An advanced control system for nitrogen removal and energy consumption optimization in full-scale wastewater treatment plants.

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Abstract

The development and implementation of advanced control systems enable the successful and efficient conversion of wastewater treatment plants into water resource recovery facilities. This work presents an advanced control system based on low-cost sensors (pH, ORP and DO) which enhances biological nitrogen removal and improves energy efficiency. It consists of three independent fuzzy-logic-based control loops (for nitrification, simultaneous nitrification-denitrification, and denitrification, respectively) combined with a set of knowledge-based rules. The control system was implemented in three facilities and test-run for over two years. During this time, proper process performances were achieved both in terms of water quality and of operating cost savings. Energy consumption, calculated as kWh per kg COD equivalent removed (including nitrogen removal), was reduced between 14 % and 33 %.

Keywords

Denitrification controller; fuzzy-logic control; low-cost sensors; nitrification controller; simultaneous nitrification-denitrification (SND) controller.

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1. Introduction

The need to integrate the principles of Circular Economy within the water sector is pushing the transformation of existing wastewater treatment plants (WWTPs) into water resource recovery facilities (WRRFs). To this end, current research is focused on developing sustainable technologies aimed at recovering resources from wastewater such as energy, nutrients, and reclaimed water. However, implementation of these technologies is still scarce, the main reasons being low TRLs (non-mature technologies) or high investment costs required to upgrade or transform existing WWTPs. Therefore, current efforts are also directed at achieving compliance with more and more stringent regulatory effluent criteria while increasing efficiency of available WWTPs infrastructure [1]. Essential tools to accomplish these objectives are proper monitoring of process performance and process optimization with efficient control systems.

WWTPs use approximately 1 % of the total electricity consumption in each country [2]. Activated sludge systems are the most widely implemented technology for wastewater treatment and their aeration costs commonly entail between 45 and 75 % of total operating costs of wastewater treatment [3,4]. In these cases, energy consumption of aeration systems has thus become a clear target for process optimization. Advanced aeration control strategies are perfect tools for such task, especially in large WWTPs where plant economy and carbon footprint can be greatly benefited [5,2,6]. In this sense, biological nitrogen removal (BNR) control strategies play a crucial role in minimizing operating costs, while complying with effluent criteria, decreasing vulnerability to process disturbances, and increasing trust within operators through a reliable and improved process operation.

Currently, two control strategies are mainly applied to minimize aeration consumption in activated sludge systems for nutrient removal [7]. On the one hand, the duration of aerated and non-aerated periods is optimized in intermittent aeration systems [1,8-10]. On the other hand, in continuous aeration systems, a supervisory control system is defined which establishes the minimum dissolved oxygen (DO) set points for the aeration layer controller [1,11-17].

In addition, a third alternative process to minimize aeration consumption in nutrient removing WWTPs is simultaneous nitrification and denitrification (SND), which is achieved, among other operating actions, by maintaining low dissolved oxygen concentrations [8,18,19].

On-line nitrogen sensors or analyzers are often used in large WWTPs for control purposes. For instance, nitrification is usually controlled based on the ammonium concentration in the aerobic reactor, establishing a certain DO concentration for this reactor and modifying the aeration rate accordingly [1,16,20]. At the same time, denitrification is usually controlled based on the nitrate concentration in the anoxic reactor and/or the aerobic reactor, establishing the internal recycle flow rate and/or the external carbon dosage [1,21,22].

Oxidation-reduction potential (ORP), pH and DO sensors can also be applied for monitoring and controlling BNR processes. Their main advantages compared to nitrogen sensors are their lower investment costs and easier handling. Indeed, different BNR control strategies have been developed so far based on this alternative, mainly focusing on the time evolution of the measures obtained by these sensors. However, this has generally been done in sequencing batch reactors [10,23], whereas it is still scarcely applied in neither intermittently aerated [24], continuously fed nor continuously aerated biological processes at full-scale [14,25].

In the last years, the reliability of control strategies based on low-cost sensors has increased with the improved mechanistic understanding of the relationships between changes in the biological processes and the signals measured by these low-cost sensors. For example, the pH profile over the aerobic zone (either in a single tank or in a series of tanks) has been related with the concentration of ammonia in the reactor and in the effluent [14,26]. Thürlimann et al. [27] developed a low-maintenance ammonia control strategy for small to medium WWTPs by incorporating prior knowledge on the time evolution of the pH signal. Specifically, the combination of qualitative trend analysis with a rule-based controller showed promising results: it was robust and tolerant to sensor drifts in the pH signal, thus reducing sensor maintenance requirements.

Based on previous works [14,25] and the know-how acquired after intensive full-scale process monitoring in several WWTPs with different schemes and treatment capacities, an advanced control system based on low-cost sensors (pH, ORP and DO) has been developed. It has been validated with exhaustive on-line and off-line monitoring campaigns. The control system includes different knowledge-based control strategies aimed at optimizing BNR. It consists of nitrification, denitrification, and simultaneous nitrification-denitrification (SND) control strategies, which are coupled to a lower layer aeration control system [6]. This paper presents the results of its implementation in three full-scale WWTPs to validate the adaptability of the control system to specific case constraints.

2. Materials and Methods

2.1. WWTP layout and configuration

The control system was implemented in three Spanish WWTPs with different treatment capacities (WWTP#1 with 23 500 m^3/d, WWTP#2 with 50 200 m^3/d and WWTP#3 with 11 400 m^3/d). Table 1 shows the influent characteristics and main operating conditions (mean values and standard deviation) of each activated sludge system. The three systems were fed with the effluent of the pre-treatment step (screening, degritting, grease removal and primary settling) of the WWTPs, and consisted in a two-lanes plug-flow reactor (one lane in the case of WWTP#3) with an A2O configuration for biological nutrient removal. Additionally, chemical phosphorus precipitation (before the secondary settlers) using ferric salt was carried out in all facilities.

The A2O biological reactors (Appendix, Fig A1) which consisted of one anaerobic chamber, one anoxic chamber, one facultative chamber for WWTP#1 and WWTP#2, two facultative chambers for WWTP#3, and two consecutive aerobic chambers. Air within facultative and aerobic zones was supplied by blowers and turbo blowers which were controlled by the lower layer aeration control system described in [6]. Each facultative and aerobic chamber was equipped with a diffuser grid, a control valve (CV), and a DO probe (installed at the end of the grid). Nitrogen based sensors were additionally used as process monitoring in WWTP#1.

The WWTP effluent limits were as follows: Total Nitrogen (TN) < 10 mg L^{-1}; Total Phosphorus (TP) < 1 mg L^{-1}; Total Suspended Solids (TSS) < 35 mg L^{-1}; Biochemical Oxygen Demand (BOD_5) < 25 mg L^{-1}; and Chemical Oxygen Demand (COD) < 125 mg L^{-1}.

