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# A novel control strategy for efficient biological phosphorus removal with carbon-limited wastewaters

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**ABSTRACT**

This work shows the development and the *in silico* evaluation of a novel control strategy aiming at successful biological phosphorus removal in a WWTP operating in an $A^2O$ configuration with carbon-limited influent. The principle of this novel approach is that the phosphorus in the effluent can be controlled with the nitrate setpoint in the anoxic reactor as manipulated variable. The theoretical background behind this control strategy is that lowering nitrate entrance to the anoxic reactor would result in more organic matter available for biological phosphorus removal. Thus, phosphorus removal would be enhanced at the expense of increasing nitrate in the effluent (but always below legal limits). The work shows the control development, tuning and performance in comparison to open-loop conditions and to two other conventional control strategies for phosphorus removal based on organic matter and metal addition. It is shown that the novel proposed strategy achieves positive nutrient removal results with similar operational costs to the other control strategies and open-loop operation.

**KEYWORDS**

Benchmark; control; Cascade+Override-Phosphorus control strategy; EBPR; nitrate.

## INTRODUCTION

Simple feedback controllers for essential parameters have been successfully applied in wastewater treatment plants (WWTP) in view of improving its performance, particularly on enhancing biological carbon (C) and nitrogen (N) removal (Baeza *et al.*, 2002; Nopens *et al.* 2010). Regarding phosphorus (P), the implementation of enhanced biological P removal (EBPR) is considered the most sustainable approach to meet the required P discharge levels, but few studies have proposed successful control strategies in full-scale WWTP for improving P-removal despite the increasingly stricter legislation. The current knowledge gained on this process has raised the opportunity of developing new control structures to specifically control effluent P concentration (Gernaey *et al.*, 2002; 2004; Machado *et al.*, 2009; Ostace *et al.*, 2013).

EBPR is nowadays a quite known technology but its interaction with biological N removal may still lead to P removal failures in full-scale WWTP, mostly due to the interaction with nitrate. The influent COD/P ratio and the nature of the carbon source have been shown to be key parameters to understand this failure (Guerrero *et al.*, 2011). In some cases, the COD content in the wastewater is deficient in view of accomplishing simultaneous N and P removal. Adding an external carbon source or a chemical for phosphorus precipitation are widely used technical solutions to cope with successful P removal in COD-limited wastewater at the expense of increasing the plant operational costs.

In this framework, this study describes a novel control strategy to accomplish P removal legislation for WWTP with carbon shortage. This strategy was designed for its application in a conventional anaerobic/anoxic/aerobic ($A^2/O$) WWTP for simultaneous C/N/P removal.

## MATERIALS AND METHODS

### Wastewater treatment plant description

A benchmark $A^2/O$ WWTP was simulated for the theoretical development of the control strategy using an extension of the ASM2d model that also includes nitrite as state variable (Guerrero *et al.*, 2013). The WWTP consisted of two anaerobic reactors (ANAE1 and ANAE2, 1250 $m^3$ each), two anoxic reactors (ANOX1 and ANOX2, 1500 $m^3$ each) and three aerobic reactors (AER1, AER2 and AER3, 3000 $m^3$ each) with a total volume of 14500 $m^3$ (Figure 1). The settler was modelled using the 10-layer model of Takács *et al*. (1991) but including reactive capacity as in Guerrero *et al.* (2013).

