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# Controlled crude glycerol dosage to prevent EBPR failures in C/N/P removal WWTPs

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## HIGHLIGHTS

- A controlled addition of crude glycerol can improve biological N and P removal.
- JHB performed better than $A_2/O$ under open loop even with $NO_X$ disturbances.
- P was properly controlled in JHB with 18% less crude glycerol dosage than in $A^2/O$.
- Two novel control extensions improve the slow dynamics of effluent P sampling.

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## ABSTRACT

Enhanced biological phosphorus removal (EBPR) failure due to nitrate/nitrite presence in the anaerobic reactor is a common problem in full-scale WWTPs aiming at simultaneous C/N/P removal. This work evaluates the performance of two common EBPR configurations ($A^2/O$ and JHB) under normal conditions and under two detrimental scenarios: (i) increase of ammonium nitrogen in the influent and (ii) increase of nitrite in the external recycle. EBPR failure due to nitrate/nitrite entering the anaerobic phase can be avoided with a controlled addition of a carbon source. In this work, crude glycerol, a biodiesel by-product, was used as a low-cost external carbon source. A control strategy to dose an optimal amount of crude glycerol was theoretically designed through a modelling-based study. Hence, a model was firstly calibrated and validated with the open-loop experimental data. Then, the optimal control strategy was experimentally evaluated in the pilot plant under both configurations and under the same detrimental scenarios revealing the real benefits of the control action. JHB obtained the best results under open- and closed-loop conditions: P was satisfactorily controlled with 18% less crude glycerol dosage than $A^2/O$. Finally, two control alternatives were tested *in silico* to overcome problems derived from the slow dynamics of P effluent concentration with respect to glycerol addition resulting in a better control performance.



## 1. Introduction

Enhanced biological phosphorus removal (EBPR), the most economical and sustainable technology to meet the current P discharge requirements of wastewater treatment plants (WWTP), is based on the enrichment of activated sludge systems with polyphosphate accumulating organisms (PAO). Despite EBPR is a very studied and understood process, its full-scale implementation still presents some issues to be solved as for example, the interactions with biological nitrogen removal. The most common WWTP configuration aiming at simultaneous C, N and P removal is the anaerobic/anoxic/aerobic ($A^2/O$) configuration (Fig. 1 up) [1]. This configuration works properly provided that the anaerobic reactor does not receive a high amount of nitrate. Otherwise, denitrifying OHO could outcompete PAO for the carbon source resulting in less COD for EBPR [2]. Alternative configurations to $A^2/O$ have been proposed to reduce in some way the nitrate content in the external recycle and thus, in the anaerobic reactor. For example, Johannesburg (JHB) configuration (Fig. 1 down) is based on the inclusion of an additional reactor in the external recycle for nitrate denitrification [1,3]. Although the benefits of JHB configuration on EBPR performance are widely known [1,3], a comprehensive experimental comparison of its performance vs. $A^2/O$ under different detrimental scenarios (i.e. disturbances of high

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**Nomenclature**

| | | | |
|---|---|---|---|
| $A^2/O$ | anaerobic, anoxic and aerobic WWTP configuration | $NO_X$ | nitrogen oxides (nitrate, nitrite or other denitrification intermediates) |
| ASM2d | activated sludge model 2d (IWA) | OHO | ordinary heterotrophic organisms |
| EBPR | enhanced biological phosphorus removal | P | phosphorus |
| C | carbon | PAO | polyphosphate accumulating organisms |
| CGCL | crude glycerol control loop in R3 | PHA | poly-β-hydroxyalkanoates |
| $CGCL_{P\text{-}R1}$ | crude glycerol control loop in R1 | PI | proportional-integral controller |
| $C_{NH_4,in_{av,n}}$ | 2 h average ammonium influent concentration | $Q_{EFF}$ | effluent flow-rate |
| COD | chemical oxygen demand | $Q_{IN}$ | influent flow-rate |
| DO | dissolved oxygen | $Q_{REXT}$ | external recycle flow-rate |
| DPAO | denitrifying polyphosphate accumulating organisms | $Q_{RINT}$ | internal recycle flow-rate |
| FF-CGCL | feed forward crude glycerol control loop | Ri | reactor number $i$ (1–4) |
| FIM | Fisher Information Matrix | SRT | sludge retention time |
| FNA | free nitrous acid | $t_n$ | time $n$ |
| HAD | high ammonium disturbance | TSS | total suspended solids |
| HND | high nitrite disturbance | VFA | volatile fatty acids |
| HRT | hydraulic retention time | VSS | volatile suspended solids |
| ITAE | integral of the time-weighted absolute value of error | WWTP | wastewater treatment plant |
| JHB | Johannesburg WWTP configuration | $\varepsilon$ | error of the measured variable |
| $K_C$ | proportional gain | $\tau_I$ | integral time constant |
| $K_{FF}$ | feed forward proportional gain | | |
| N | nitrogen | | |

ammonium influent concentration or anaerobic nitrite presence) cannot be found in the literature.