	Parameter	WWTP#1	WWTP#2	WWTP#3
Influent	Inflow ($m^3 \cdot d^{-1}$)	50 200 ± 7 800	23 500 ± 1 800	11 400 ± 630
	TSS ($mg \cdot L^{-1}$)	436 ± 105	249 ± 134	238 ± 11
	COD ($mg \cdot L^{-1}$)	833 ± 143	434 ± 21	518 ± 28
	BOD_5 ($mg \cdot L^{-1}$)	500 ± 92	307 ± 92	240 ± 11
	TN ($mg \cdot L^{-1}$)	64.8 ± 9.1	69.8 ± 3.5	53.8 ± 5.7
	NH4-N ($mg \cdot L^{-1}$)	55.6 ± 7.7	66.7 ± 3.5	29.4 ± 4.1
	TP ($mg \cdot L^{-1}$)	11.3 ± 2.4	9.0 ± 2.0	8.0 ± 0.2
A2O process operation	SRT winter (d)	13 ± 1.4	22 ± 1.6	18 ± 3.4
	SRT summer (d)	10 ± 1.3	19 ± 1.4	13 ± 2.6
	T winter (ºC)	17.9 ± 0.9	17.2 ± 2.0	14.8 ± 1.7
	T summer (ºC)	22.9 ± 1.6	24.3 ± 1.5	21.3 ± 1.9
	HRT (h)	15.2 ± 0.4	18.2 ± 1.4	23.0 ± 2.2
	Aeration equipment	1 turbo blower 5 blowers	3 turbo blowers 1 blower	1 turbo blowers
	DO set points before implementation: DO_{Fac_SP}; DO_{Ae1_SP}; DO_{Aef_SP}	2.7; 2.5; 1.4	0; NC*; 2.6	NC; NC; 1.5**; NC
	DO set point ranges after implementation (winter): DO_{Fac_SP}; DO_{Ae1_SP}; DO_{Aef_SP}	0.8-2; 1.8-3.5; 1.8-3.5	0.2-0.8; 1.2-2.5; 0.7-1.5	0.2-1; 0.7-1.5; 1.5-3**; 1.5-3
	DO set point ranges after implementation (summer): DO_{Fac_SP}; DO_{Ae1_SP}; DO_{Aef_SP}	0.4-1; 1.0-3.5; 1.0-3.5	0.2-0.6; 1.1-2.5; 0.6-1.5	0.2-0.8; 0.6-1.5; 1.2-3**; 1.2-3
	Number of nitrate recycling pumps	2	2	1

*non-controlled; ** DO_{Ae2_SP}

Table 1. Mean values and standard deviation of influent characteristics and main operating conditions for the three WWTPs.

2.2. Sampling and laboratory measurements

Analytical campaigns were carried out in each WWTP. They consisted of 24-h composite samples from the influent and effluent of the system, as well as grab samples from the end of the biological reactor. The following parameters were analyzed: TSS according to APHA, 2005, BOD_5, COD, TN, TP, ammonia nitrogen (NH_4-N) and nitrate nitrogen

(NO_3-N), the last four using commercial kits (LCK, Hach) after previous digestion when necessary (TN and TP).

In addition, two samples were collected every week to verify that output data from the nitrogen sensors (ammonium and nitrate) was consistent with laboratory-obtained data. These comparative measurements determined the calibration periodicity needed for the sensors. The average maintenance effort (cleaning and calibration) took around 30-60 minutes per nitrogen sensor and month. On the other hand, the pH and ORP sensors were calibrated every two weeks and required around 20 minutes per sensor and month (cleaning and calibration).

2.3. Control system description

The control system was implemented through a software application called LoDif BioControl®, which was installed in the control computer of each WWTP. LoDif BioControl® consists in a configurable software that integrates different control systems aimed at optimizing the main processes involved in WWTPs, improving process performance, and reducing the associated operating costs. The principles guiding its development are user friendliness, flexibility to enable a guided configuration of different control strategies in accordance with the WWTP characteristics, and standardization to facilitate and/or enable the implementation of the control algorithms at any type of WWTP and plant configuration. The software application communicated with sensors and actuators via the Open Platform Communications (OPC) protocol.

Based on the common characteristics of the three facilities, a similar control strategy was defined for all of them. The first chamber of each biological reactor was operated as anaerobic zone. The second chamber was operated as anoxic zone by recirculating nitrate from the end of the biological reactor. The third (and fourth in the case of WWTP#3) chambers were operated as facultative zones, with a variable DO set point ranging in a low interval (in some cases below 0.5 mg L^{-1}) to favor the SND in the cases when the nitrification process was not limited (e.g., periods with low load periods and/or high temperature). In the last two chambers, variable DO set points were defined to optimize the nitrification process while preventing excessive air supply. This control strategy integrates a lower layer controller to supply the air demanded by the nitrification and SND controllers, which is aimed at optimizing the process under the minimum energy consumption by using a Most-Open-Valve (MOV) approach, combining fuzzy-logic-based control with knowledge-based rules [6].

2.3.1 BNR control system

The BNR control system (Figure 1) consisted of (per treatment lane):

i) One nitrification controller based on pH sensors, acting as a supervisory controller of the aeration control system.

ii) One SND process controller based on pH and ORP sensors, acting as a supervisory controller of the aeration control system.

iii) One denitrification process controller based on pH and ORP sensors, manipulating the recycling pumps flow rate.

These controllers consist of a Multiple-Input-Single-Output (MISO) structure where the control parameters are the time evolution profiles (first derivative) of pH and ORP, and the manipulated variables are the change to be applied to the DO set point in the different aerated zones (facultative and aerobic), as well as the nitrate recycling flow rate in the denitrification controller. This nitrate recycling flow rate was controlled by regulating the frequency of the recycling pumps (2 pumps in WWTP#1 and WWTP#2, 1 pump in WWTP#3).

