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A novel storage driven granular post denitrification process: Long-term effects of volume reduction on phosphate recovery

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HIGHLIGHTS

- New storage driven granular post-denitrification process was successfully validated.
- The process enabled P recovery at > 100 mg-P/L in a single sequencing batch cycle.
- Both DPAOs and DGAOs contributed towards the N removal and concentration of P.
- Food to microorganism ratio (F/M) affected sludge settling & dewaterability.
- Proper control of F/M ratio is critical for efficient P recovery & denitrification.

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ABSTRACT

Anoxic granular biomass with enhanced biological phosphorus (P) removal was used in a post-denitrification configuration to concentrate P in wastewater. The study examined the use of anoxic granules to facilitate application of volume reduction to create a P-enriched stream (> 100 mg-P/L). The results indicated the importance of maintaining a food to microorganism (F/M) ratio of ~0.124 g-COD/g-MLSS.d to achieve P and nitrogen (N) removal close to 100%. While granulation required a short settling time and a high-volume exchange ratio, biomass wasting was essential to control the F/M ratio to maintain a suitable microbial diversity and abundance. Diversity and abundance were also impacted by volume reduction, but the effect of this was marginal compared with the effect of decreasing F/M ratio. Furthermore, a decrease in the F/M ratio enhanced sedimentation (SVI_5 decreased from 55.5 to 32.0 mL/g-MLSS) but decreased dewaterability (capillary suction time increased from 15.5 s to 19.4 s). Recovery of P as a concentrated liquor had minimal impact on the bacterial diversity.

1. Introduction

Phosphorus (P) is a non-renewable element that is essential for life. With increasing demand for P fertilisers, there is a push towards recycling of P from waste streams such as municipal wastewater [1]. However, as P concentration in municipal wastewater is typically low (< 10 mg/L), recovering P directly from the water is economically challenging [2]. To achieve economies of scale, the P concentration in wastewater needs to be elevated. Recently, biological strategies have been developed to create P concentrated side streams, enabling recovery of P as a chemical precipitant such as struvite (NH_4MgPO_4) or calcium phosphate ($Ca_3(PO_4)_2$) [3].

The biological P-concentrating strategies developed so far have exploited the metabolic pathways of a group of microorganisms naturally abundant in activated sludge [4]. This group of microorganisms, which can store P in excess of their growth and metabolic requirements, are broadly termed phosphate-accumulating organisms (PAOs). Under aerobic (oxygen as a final electron acceptor) or anoxic (nitrate or nitrite as final electron acceptors) conditions, PAOs are able to take up and store P as polyphosphate (poly-P). The energy requirements for this process is derived from the oxidation of intracellular carbon reserves (polyhydroxyalkanoates (PHA)) [5,6]. PAOs that utilise nitrate or nitrite as final electron acceptors are often called denitrifying-PAOs or DPAOs. When PAOs/DPAOs are exposed to anaerobic conditions in the presence of volatile fatty acids (VFAs, e.g. acetate), they can take up the VFAs and replenish their carbon reserves. The beneficial aspects of

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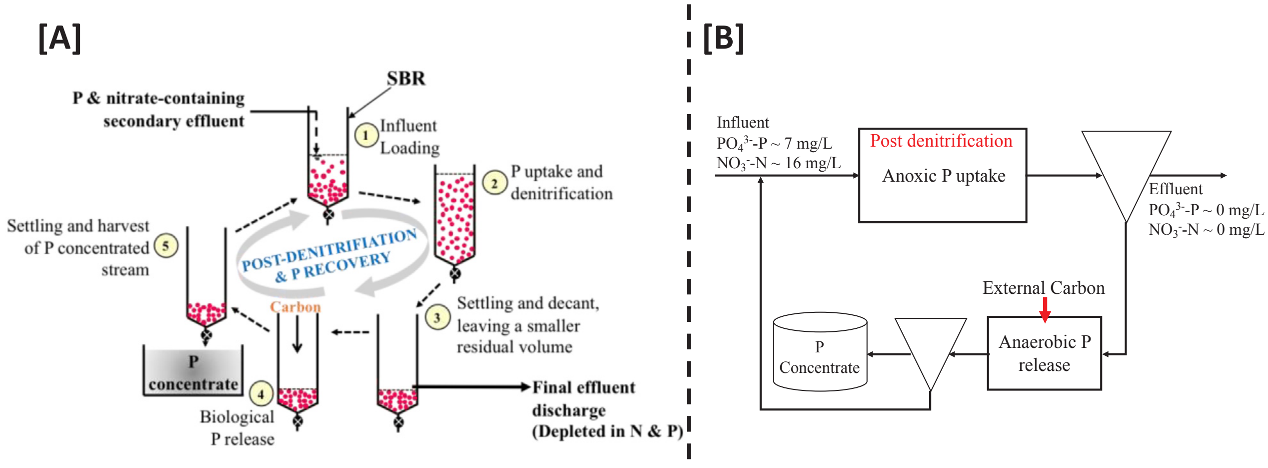

Fig. 1. [A] A step-wise illustration of an operational SBR cycle. [B] A schematic illustration of the post denitrification and P recovery process.

using VFAs over other carbon to facilitate anaerobic P release is well demonstrated [7]. The energy requirements to uptake carbon are fulfilled by poly-P hydrolysis, which releases P as phosphate (PO_4^{3-}) to the surrounding water. The P uptake-release ability of PAOs/DPAOs has been exploited to concentrate P in wastewater, improving the economies of scale to recover P from municipal wastewater [8–10].

