the case in most biological reactions [21]. Moreover, low temperatures have been found to improve EBPR performance in some lab-scale studies [22,23,24]. This improved performance has been hypothesised to be due to a shift in the microbial community from GAOs to PAOs. Whang and Park [22] showed that an SBR exhibited good EBPR performance at 20 °C, while another SBR operated at 30 °C exhibited a lower level of P release and uptake with higher anaerobic acetate uptake. High temperatures have an adverse effect on phosphorus removal due to the increasing impact of GAOs. GAOs can predominate at higher temperatures because of their increased ability to uptake acetate at those temperatures, compared to PAOs [22]. This implies that competition by GAOs with PAOs in EBPR plants may be more problematic in warm climates, and during the summer months.

2.4. pH

pH strongly influences the PAO–GAO competition, and an increase in pH can improve P removal performance by selecting for PAOs over GAOs. It has been postulated that an anaerobic pH of 7.25 is a critical point, whereby GAOs are able to anaerobically take up VFA faster than PAOs below a pH of 7.25, and PAOs take up acetate faster above this pH value [25]. Several studies have indeed shown higher P removal when the anaerobic and/or aerobic pH level was increased (from pH 7 to 7.5–8.5) [26,27]. The reason for the improved performance was hypothesized to be from a shift in the microbial competition from GAOs to PAOs. This hypothesis has been supported through assessing population changes in the microbial community. In the study of Zhang et al. [28] a complete loss of phosphate-removing organisms was observed when the pH was decreased from 7.0 to 6.5; at the same time a shift in the microbial population was also observed.

In some studies, a decrease in the VFA uptake, P release and P uptake rates have been observed at pH values above 8.0 [26,29,30]. Therefore, an upper limit for pH should be also considered. It should also be noted that the fraction of P removed via biologically induced chemical precipitation increases with increasing pH [31].

2.5. Cations

The cation concentration and composition of the influent wastewater plays an important role in maintaining the stability of the enhanced BPR process and in the binding mechanisms of phosphorus in the activated sludge [32]. Because each phosphate molecule (PO_4^{-3}) contains three negative charges, it is unable to pass through the cell membrane on its own. To pass through the cell membrane, the phosphate molecule must bond with positively charged ions such as magnesium (Mg^{+2}) and potassium (K^+). Once the phosphate molecule bonds with these charged ions, it becomes neutral and can be transported across the cell membrane. Experiments have shown that magnesium and potassium are essential cations for BPR rather than just providing charge neutralization, whereas calcium and other cations that might become involved are not essential [33].

The release of phosphate from PAO cells is a critical step in the anaerobic zone of BPR wastewater treatment systems. The phosphate will not be released in the anaerobic zone once either magnesium or potassium is depleted, and BPR will cease. It can be assumed that municipal wastewater contains an excess of K^+ and Mg^{2+} and that ion limitation of the enhanced BPR process is unlikely to occur [34]. However, full-scale sewage treatment plants designed for EBPR may periodically experience short- or long-term shortage of potassium in the influent, while excess potassium strongly influences the properties of activated sludge, and results in the poor dewatering property and effluent quality [35].

2.6. Dissolved oxygen

When dissolved oxygen is present in the anaerobic zone, heterotrophic aerobic organisms can use the oxygen as the electron acceptor and will compete with the PAOs for VFAs. This results in less VFA storage and, subsequently, less BPR.

PAOs need oxygen to digest the storage products and uptake and retain phosphorus in the aerobic zone. A study by Brdjanovic et al. [36] revealed that excessive aeration negatively affects the BPR process as cessation of P-uptake occurs due to depletion of poly-hydroxy-butyrate (PHB) in an over-aerated process. The DO concentration has also been hypothesized to affect the competition between PAOs and GAOs, therefore impacting EBPR performance [35]. In this study, the DO concentration was adjusted in numerous full-scale wastewater plants and changes in process performance were identified. The abundance of PAOs and tetrad forming organisms (TFOs) in the sludge was assessed using staining techniques, and it was found that poor P removal performance and a high number of TFOs were more frequently observed at very high DO concentrations of 4.5–5.0 mg/L, while DO concentrations of approximately 2.5–3.0 mg/L seemed to correlate with a greater abundance of PAOs. When a high DO containing stream (i.e., 5 mg/L) is returned back from the aerobic zone to the anaerobic zone it may adversely affect EBPR performance regardless of PAO and GAO competition.

2.7. Solid retention time (SRT)

SRT has been indicated as one parameter that can influence the EBPR performance and the competition between PAOs and GAOs. It was demonstrated that the increase of SRT could lead to the decrease of biomass yield and excess sludge discharged, which reduced the P removed by discharging excess sludge [36].