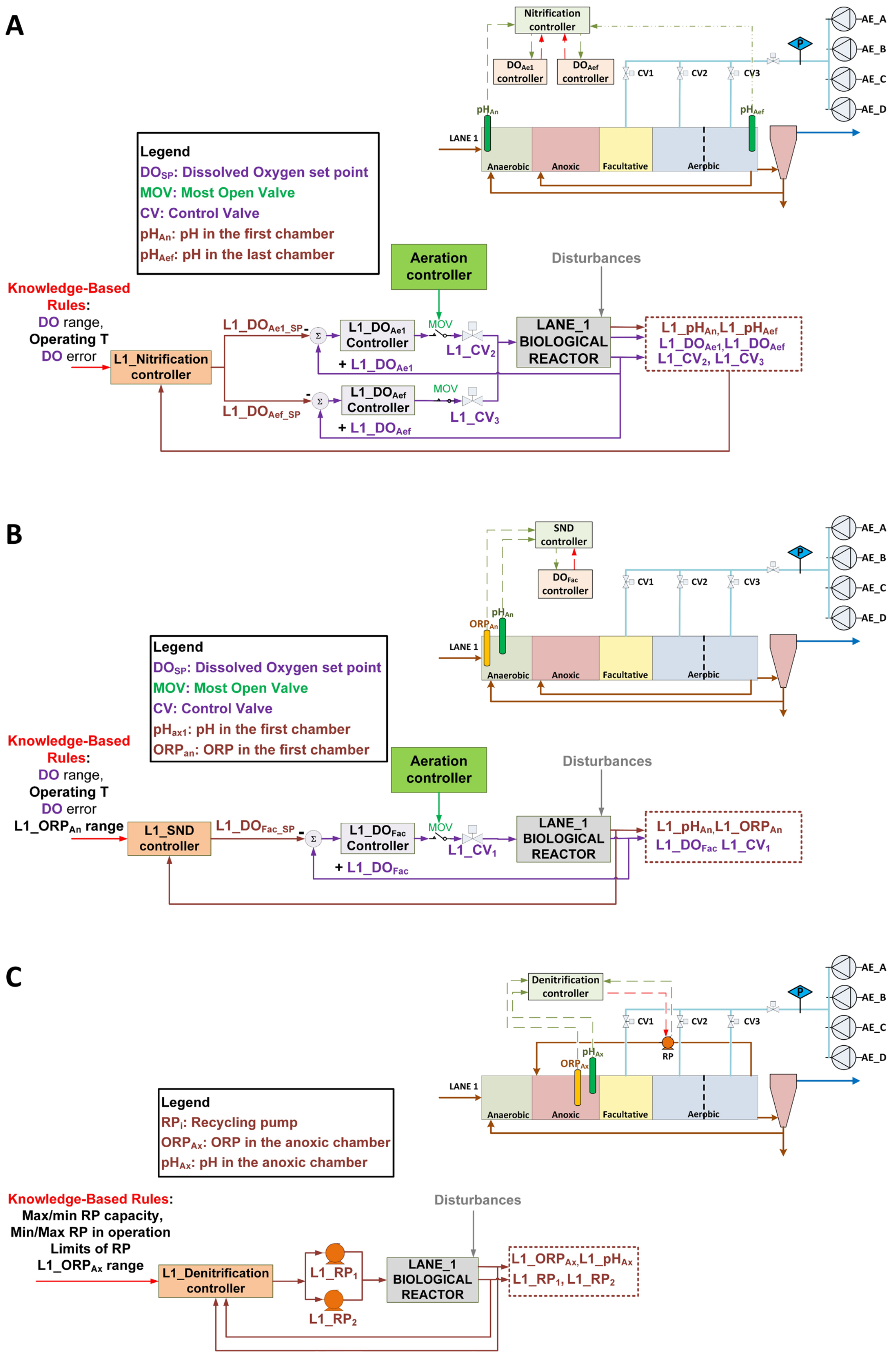

Figure 1. Architecture of the BNR control system: A) nitrification; B) SND controllers, and C) denitrification.

Table 2 presents the assumption/hypothesis that were made with respect to the relationship between pH/ORP measurements and process state (nitrification, denitrification, influent load…), which are knowledge-based and have been also evaluated in previous works [14, 25, 26].

Know-how	Assumption/Hypothesis
Nitrification decreases pH	The nitrification process can be evaluated by measuring the pH in the aerobic chamber.
In anoxic chambers, the ORP shows a strong correlation with nitrate concentration	The denitrification process can be evaluated by measuring the ORP in the anoxic chamber.
Denitrification increases pH	The denitrification process can be evaluated by measuring the pH in the anoxic chamber.
Influent pH and ORP increase and decrease, respectively, as the influent loading increases (related to ammonium and organic matter, respectively).	The dynamics in the influent load can be evaluated by measuring the pH and ORP in the reactor influent.
CO_2 stripping increases the pH	An increase in the pH in the aerobic chamber can be caused by over aerating.

Table 2. Relationships between pH/ORP measurements and process state (nitrification, denitrification, and influent load).

The control algorithms are based on the fuzzy-logic theory [6,14,28-31] and consist of five stages. Stage 1 corresponds to the input step, where the input variables (linguistic variables) were calculated using a sample of accumulated data between two control actions. The time interval between two control actions was set to 30 minutes for the three controllers. The input linguistic variables were:

- Nitrification controller: first derivative of the 0.5-h moving-average of the pH located in the first chamber (pH_{An}) and first derivative of the 0.5-h moving-average of the pH located in the last chamber (pH_{Aef}).
- SND controller: first derivative of the 0.6-h moving-average of the ORP located in the first chamber (ORP_{An}) and first derivative of the 0.5-h moving-average of the pH located in the first chamber (pH_{An}).
- Denitrification controller: first derivative of the 0.5-h moving-average of the pH located in the second chamber (pH_{Ax}) and first derivative of the 0.6-h moving-average of the ORP located in the second chamber (ORP_{Ax}).

The moving average was used to filter the typical signal noise from the corresponding sensors and to gather information on the biological nitrogen removal process between two control actions. Each linguistic variable consists of a fuzzy set represented by membership functions [30,31], Gaussian shape in this study, defined by equation 1 at stage 2 of the algorithm:

$$\mu(p) = \exp\left(-\frac{(p-c)^2}{2\cdot\sigma^2}\right) \qquad \text{(Eq. 1)}$$

where p is the numerical value of the linguistic variable; and c and σ are the center and amplitude of the Gaussian membership function for a given linguistic label, respectively. The nitrification controller used four Gaussian membership functions to fuzzify each input variable (“High Negative”, HN; “Low Negative”, LN; “Low Positive”, LP and “High Positive”, HP), SND and the denitrification controllers used three Gaussian membership functions to fuzzify each input variable of each controller (“Negative”, N; “Zero”, Z;, and “Positive”, P).

In stage 3, the so-called inference engine [6, 14, 28], a set of rules was applied to calculate the relationship between antecedent (input linguistic labels) and consequents (output linguistic labels). The output linguistic variables of the controllers were the change in the oxygen set point value (nitrification and SND controllers) and the change in the nitrate recycling flow rate (denitrification controller). The value assigned to each output linguistic label was obtained through the Max-Prod operator, following Larsen's fuzzy inference method. Thus, for each rule defined, the following operator was applied:

$$\mu_{rule,i} = \prod_{1}^{j} \mu_j \qquad \text{(Eq. 2)}$$

where *j* represents the degree of truth of each input fuzzy set involved in the rule *i*, and $\mu_{rule,i}$ represent the degree of activation of the output linguistic label involved in rule *i*.