The influent wastewater used mimicked the yearly flow pattern (609 days) of an urban carbon-limited wastewater with low COD/P and low COD/N ratios (average values in $g\cdot m^{-3}$: 240 COD, 20 $NH_4^+$-N, 10 $PO_4^{-3}$-P). The carbon source was considered mainly as $X_S$ (slowly biodegradable organic matter) in other to simulate the high content of complex carbon sources commonly present in urban wastewater (Gernaey and Jørgensen, 2004). The influent flow rate average value was 20648 $m^3\cdot d^{-1}$ resulting in a hydraulic retention time (HRT) of 17 hours. In order to assess and compare the goodness of the control strategies, an open-loop scenario was defined where the internal recycle ($Q_{RINT}$) and the external recycle ($Q_{REXT}$) were set to 300% and 100% of the averaged influent flow rate, respectively. In a previous study (Guerrero *et al*., 2013), it was observed that the waste flow rate ($Q_W$) recommended in benchmarking for COD and N removal ($Q_W$ = 385 $m^3\cdot d^{-1}$) was too low to obtain reasonable biological P removal. Then, $Q_W$ was fixed at 700 $m^3\cdot d^{-1}$ to maintain a sludge retention time (SRT) of 10 d as recommended to favour EBPR (Carrera *et al*., 2001). The aeration in this open-loop scenario was assumed to be constant by fixing the global oxygen transfer coefficient in each aerobic reactor ($k_La_1$, $k_La_2$ and $k_La_3$ values were set to 120, 120 and 60 $d^{-1}$, respectively). For comparison purposes, only the last 364 days were used for evaluation. All simulations were preceded by steady state simulations (300 days under constant influent conditions with the average pollutant concentrations).

## RESULTS AND DISCUSSION

### Principle of the Cascade & Override Phosphorus control strategy (COPCS)

EBPR fails when the carbon source is more complex than volatile fatty acids (VFA) and nitrate enters in the anaerobic phase. Guerrero *et al.* (2011) showed that nitrate detrimental effect was not to inhibit the P-release process itself but to prevent the fermentation process for the VFA production.

The principle of the proposed control strategy is: effluent phosphorus (i.e. phosphorus in the last aerobic reactor) can be the controlled below its discharge limit (1.5 g $PO_4^{3-}$-$P\cdot m^{-3}$ according to Gernaey and Jørgensen (2004)) with the nitrate setpoint in the anoxic reactor as the manipulated variable. Then, when effluent P is high, the nitrate setpoint in the anoxic phase should be lowered so that more COD is diverted to EBPR at the expense of less denitrification, but always below legal limit (15 g $TN \cdot m^{-3}$ according to Directive 91/271/EEC). The control strategy (Figures 1 and 2) is based on a cascade configuration with two proportional integral (PI) feedback control-loops and complemented with an override control to prevent excess of nitrate in the effluent:

i) Primary loop: Phosphorus is controlled in AER3 by manipulating the nitrate setpoint for ANOX2. The phosphorus setpoint chosen in AER3 was 0.5 g $PO_4^{3-}$-$P \cdot m^{-3}$.

ii) Secondary loop: Nitrate is controlled in ANOX2 by manipulating the $Q_{RINT}$. The controller parameters were fixed according to Gernaey and Jørgensen (2004).

iii) Override loop: When nitrate concentration in AER3 is higher than 13 g $NO_3^-$-$N \cdot m^{-3}$, the primary loop is deactivated and a default setpoint of 1 g $NO_3^-$-$N \cdot m^{-3}$ for nitrate in ANOX2 is established for the secondary loop.