Randall et al. [34], however, reported that the phosphorus content in biomass increases but phosphorus removal efficiency did not change as SRT increases. Additionally, Barnard [39] reported that SRT plays a smaller role in phosphorus removal in practice than expected in enhanced biological phosphorus removal (EBPR). Mamais and Jenkins [40] showed that there is a washout SRT for all temperatures over the range 10 to 30°C. It clearly indicates that, if the SRT-temperature combination is below a critical value, EBPR ceases before other heterotrophic functions.

The mechanisms leading to washout or cessation of EBPR activity before other heterotrophic functions halt was investigated by Erdal et al. [23,41], and after examining the underlying biochemical methods, they showed that the main effect of system SRT in EBPR systems is on the PHA and glycogen polymerization reactions. A more recent study from Li et al [42] has reported performance degradation and worse settleability of the sludge when the SRT was increased from 8 to 16 days. In summary, there is still a lot of apparent contradiction about the effect of SRT on EBPR performance.

There are also very few studies that have tried to determine the effect of the SRT on the competition between PAOs and GAOs. Seviour et al. [43] reported that GAOs could successfully compete with PAOs at a long SRT, which resulted in the decrease of phosphorus removal in EBPR system. Rodrigo et al. [44] concluded that shorter SRT are beneficial for PAO after observing that the EBPR biomass activity decreased as the SRT was extended, suggesting that GAO may tend to dominate at longer SRT. In an acetate-fed lab-scale reactor operated at 30 °C and pH 7.5, Whang and Park [45] observed the switch in the dominant microbial population from an enriched-GAO to an enriched-PAO culture when lowering the applied SRT from 10 to 3 d. Whang et al. [46], through a model-based analysis, inferred that, under the operating conditions applied by Whang and Park [45], GAO had a lower net biomass growth rate than PAO and, therefore, were outcompeted after the SRT was shortened. However, those studies do not provide further details related to the effect of SRT on the population dynamics and microbial and biochemical mechanisms involved. Moreover, considering the temperature applied by Whang and Park [45] of 30 °C, their observations may not represent the scenario at ambient temperatures similar to those at full-scale facilities. Although studies regarding the minimum anaerobic and aerobic SRT of PAO are available in literature [47,48], no data concerning the effect of SRT on GAO cultures have been reported.

2.8. Secondary phosphorus release

Release of phosphorus, as described in earlier sections, under anaerobic condition with simultaneous uptake of acetate, and its storage as PHB, is called the *Primary Release* [49]. However, phosphorus is also released from stored polyphosphate under anaerobic conditions even in the absence, or inadequate presence, of VFA in order for the microorganisms to derive sufficient energy for maintaining their metabolic activities. This is called the *Secondary Release* of phosphorus [50]. Secondary release takes place at a much slower rate than the primary release. Phosphorus resulting from the secondary release mechanism is not removed under a subsequent aerobic or anoxic environment due to the unavailability of stored PHB. Therefore, secondary release should be avoided as much as possible because it adversely affects the performance of an EBPR process.

A very common location for secondary release of phosphorus in an EBPR plant is in the secondary clarifier(s). If the sludge blanket in secondary clarifier is deep, or the sludge is not removed from the clarifier bottom on a regular basis, the resulting anaerobic environment leads to secondary release.

Another possible location is in the upfront anaerobic compartment of an EBPR activated sludge plant. If the anaerobic compartment volume is too large, and HRT is much longer than the time needed for the fermentation of the incoming COD then secondary release can take place in the anaerobic compartment. On the other hand, if the compartment volume is too small then the incoming COD may not have adequate HRT for fermentation to acetic acid, which is a precursor to the formation of PHB as the storage product. In this case, the stored PHB may not be adequate to supply the energy necessary for the subsequent aerobic uptake of orthophosphate over and above that released by the primary mechanism. Inadequate amount of PHB limits the capacity of the PAO cells to uptake all the released orthophosphate in the subsequent aerobic or anoxic compartment.

3. Conclusions

EBPR is one of the most widely studied biological wastewater treatment processes due to its role in the control of nutrients discharged to the aquatic environment in a manner that is cost effective and free from usage of chemical. Many full scale plants demonstrate excellent phosphorus removal performance under stringent discharge limits on a consistent basis but they are not free from occasional process upsets, potentially resulting in permit violations. However, it is still not totally known how certain environmental and operating conditions influencing the stability and reliability of the EBPR systems. It becomes extremely important to find and suggest strategies and control measures to favour the development of PAO and suppress the growth of GAO in EBPR activated sludge systems.

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