To obtain only one degree of activation for each output linguistic label (fuzzy set) when the consequences of different rules were the same, the following operator was applied:

$$\mu_k = \text{Max}(\mu_{rule,i}) \qquad \text{(Eq. 3)}$$

In stage 4, the so-called defuzzification, the output fuzzy sets were converted into the corresponding output linguistic variable [28,31]. Four Singleton membership functions were used: "High Negative", HN; "Low Negative", LN; "Low Positive", LP and "High Positive", HP. To obtain a unique output value (P) from the four fuzzy sets defined, the Height defuzzifier method was employed:

$$P = \frac{\sum_{i=1}^{n} k_i \cdot \mu(p_i)}{\sum_{i=1}^{n} \mu(p_i)} \qquad \text{(Eq. 4)}$$

where P is the output linguistic variable and k is the numerical value of the Singleton membership function for a given linguistic label.

Finally, stage 5 corresponds to the output stage, where the numerical control actions of the different controllers were obtained: the DO set points and the nitrate recycling flow rate (number and frequency of the recycling pumps in operation).

In addition, different knowledge-based and boundary-based rules were defined to adapt the BNR control system to different treatment schemes and to set a trade-off between effluent criteria compliance, energy savings, and operation limits. Thus, these rules modify the control actions from the fuzzy logic-based controllers according to the aeration demand dynamics, the WWTP layout and the system boundaries. These rules, as well as the inference engine rules, are explained below for each controller.

2.3.1.1 Nitrification controller

The variation of the pH in the aerobic chamber during the nitrification process gives an indication of its extent, and the variation of the influent pH gives an indirect indication of the variation of the influent nitrogen load, as explained in Table 2. Therefore, the nitrification degree of each lane was assessed by comparing the time profile of pH_{An} with the time profile of pH_{Aef}. The higher the relative decrease of the pH_{Aef} in relation to the pH_{An}, the stronger indication of nitrification process occurring in the system. This change in the nitrification degree depends on the influent load (mg NH_4-N·h^{-1} and mg BOD·h^{-1}) and the DO concentration in the system. For instance, a decrease in the nitrification degree for a certain DO level could be due to either an increase or decrease in influent load. In this respect, the trend of pH_{An} reveals indirectly the dynamics of the influent load profile. Thus, based on the information provided by these two control variables (pH_{An}, pH_{Aef}), the nitrification controller modified appropriately the DO_{Ae1} and DO_{Aef} set points. Particularly, if pH_{Aef} decreased and pH_{An} increased, the DO set points were increased, considering that the ammonium influent load was increasing and there was not enough aeration in the system. Alternatively, if pH_{Aef} increased, the DO set points were slightly modified according to the evolution of pH_{An}. If pH_{An} increased/decreased, the control system slightly increased/decreased the DO set points, respectively, assuming that the ammonium influent load was increasing or that the DO level was enough to nitrify the current ammonium influent load, respectively. On the other hand, when pH_{Aef} was stable over time, the information of the time profile of pH_{An} was used to anticipate the ammonium load entering the biological reactor. Using this information, and in order to obtain low ammonium concentration in the effluent, the controllers could establish the appropriate set points for the DO concentration in the two aerobic chambers of each lane. The control was performed independently for each of the two lanes in the WWTPs and an exhaustive analysis was performed in each chamber to determine the proper ranges for the DO set points (their maximum and minimum). For this, the hydrodynamics of the two lanes of the biological reactor, the aeration capacity of the facility and the yearly environmental variations, mostly associated to temperature changes, were taken into account. In this respect, acting as a supervisory controller of the nitrification and SND core algorithms, the following knowledge-based rules were defined for the nitrification and SND controller:

- DO range profile: the DO range along the aerobic chambers of each lane. It was determined mainly based on the diffuser's density along the aerobic chambers. In this respect, when the diffuser's density was higher in the last aerobic chamber, the maximum and minimum DO_{Aef} values were higher than the maximum and minimum DO_{Ae1} values and vice versa (see Table 1). This difference in the DO range profile is due to the different aeration capacity supplied for the higher/lower diffuser's density along the aerobic chambers.

- Variable DO lower bound: This bound was automatically adjusted based on the minimum aeration requirements to ensure proper nitrification depending on the operating conditions of the WWTP, i.e., combination of the operating sludge retention time (SRT) and temperature (T). The minimum DO for each aerobic chamber was higher in the winter season (lowest T) than in summertime. In this respect, a feature of the control system consists in informing the user of the need to increase the operating SRT and the minimum operating DO for the facultative/aerobic chambers. This action is suggested when the supervisory control system establishes for a long period (set to 2 weeks in this work) the maximum DO set points in the facultative/aerobic chambers. This performance indicates that the operating SRT is not enough to comply with the effluent requirements due to a change in the influent load or/and operating temperature. On the contrary, when the control system sets the minimum DO set points in the facultative/aerobic chambers during a significant period (set to 2 weeks), the control system suggests the user to reduce the operating SRT and to decrease the minimum operating DO for the facultative/aerobic chambers.
- Supervision of DO set point variation: DO set point cannot be increased when the DO set point is already 15 % higher than the measured value. In the same way, the DO set point cannot be decreased when the DO set point is already much lower than the measured value.

2.3.1.2 Simultaneous Nitrification-Denitrification (SND) controller

These fuzzy logic-based control systems commanded the DO set point value of the facultative chamber of each treatment lane (DO_{Fac_SP}) within the operating range defined by the knowledge based-rules explained above. In this case, the DO range was lower than the one defined for the aerobic chambers (DO_{Ae1} and DO_{Aef}), see Table 1. The control variables for the SND process were related to the organic/ammonium loading rate entering the system, and therefore, according to the assumptions listed in Table 2, the time profiles of ORP_{An} and pH_{An} were examined: the lower the ORP, the higher the organic loading rate entering the system, whereas the higher the pH_{An}, the higher the ammonium loading rate entering the system. Whenever the pH decreased and the ORP increased (periods of lower influent load), the DO set point was decreased by the controller to favor the SND process. On the contrary, when influent load was increasing, the DO_{Fac_SP} was increased to favor the nitrification process.

The following knowledge-based rule was added to the ones defined for the nitrification controller. They all acted as a supervisory controller of the SND core algorithm:

- ORP_{An} range: this range was defined as control boundaries for the SND controller. Based on the on-line and off-line monitoring of the biological process of each treatment lane, minimum and maximum values of ORP_{An} were set, defining different ranges for winter and summer conditions. In this respect, at each control time, if the 0.6-h moving average of ORP_{An} was lower than the fixed minimum value, more abrupt control actions were allowed (i.e., drastic increase in DO_{Fac_SP}) to support the nitrification process under high loading conditions. Conversely, if the 0.6-h moving average of ORP_{An} was higher than the fixed maximum value, the DO_{Fac_SP} was quickly decreased to its minimum value (increasing the maximum control action 20 % each control time) to push the denitrification degree via SND process.