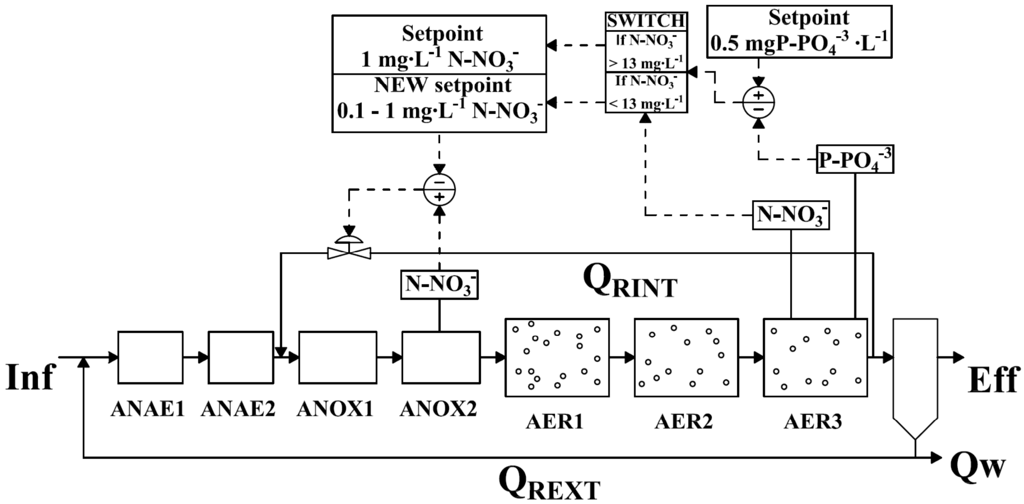


**Figure 1** Simplified scheme of the proposed COPCS control strategy for P removal.

The COPCS strategy aimed at favouring P removal by limiting the nitrate inlet into the anoxic reactors and thus, increasing the anaerobic fraction of the plant. However, this decrease on the anoxic volume of the plant could result in higher total nitrogen (TN) levels in the effluent, since less nitrate would be denitrified. Therefore, an override control loop was also considered: the primary loop of the cascade control is disabled when nitrate concentration in the effluent is above 13 g $N \cdot m^{-3}$. This value was selected for being a warning level below 15 g $TN \cdot m^{-3}$, the legal discharge limit for TN. In this scenario, only the secondary control loop is operative with a nitrate setpoint of 1 g $NO_3^-$-$N \cdot m^{-3}$. $NO_3^-$-N was considered instead of TN, since most of the effluent nitrogen is nitrate. Some conventional control loops proposed for controlling phosphate (Table 1) were also implemented and compared with the COPCS performance and with the open-loop operation: i) CARBCS: External carbon addition in ANAE1 to favour biological P removal (Olsson *et al.*, 2005) ii) METCS: Metal addition in AER3 to precipitate P (Gernaey *et al.*, 2002). For all the control loops tested, DO was also controlled at 2 g $DO \cdot m^{-3}$ in AER2 by $k_La_1$ and $k_La_2$ manipulation and 1 g $DO \cdot m^{-3}$ in AER3 by $k_La_3$ manipulation (Nopens *et al.*, 2010).

**Table 1** Characteristics of reported control strategies for controlling effluent P concentration.

| | CARBCS | METCS |
|---|---|---|
| Controlled variable | $PO_4^{-3}$-P AER3 | $PO_4^{-3}$-P AER3 |
| Setpoint | 0.5 g P · $m^{-3}$ | 0.5 g P · $m^{-3}$ |
| Manipulated variable | $Q_{CARB}$ ANAE 1 | $Q_{MET}$ AER 3 |
| Control algorithm | PI | PI |
| Objective | Favouring EBPR activity | Phosphorus precipitation |

## Control tuning

The controller parameters were optimised according to different textbook tuning methods (Stephanopoulos, 1984): Integral Absolut value of Error (IAE), Integral of the Time-weighted Absolut value of Error (ITAE), Integral of the Square Error (ISE) and Integral of the Time-weighted Square Error (ITSE). A constant influent (90 days) in terms of flow rate (20648 $m^3 \cdot d^{-1}$) but with step changes in ammonium (20 to 25 g $N \cdot m^{-3}$), phosphate (10 to 13 g $P \cdot m^{-3}$) and organic matter (240 to 200 g $COD \cdot m^{-3}$) concentrations was used. As figure 2 shows, IAE criterion was selected because it resulted in the most robust control response since i) the setpoint was reached fast after COPCS activation (Figure 2B) and ii) the response observed after step changes was the least oscillatory (Figure 2C). The optimised controller parameter values were: Kc = 0.35 g $NO_3^-$-$N \cdot m^{-3} \cdot$ (g $PO_4^{-3}$-P $\cdot m^{-3})^{-1}$ and $\tau_I$ = 0.24 days, where $K_C$ was the proportional gain and $\tau_I$ the integral time constant.