On the other hand, the addition of an external carbon source is also presented as another fast and successful solution to provide enough COD for either denitrification (i.e. OHO and denitrifying PAO) and EBPR (i.e. PAO). However, not only the COD availability is important to achieve high EBPR activity but also the nature of the carbon source plays an important role. Several studies [2,4–6] reported that the presence of volatile fatty acids (VFA) in the wastewater is mandatory to obtain a high P removal capacity. Unfortunately, an external VFA addition is not usually cost-effective and it increases the overall plant carbon footprint [7,8]. A promising and very attractive alternative would be the utilization of waste materials that could be fermented to VFA.

Many studies reported successful pure glycerol utilization as an external carbon source for denitrification process [9–13] and for improving EBPR activity when treating influents with carbon shortage [14]. Biodiesel fuel production generates 1 L of crude glycerol for every 10 L of fuel [15]. Crude glycerol has a low cost due to its high production and its impurities such as methanol, salts or long chain fatty acids. Thus, in comparison with conventional external carbon sources as VFA it could be a cost-effective alternative [16] to reduce the detrimental effect of nitrate under anaerobic conditions since it can be used in both N and P removal processes. However, there are not previous studies about crude glycerol utilization as a carbon source for improving EBPR in a system performing simultaneous N and P removal. The feasibility of using crude glycerol is also related to the potential detrimental effect of its impurities on the on-going biological processes. The potential effects of such impurities [17] will limit the amount of crude glycerol to be dosed and, hence, its dosage should be reliably controlled.

Most of the control strategies reported in literature regarding WWTP operation are focused on C and N removal [18–20]. Recently, a better understanding of the EBPR process has brought the possibility of designing novel control structures considering simultaneous C/N/P removal [21–24] but none has been experimentally validated yet. In addition, few of them have been focused on designing control strategies for carbon addition, being acetic acid the most usual carbon source chosen [23,25]. Once again, developing new control strategies for adding alternative carbon sources, such as crude glycerol, should be a hot research topic in the future since not only is a cost-effective alternative but also could present some practical advantages in comparison with conventional carbon sources (storage problems for acetic acid due to its corrosive properties or for methanol and ethanol that are flammable products).

Thus, the main objective of this work was to study the feasibility of a controlled addition of crude glycerol to avoid EBPR failure due to anaerobic nitrate and nitrite presence. Two different pilot plant configurations ($A^2/O$ and JHB) were experimentally compared under conventional operation. Moreover, both configurations were subjected to two different disturbances (nitrate or nitrite anaerobic load increase) to evaluate the best configuration in terms of higher capacity to deal with detrimental disturbances for EBPR. The plant operation was also modelled in order to design optimal control strategies for the glycerol dosage. Once the model was calibrated and validated, a novel phosphorus feedback control loop based on crude glycerol addition was designed and experimentally validated. The novelty of this work lays on the utilization of a real and low-cost by-product, crude glycerol, under controlled operation, for reducing the detrimental effect of anaerobic nitrate and nitrite presence in the EBPR process.

## 2. Material and methods

### 2.1. $A^2/O$ and JHB pilot plant description

Two different pilot plant configurations with simultaneous C, N and P removal were used in this work. The $A^2/O$ pilot plant consisted of three continuous stirred tank reactors (R1 to R3) with a total volume of 146 L (R1:28L, R2:28L and R3:90L) and a 50 L settler (Fig. 1 up). The sludge retention time (SRT) was maintained around 11 days with automatic sludge wastage from the aerobic reactor. SRT of 11 days was selected to ensure high P removal capacity as reported by Carrera et al. [26]. The influent ($Q_{IN}$) flow-rate was 240 L $d^{-1}$ resulting in a hydraulic retention time (HRT) of 14.6 h.