2.3.1.3 Denitrification controller

Each facility incorporated one independent denitrification controller per lane. These fuzzy logic-based control system aimed at minimizing the nitrate recycling flow rate, thus minimizing associated energy consumption, while maintaining low nitrate concentrations at the end of the anoxic chamber. The nitrate recycling flow rate was controlled by modifying the number of recycling pumps (RP) in operation in each treatment lane and by adjusting their frequency converters in order to maintain their rotation speed within the operating range defined by the knowledge-based rules described in this section. This nitrate recycling flow rate was set depending on the denitrification capacity of the system. For this, the time profiles of pH_{Ax} and ORP_{Ax} were observed, knowing, according to Table 2, that the former refers to the denitrification potential of the system and the latter is related to the time evolution of nitrate concentration: the higher the increase in the pH_{Ax} trend related to the ORP_{Ax} trend (nitrate concentration), the stronger indicator of denitrification process occurring in the system.

Acting as a supervisory controller of the denitrification control algorithm, the following knowledge-based rules were defined:

- ORP_{Ax} range: this range was defined as control boundaries for the denitrification controller. Based on the on-line and off-line monitoring of the biological process of each treatment lane, minimum and maximum values of ORP_{Ax} were set. In this respect, at each control time, if the 0.6-h moving average of ORP_{ax} was higher than the fixed maximum value, the nitrate recycling flow rate was sharply decreased to minimize energy consumption derived from pumping due to low denitrification capacity. Conversely, if the 0.6-h moving average of ORP_{ax} was lower than the fixed minimum value, the nitrate recycling flow rate was sharply increased to promote denitrification.

- Maximum/minimum number of nitrate recycling pumps in operation: plant operator was able to set the maximum number of RP that could be running simultaneously.
- Pumping levels hierarchy: when different RP are available in the WWTP, different nitrate recycling levels can be defined. Each pumping level is characterized by the specific number and type of RP that are simultaneously commanded by the controller, jointly with their minimum and maximum pumping capacity. When the defined maximum/minimum pumping capacity is reached and maintained for more than a predefined time interval, a higher/lower pumping level is needed, respectively.
- Conditions for level change: to avoid RP being unnecessarily switched on/off, two conditions were stablished to allow the pumping level to change. The supervisory control system verified the following two conditions to be fulfilled: (1) pumping regulation was working within a given minimum/maximum band for a given time interval; and (2) pumps were working in the same level for a given time interval (time since last RP start/stop). All these parameters (error bands and time intervals) can be modified by plant operators.
- Operation mode of RP: the operator was able to choose the criteria for the selection of the RP to be connected/disconnected when all the previous conditions for pumping level change were fulfilled. This could be done either based on hours of operation (same for all RPs) or on a specific hierarchy.

2.3.2 Aeration control system

An advanced aeration control system (ACS) based on the most open valve (MOV) principle was firstly implemented as a lower layer controller [6] of the BNR control system previously described. It consisted of a combination of cascade controllers (Appendix, Fig A2) aimed at reaching the needed DO concentration in each aerobic or facultative chamber under the minimum aeration equipment discharge pressure. The controller was subdivided into i) a basic level consisting in a cascade of fuzzy logic lower-layer controllers, and ii) an upper level consisting of knowledge-based rules on which the final control actions were based, setting a trade-off between effluent criteria compliance, energy savings and operation limits. The lower-layer controllers were the following:

i) DO controller: an algorithm which maintains the DO concentration set point in each aerobic/facultative chamber by regulating the control valve opening. An aerobic/facultative chamber is defined by the presence of an independent air feed (grid of diffusers, control valve) and DO measurement (DO probe). There are as many independent algorithms implemented as aerobic/facultative chambers defined. Particularly for this case, the control system in WWTP#1 and WWTP#2 had 6 DO controllers (two lanes with 3 aerobic/facultative chambers each) and the control system in WWTP#3 had 4 DO controllers (1 lane with 4 aerobic/facultative chambers).

ii) Pressure set point controller: an algorithm which sets the system pressure set point by defining the minimum required pressure to optimize energy consumption. Specifically, this control system modifies the pressure set point to maintain the DO set point of the aerobic/facultative chamber where the MOV is located. The knowledge-based rules set the MOV location in the facultative/aerobic chamber with both the highest oxygen deficit (the maximum difference between DO set point and DO measurement) and the control valve completely open.

iii) Pressure controller: an algorithm which maintains the system air pressure close to the set point by regulating each aeration equipment (blower or turbo blower) and the number of aeration equipment in operation. The output variable for this controller was different amongst the three WWTPs, taking into account the type of aeration equipment and their different regulation possibilities.

In WWTP#1, the control system acted upon the position of the turbo blower diffuser vanes and/or the frequency converters of the blowers, allowing for the sharpest tuning of the DO concentration. In WWTP#2 the vanes position of the turbo blowers could not be set directly. Instead, a pulse was sent to the equipment to indicate if the vane must open or close. In WWTP#3 it was not possible to manipulate the turbo blowers since they were blocked by the supplier. Instead, a pressure set point was sent to the internal PID controller of the equipment, which performed the internal regulation accordingly. The aeration control system was able to adapt to all these different circumstances and operating restrictions that are typical in real applications.

A detailed description of the aeration control system can be found elsewhere [6]. Regarding the MOV principle, a more comprehensive description can be found in [20, 32-33].

3. Results and discussion

This section presents the performance of the BNR control system and the ACS. The differences amongst the three WWTPs are also discussed. Subsequently, the results obtained from WWTP#1 operation are shown as a specific example of the BNR system implementation in a large WWTP.

3.1. Aeration control system performance

Prior to the implementation of the ACS, all DO concentration set points were manually set by the operators around the values shown in Table 1. Usual values for WWTP#1 were 2.7 mg·L^{-1}, 2.5 mg·L^{-1} and 1.4 mg·L^{-1} for the first, second and last aerobic chambers of each lane, respectively. To achieve these DO concentrations, an aeration equipment discharge pressure between 695-720 mbar was maintained. The viability of reducing such pressure without disturbing the process was demonstrated by the fact that there were periods when none of the control valves allowing the air into the reactors was completely open. In WWTP#2, only the DO of the first and last aerobic chamber were controlled (DO set points of 0 mg·L^{-1} and 2.6 mg·L^{-1}, respectively) before the implementation of the ACS. Regarding WWTP#3, only the DO of the third aerobic chamber was controlled at a set point of 1.5 mg·L^{-1} prior to the implementation of the ACS.