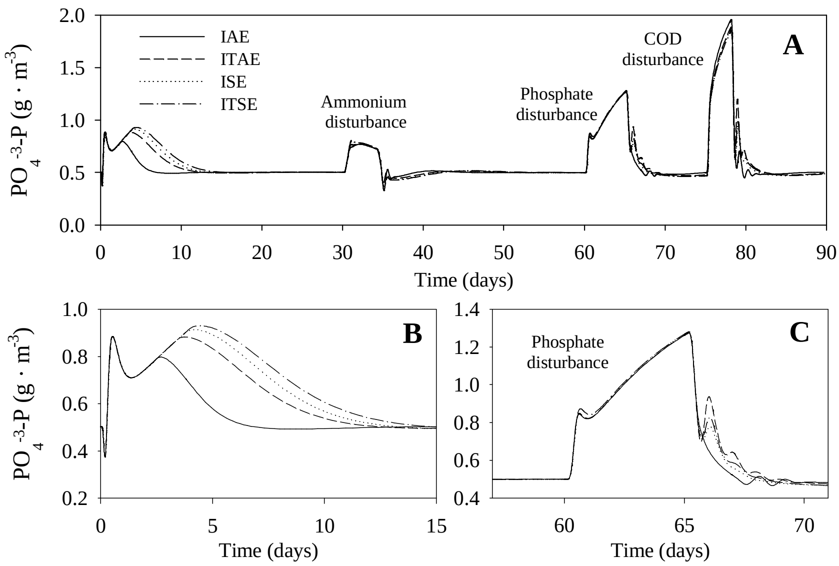


**Figure 2** Optimised response of COPCS for the different tuning methods tested. Setpoint = 0.5 g $PO_4^{3-}$-P $\cdot m^{-3}$. A: P effluent behaviour for the three step changes. B: Zoom for P effluent during COPCS activation. C: Zoom for P effluent during phosphate perturbation.

## COPCS performance

Figure 3 compares the COPCS performance to the open-loop conditions. P-removal capacity increased (effluent phosphorus decreased around 54%) when COPCS was implemented. The increase of the anaerobic fraction of the plant by reducing $Q_{RINT}$ flow rate favoured complex carbon source fermentation to more readily biodegradable components, which are preferred substrates in the EBPR process. As an overall result, the EBPR process was highly favoured at the expense of increasing the total nitrogen effluent concentration but always keeping it below the legal discharge limit. If stricter discharge limits had been considered, for example 10 g TN·$m^{-3}$ according to the Council Directive 91/271/EEC, COPCS also resulted in an effluent TN that would be below this stricter limit most of the time (Figure 3F).