Wong et al. [10] exploited the metabolism of DPAOs, demonstrating a new post denitrification configuration to facilitate removal of nitrate and recovery of P from municipal wastewater. This new configuration, termed as Enhanced Biological Phosphorus Removal and Recovery (EBPR-r), unlike conventional post denitrification processes utilised intracellular carbon reserves of a biofilm to remove P and nitrate from wastewater. This utilisation of internal carbon was advantageous in preventing discharge of carbon with effluent. The replenishment of internal carbon reserves and recovery of phosphate from the biofilm were facilitated by allowing the biofilm to release P into a separate recovery stream, which is several times smaller in volume compared to the wastewater stream. This enabled Wong et al. [10] to recover P in a separate liquor where P was 4 times higher in concentration compared to the P concentration in the wastewater.

Recently, Kodera et al. [11] demonstrated a similar volume reduction approach with an aerobic PAO biofilm grown in a trickling filter reactor. They successfully created a P recovery stream that was 25 times the concentration of P in the influent wastewater. Increasing the P recovery concentration further was challenging for Wong et al. [10] and Kodera et al. [11] primarily due to the large volume occupied by the biofilm carrier media. The large carrier media volume prevented a further reduction of recovery volume and averted achievement of much higher P concentrations in the recovery stream. As such, the only viable option for both studies was to repeatedly re-use its recovery volume to continue capture P released from the biofilm, until such time the desired P concentration was achieved in the recovery liquor.

A possible strategy to overcome the abovementioned limitation of biofilm carrier media to concentrate P is to utilise granular biomass. The high biomass densities and the excellent settling and dewatering properties of granular biomass may help minimise the recovery volume enabling recovery of P at elevated concentrations. The separation of the concentrated liquor from the granular biomass was also expected to be effective [12]. Additionally, the high biomass density in granular sludge may facilitate a higher P and N removal efficiency, enabling treatment of a large volume of wastewater with a single exposure to the granular sludge. While this would facilitate a smaller footprint, it is also likely to further increase opportunity to achieve a highly concentrated P liquor in the recovery stream without the need for a repeated re-use of the recovery volume to capture P.

Having realised the potential of granular sludge, Lu et al. [13] operated a granular sludge reactor to facilitate simultaneous nitrification, denitrification and P removal (SNDPR), and attempted to recover P from the granular biomass by exposing part of the biomass to acetate under anaerobic conditions. The granular biomass was subsequently separated from the concentrated P liquor and returned back into the main reactor with the use of a woven cloth [13]. Although a technology based on a woven cloth appears impractical for full-scale implementation, the study clearly demonstrated the ease of dewatering granular biomass to recover the concentrated P liquor. Without considering volume reduction, several other studies also have examined P recovery from wastewater using granular biomass [14–16].

To our knowledge, no study has explored the use of volume reduction to recover P as a concentrated liquor using granular sludge. The feasibility of this approach and its long-term implications on granular sludge warrant investigation if the wastewater industry is to capitalise from the beneficial properties of granular biomass to recover P from municipal wastewater. Therefore, this study investigates P recovery with post denitrification, using a granular biomass. A granular sequencing batch reactor (SBR) was operated to facilitate P and nitrate removal from an influent wastewater volume that was maintained constant throughout the study. The anaerobic recovery of P from the granular biomass into a small recovery stream was systematically studied over a long-term period (250 days), by gradually increasing the volumetric ratio between the wastewater and the recovery stream. The long-term performance and stability of the reactor was monitored using physiochemical and microbiological measurements.

2. Materials and methods

2.1. Reactor start-up and SBR operation

The SBR used in this study had a working volume of 3.7 L and was operated at room temperature (20–22 °C). The operational cycle (8 h) of the SBR is depicted in Fig. 1[A] and consisted of (1) a 5 min nutrient loading, (2) a 6 h anoxic P uptake and denitrification period, (3) a 20 min settling and a 5 min period of decant (2.8 L), (4) a 1 min feed of carbon source and a subsequent 2 h period of anaerobic P release, and (5) a 10 min settling and recovery of P as a concentrated liquor (recovery of P was carried out only during Phase 5 of the long term reactor operation). At the beginning of steps (2) and (4), nitrogen was sparged as required into the reactor to create anaerobic conditions (dissolved oxygen (DO) 0 mg/L). Apart from during settling and decanting, the liquor in the reactor was gently mixed (100 rpm) using an overhead stirrer (RZR2020, Heidolph, Germany). The hydraulic retention time of the SBR reactor was maintained at 10.2 h. The granulation of biomass was facilitated by applying a high volumetric exchange ratio (78%) at