3.1.1. ACS implementation in WWTP#1

The aeration system in WWTP#1 consists of one turbo blower with adjustable position of the diffuser vanes (T1) and four blowers equipped with frequency converters (B1, B2, B3 and B4).

Once the ACS was set-up, several operating parameters were established, such as: maximum and minimum frequencies and vanes position, operation mode of the aeration equipment or characteristic curve of the control valves (see [6]). The parameters of the control algorithms were calibrated (i.e., Gaussian-shape and Singleton membership functions parameters or control times) and the optimal configuration for the aeration system was found. The latter determined the hierarchy sequence of the aeration levels. Particularly, five aeration levels were defined, which were gradually allowed to come to operation in the following order to increase aeration capacity: one blower (with the least accumulated working hours), two blowers (with the least accumulated working hours), one turbo blower, one turbo blower and one blower, and one turbo blower and two blowers.

Figure 2 shows the behavior of the six implemented DO controllers once the BNR control system was implemented. The DO concentrations (in blue) were maintained close to the established set points commanded by the BNR control system (in black) by regulating the corresponding control valves (aperture degree in orange) within the control valve range previously defined.

According to the MOV theory, the control valve of the chamber with the largest oxygen deficit was set to the maximum allowed opening position (100 %), which allowed working at minimum discharge-pressure of aeration-equipment. The pressure set point controller determined the set point for the aeration system discharge pressure in order to control the DO concentration required in the chamber were the MOV was located. As Figure 2 shows, during this operating period, the largest oxygen deficit was generally observed in the second aerobic chamber in lane 2 (Figure 2D), followed by the third aerobic chamber in lane 2 (Figure 2F).

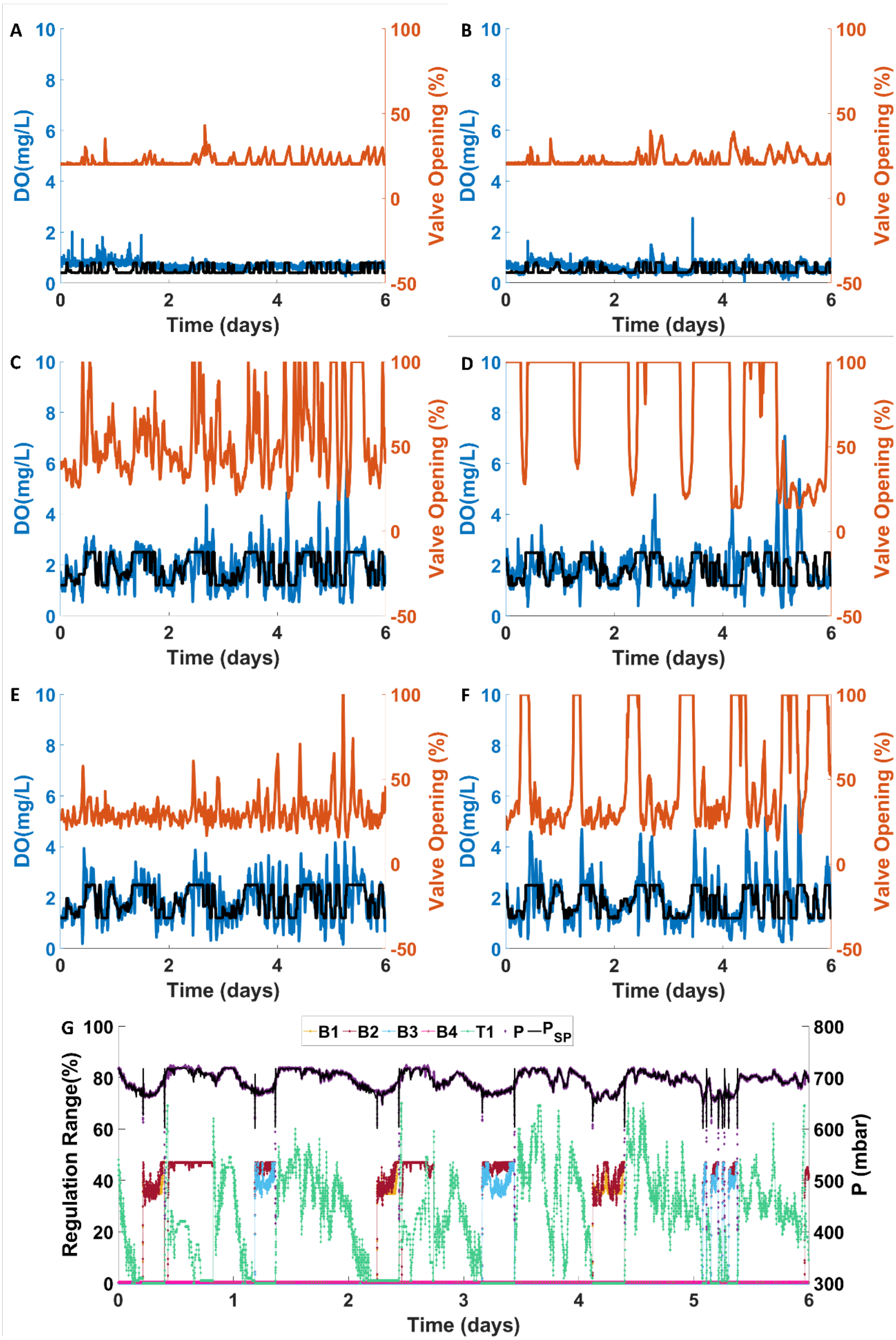

Figure 2. Aeration control system performance in WWTP#1: A) facultative chamber, C) first aerobic chamber, and E) last aerobic chamber in lane 1; and B) facultative chamber,

D) first aerobic chamber, and F) last aerobic chamber in lane 2. DO set point (black), 5-min moving-average measured DO (blue) and CV aperture (orange), and G) pressure set point is presented in black (P_{SP}), 2-min moving-average monitored aeration equipment discharge pressure in purple (P). Yellow, red, blue, pink, and green represent the regulation of the aeration equipment (B1, B2, B3, B4 and T1, respectively).

Figure 2G shows the performance of the pressure control system during the same operating period as above. Aeration equipment discharge pressure (in purple) closely met the pressure set point determined by the control system (in black), indicating a proper regulation of the aeration equipment. The second aeration level (two blowers) and the third aeration level (turbo blower) were the common aeration requirements in WWTP#1 for this period. The first aeration level (one blower) and fourth aeration level (one turbo blower and one blower) were not needed during this operating period since they required of lower and higher organic loading rates entering the plant, respectively. It is important to note that during the first 12 h of day 5, the plant demanded an aeration capacity that did not fit with the available aeration levels: two blowers working at their maximum capacity were not enough to reach the required pressure discharge level, whilst one turbo blower working at the minimum capacity provided excessive air pressure (see Figure 2G). This particular situation, which can be reached in industrial facilities where aeration equipment is not properly designed, caused an oscillatory behavior in DO profiles of aerobic chambers.