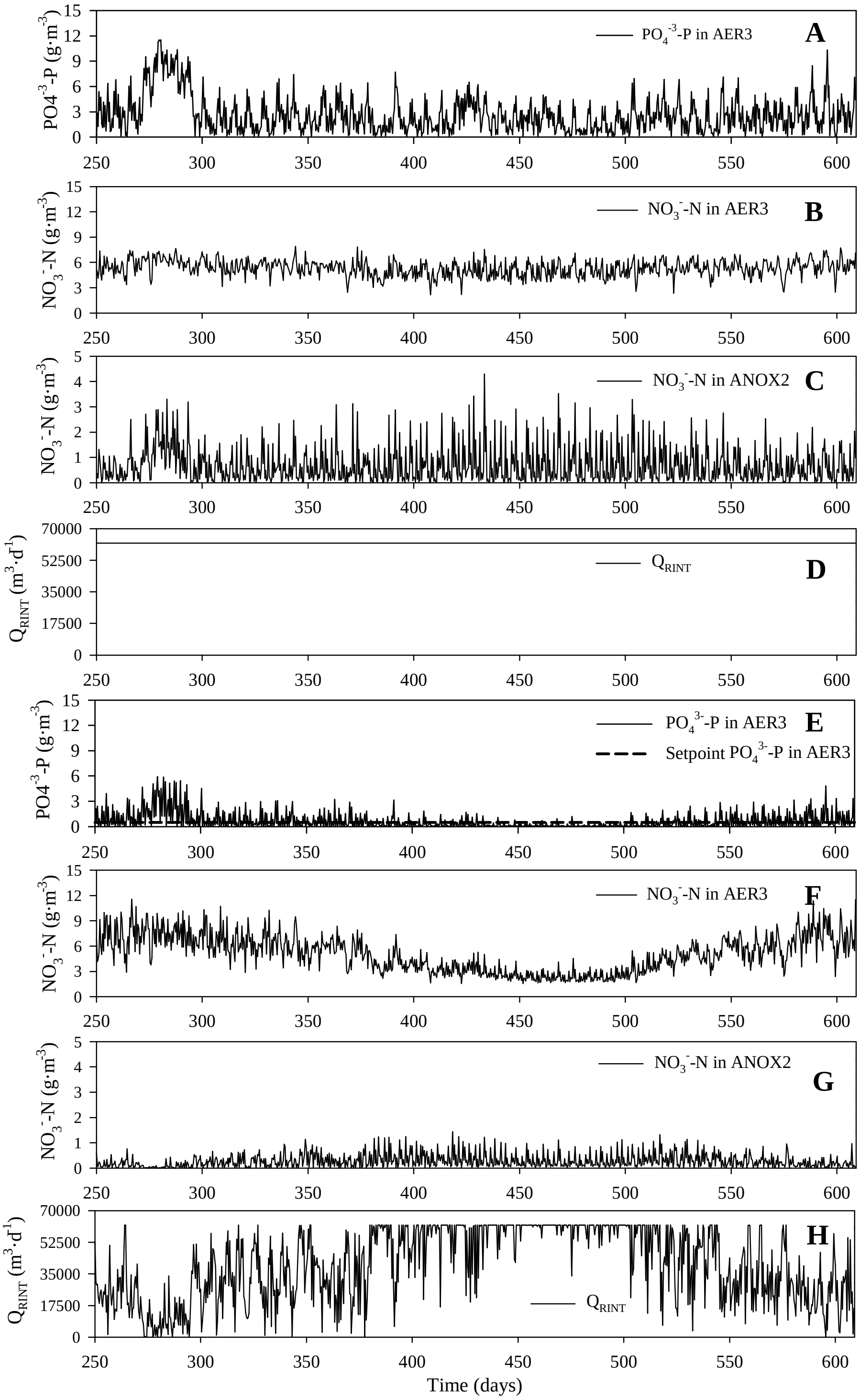


**Figure 3** Comparison between open-loop performance (A-D) with the COPCS performance (E-H).

The COPCS was also compared to two other typical control strategies aiming at improving P removal (Table 1): addition of external carbon source in the anaerobic reactor (CARBCS) and addition of metal for P precipitation in the aerobic reactor

(METCS). Table 2 shows the yearly averaged (364 days) effluent concentrations for the different tested scenarios. Regarding open-loop conditions, effluent P was above the discharge limit (1.50 g P $\cdot m^{-3}$) since the low COD entering to the anaerobic reactor was preferentially oxidised via denitrification with the nitrate brought by the $Q_{REXT}$ rather than via EBPR. When CARBCS or METCS were implemented, phosphate in AER3 rapidly decreased to the setpoint value (0.50 g P $\cdot m^{-3}$) resulting in effluent phosphorus concentrations below the discharge limit for both cases (Table 2). However, these control loops are based on external dosages and, thus, they increased operational costs. Figure 4 shows the operational cost distribution of each control strategy according to Alex *et al.* (2008). The sludge production costs represented most of OCI (around 85%) because a high purge flow ($Q_W$) was selected (700 $m^3 \cdot d^{-1}$) to guarantee high P removal. For COPCS results, the novel control strategy reached the desired effluent phosphorus concentration (Table 2) without any external mass input, which resulted in lower operational costs than CARBCS or METCS (Figure 4). As was stated before, the COPCS favoured EBPR at expenses of slightly worsening N removal and thus, obtaining higher TN effluent in comparison with CARBCS or METCS. However, it should be pointed out that under COPCS control the effluent met legal restrictions. On the other hand, its higher EQI value with respect to CARBCS or METCS led to lower OCI because, among other reasons, less energy (20% lower) was invested in pumping to recycle nitrate to the anoxic reactors (i.e. COPCS manipulated $Q_{RINT}$ to control nitrate concentration in the anoxic reactors). Compared to the open-loop scenario, similar OCI with lower EQI values were obtained for COPCS proving that the novel control strategy was able to improve P removal capacity of an existing plant (open-loop operation) with a low impact in the costs (less than 1%) and meeting discharge limits. This was one of the main achievements of this study.