3.1.2. ACS implementation in WWTP#2

The aeration system in WWTP#2 consisted of three turbo blowers with adjustable positions of the diffuser vanes and a blower with smaller capacity regulated with a frequency converter. Technical specifications limited the actuation time on the turbo blowers, meaning that the actuation frequency of the pressure control system was lower than expected. This fact implied that the response of the control system was also slower than the one achieved otherwise. Accounting for these system boundaries, it can be concluded that the DO controllers run adequately, as it can be seen in Figure 3.

In this plant, the chamber with the highest MOV was frequently the last aerobic chamber in lane 1 (i.e., DO_{Aef}, see Figure 3E), followed by the first aerobic chamber in lane 1 (i.e., DO_{Ae1}, see Figure 3C). Important to note is the particularity of this facility since the diffuser's density of the last aerobic chamber was lower than the ones of the previous aerobic chambers. For this reason, as can be seen in Table 1, the DO_{Aef_SP} range was lower than the previous aerobic chamber, i.e., DO_{Ae1_SP}. As it can be seen in Figure 3, the BNR control system set lower DO concentrations set points than the ones previously set in the plant (see Table 1), mostly during low load periods. On the other hand, the pressure controller also maintained the aeration equipment discharge pressure close to the calculated set point (Figure 3G).

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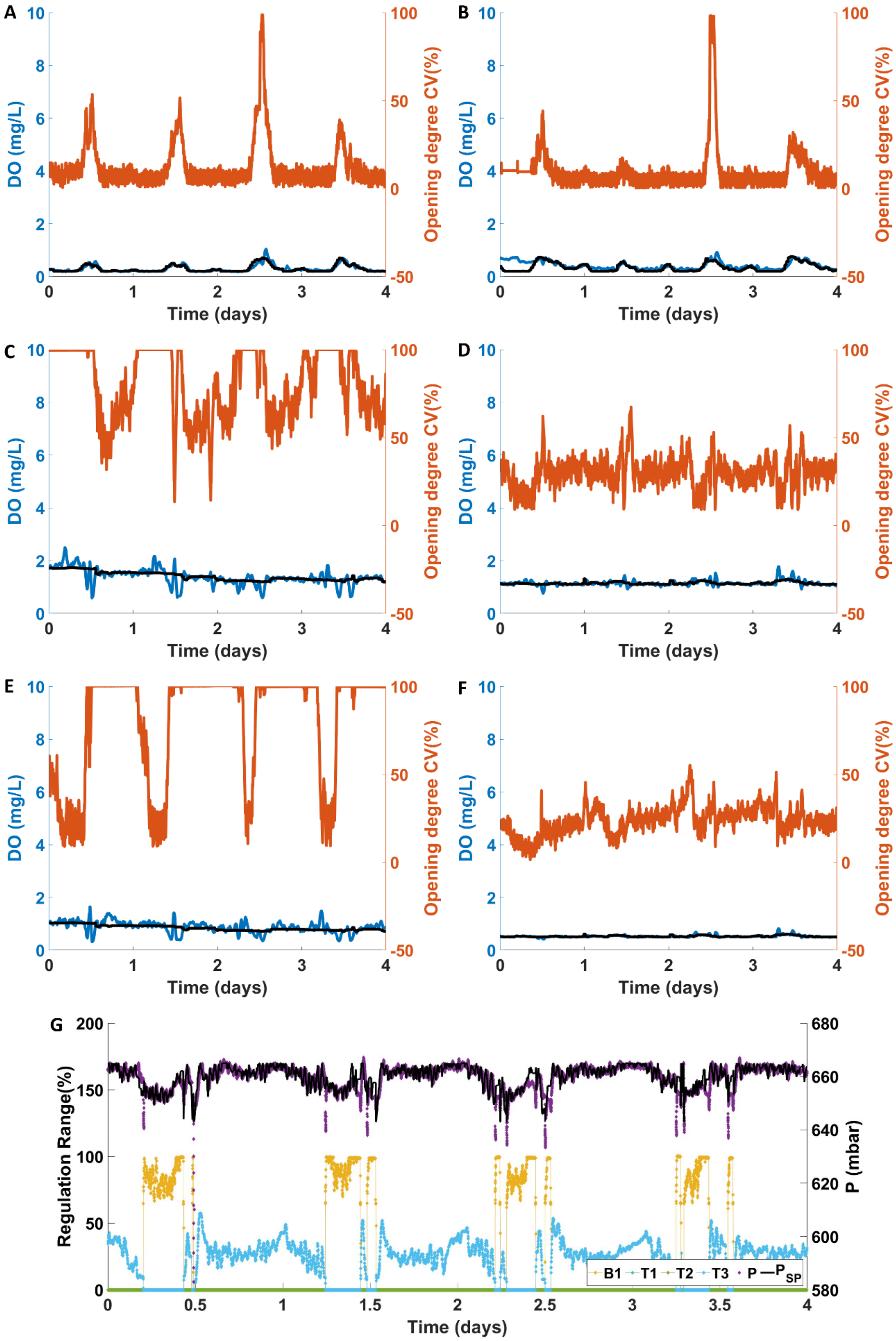

A
B
C
D
E
F
G
DO (mg/L)
Opening degree CV(%)
Time (days)
Regulation Range(%)
P (mbar)
B1
T1
T2
T3
P
P_SP

Figure 3. Aeration control system performance in WWTP#2: A) facultative chamber, C) first aerobic chamber, and E) last aerobic chamber of lane 1; and B) facultative chamber, D) first aerobic chamber, and F) last aerobic chamber of lane 2; and G) pressure set point in black (P_{SP}), 2-min moving-average monitored system pressure in purple (P), and yellow, blue, green and blue represent the regulation of the aeration equipment (B1, T1, T2 and T3, respectively). DO set point (black), 5-min moving-average measured DO (blue) and CV aperture (orange).

3.1.3. ACS implementation in WWTP#3

As explained in section 2.3.2, regulation of the air equipment was not possible in WWTP#3. A pressure discharge set point was sent to the controller of the turbo blower, which performed the regulation internally. The configuration of this case study was a response to real operational constraints, which allowed for a lower aeration control accuracy due to the constrains on the time response of the internal PID controller of the turbo blowers.

Figure 4 shows the performance of the control system in WWTP#3. In this plant, the two chambers (DO_{Ae1} and DO_{Aef}) were equally often designated as MOV. Regarding the pressure set point controller, it was possible to control the aeration demand on the system when the lower and upper limit operating boundaries were not met, i.e., minimum, and maximum aeration capacity of the turbo blower. Again, the BNR control system commanded lower DO concentrations and air requirements than the ones established before the implementation of the ACS controller, resulting in an efficient biological nitrogen removal process.