**Table 2** Nutrient averaged effluent concentrations (364 days) for the operational scenarios

| | **Effluent concentration (g·m$^{-3}$)** | | | | |
|---|---|---|---|---|---|
| | **$NH_4^+$-N** | **TN** | **$PO_4^{3-}$-P** | **TP** | **EQI** |
| **Open-loop** | 1.32 | 7.63 | 2.49 | 3.27 | 7101 |
| **CARBCS** | 1.65 | 7.14 | 0.34 | 1.24 | 5139 |
| **METCS** | 2.23 | 7.77 | 0.31 | 1.25 | 5498 |
| **COPCS** | 2.06 | 9.04 | 0.61 | 1.51 | 6241 |

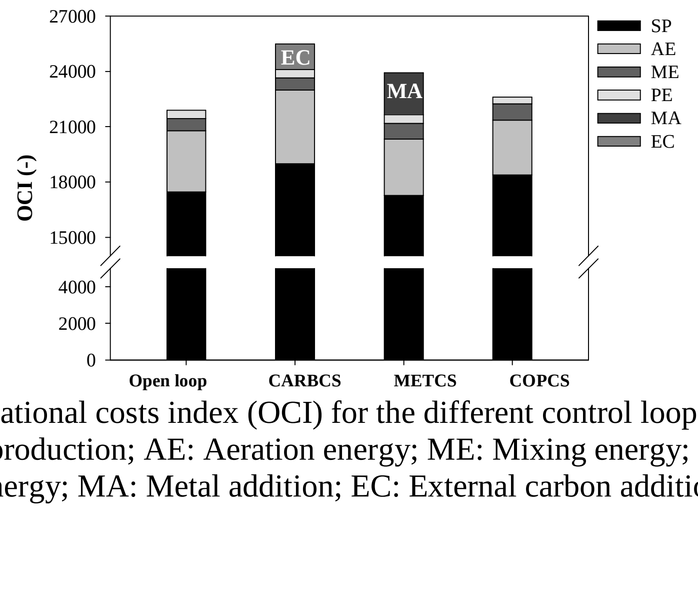


**Figure 4** Operational costs index (OCI) for the different control loops implemented. SP: Sludge production; AE: Aeration energy; ME: Mixing energy; PE: Pumping energy; MA: Metal addition; EC: External carbon addition.

Extra simulations were also performed to compare the three control strategies when CARBCS and METCS were operated to achieve similar EQI values compared to COPCS (differences lower than 10%). A limitation of external carbon source and metal dosage was necessary for CARBCS and METCS, respectively (e.g. maximum carbon addition was reduced from 5.0 to 0.75 $m^3 \cdot d^{-1}$ for CARBCS and the metal addition in METCS from 3.0 to 0.75 $m^3 \cdot d^{-1}$). Table 3 shows the EQI values and figure 5 the OCI obtained for each control strategy. As expected, similar EQI values resulted in similar OCI results. Hence, it can be concluded that the implementation of COPCS could be as efficient as other conventional control strategies used to improve P-removal, but without the need to add external carbon source or metal salts.

**Table 3** Nutrient averaged effluent concentrations (364 days) for the operational scenarios

| | Effluent concentration ($g \cdot m^{-3}$) | | | | |
|---|---|---|---|---|---|
| | **$NH_4^+$-N** | **TN** | **$PO_4^{3-}$-P** | **TP** | **EQI** |
| **Open-loop** | 1.32 | 7.63 | 2.49 | 3.27 | 7101 |
| **CARBCS** | 2.87 | 8.02 | 0.50 | 1.40 | 5946 |
| **METCS** | 2.54 | 8.08 | 0.61 | 1.52 | 5703 |
| **COPCS** | 2.06 | 9.04 | 0.61 | 1.51 | 6241 |

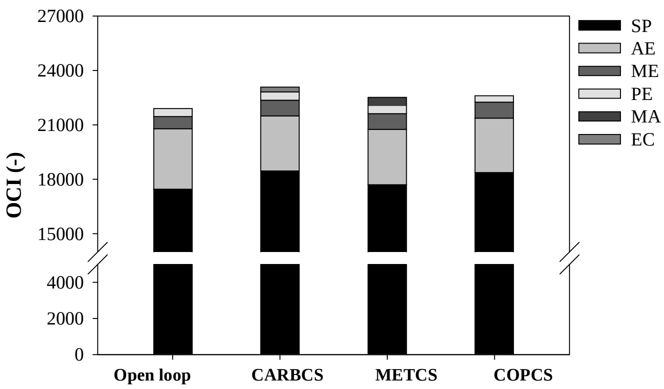


**Figure 5** Operational costs index (OCI) for the different control loops implemented when CARBCS and METCS actuation were limited. SP: Sludge production; AE: Aeration energy; ME: Mixing energy; PE: Pumping energy; MA: Metal addition; EC: External carbon addition.

## Practical implications

This study only considers the water line and hence further research would be necessary on plant-wide simulations integrating the sludge line before its full-scale implementation. With high EBPR activity, part of the P from the sludge could be resolubilised during anaerobic digestion, which will be then recycled to the water line increasing the total influent P load. If part of the P-removal came from METCS, less P would be recycled to the plant inlet since P-precipitation products are highly insoluble. On the other hand, CARBCS would have high possibilities to sort out the problem by increasing carbon dosage. Despite the worth of COPCS is not clear a priori, the good results here obtained suggest that proper bio-P removal would also be achieved. In this sense, the inclusion of VFA production via pre-fermentation of primary sludge in the settler should also be considered because it would favour EBPR and, thus, reduce the control requirements in VFA-limited scenarios.

The full-scale implementation of COPCS does not require the addition of chemicals, avoiding some issues such as chemicals purchase or storage of, in some cases, toxic products (ferric chloride for METCS) or corrosive products (acetic acid for CARBCS). In addition, not using an external carbon source in COPCS would also reduce the plant carbon footprint (Yuan *et al.*, 2010) and not using metal dosage would avoid an increase of inorganic compounds in the sludge with the consequent problems during tertiary treatment (e.g. less methane production during anaerobic digestion).

Finally, the benefits of this strategy for low-COD wastewaters could be partially obtained in a non-automated WWTP by manually decreasing the internal recycle when high P-effluent concentration is detected. This would decrease the amount of nitrate applied to the anoxic reactor, leading to more VFA production by fermentation of complex carbon sources and then higher PAO activity. However, the on line implementation would allow the adaptation of the WWTP operation to variable influent characteristics obtaining a more stable and reliable operation thanks to the benefits of automatic control.

## CONCLUSIONS

A novel control strategy based on a cascade plus override control structure was proposed to enhance phosphorus removal for carbon-limited wastewaters in WWTP aiming at simultaneous C/N/P removal. This strategy allows diverting the available COD to P removal by modifying the nitrate setpoint in the anoxic reactor of the slave control loop. When effluent P is high, the nitrate setpoint in the anoxic phase is decreased so that more COD is diverted to EBPR at the expense of less denitrification.

This strategy shows very good performance when compared to open-loop conditions and it is a proper alternative to other control strategies applied to low carbon strength systems as external carbon dosage or metal addition.

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