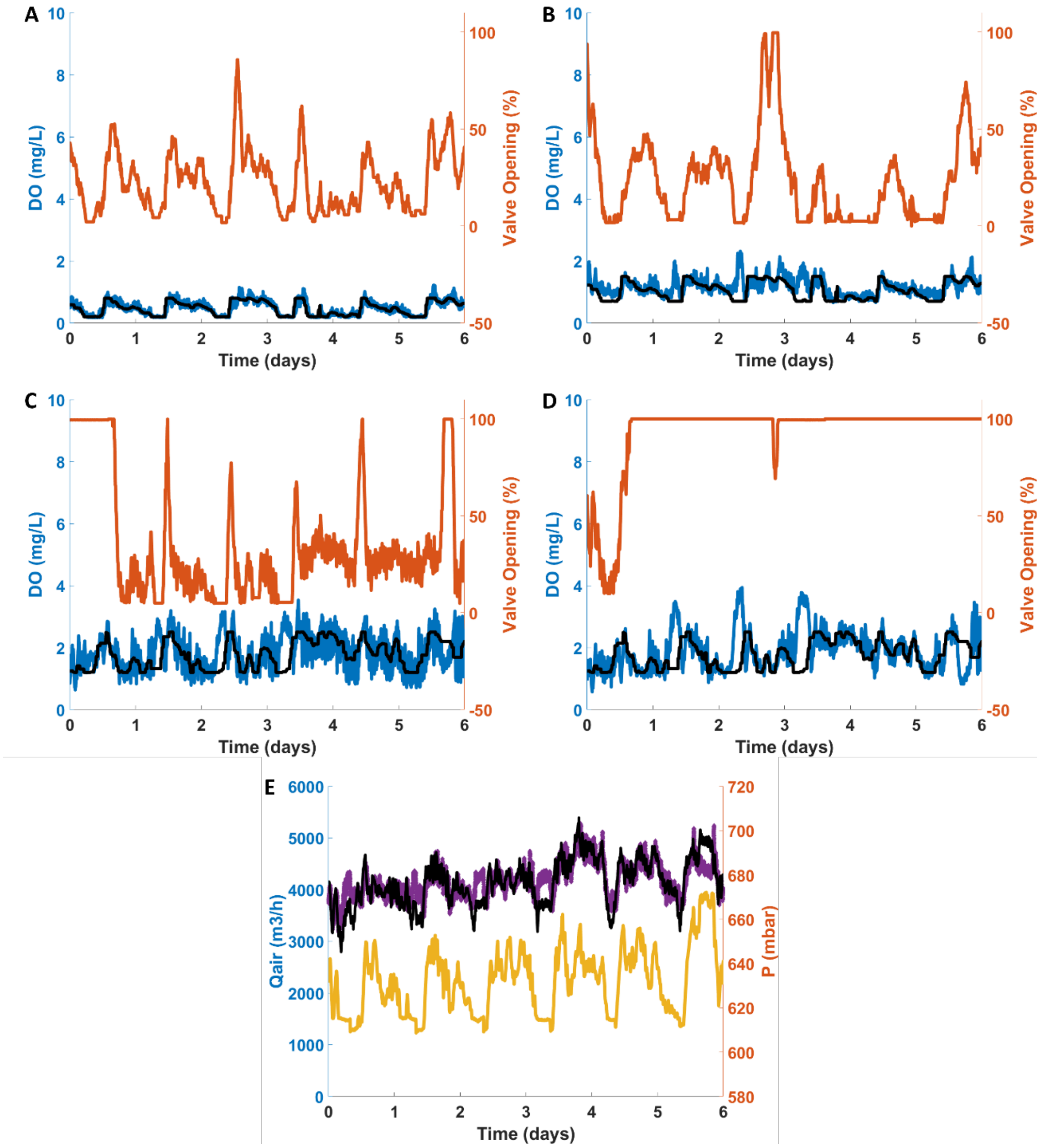

Figure 4. Aeration control system performance in WWTP#3: A) first facultative chamber, B) second facultative chamber, C) first aerobic chamber, D) last aerobic chamber, and E) pressure set point in black (PSP), 2-min moving-average monitored system pressure in purple (P), and commanded aeration capacity in yellow. DO set point (black), 5-min moving-average measured DO (blue) and CV aperture (orange).

3.2. BNR control system implementation in WWTP#1

3.2.1. Nitrification controller

Prior to the BNR control system implementation, the set points for the DO concentration were manually set, which at times resulted in too low or too high values for the nitrification process. Influent and effluent ammonium concentrations to and from the reactor varied between 11.4 - 36 mg/L and 0.04 - 4.9 mg/L, respectively.

Figure 5 shows the performance of the nitrification control system in WWTP#1 during the month of January, when the average temperature was 15 ºC, by representing inputs and outputs to the control system (i.e., 0.5-h moving-average of pH_{An} and pH_{Aef} and DO_{Ae1_SP}, DO_{Aef_SP}, respectively) together with the 0.5-h moving-average of ammonium concentration in the anoxic chamber and effluent. It must be noted that corresponding values for pH, DO and ammonium concentration of the anoxic chamber are shown for the two parallel lanes, whereas the ammonium concentration was measured in the effluent of the activated sludge system. This ammonium measurement corresponds to the only ammonium probe installed, located at a point after the effluent of the two lanes had come together, downstream of the secondary clarifier.

The pH measurements in the anaerobic chamber (pH_{An}) presented a daily oscillation with a trend similar to that of the ammonium concentration in the anoxic chamber ($NH4_{Ax}$), showing that higher values of pH at the beginning of a plug-flow biological reactor indicate higher concentrations of ammonium entering the system with the wastewater. It must be noted that there was a delay in the figure between both pH_{An} and $NH4_{Ax}$ variations due to different locations along the treatment lane (beginning of the anaerobic chamber and end of the anoxic chamber, respectively).

As Figure 5 illustrates, the set points for the DO concentration in the aerobic chambers (DO_{Ae1_SP} and DO_{Aef_SP}) were increased accordingly to the ammonium peaks incoming to the reactor, revealing proper controller performances. Nonetheless, even achieving a quick response in the reactor, a slight increase in ammonium effluent concentration ($NH4_{Ef}$) was observed, accounting for the corresponding delay due to the hydraulic retention time of the system. These slight effluent peaks revealed the extent to which the capacity of the aeration equipment installed in the WWTP was not able to respond fast enough to cope with the peak in the incoming load.

Important to note are the differences on the nitrification controller performance between the two lanes. As it can be observed in the $NH4_{Ax}$ profile, the ammonium load in lane 2 was lower than in lane 1. For this reason, lane 2 presented lower DO set points than lane 1. These differences were due to an unequal distribution of both influent flow and air distribution among the lanes.

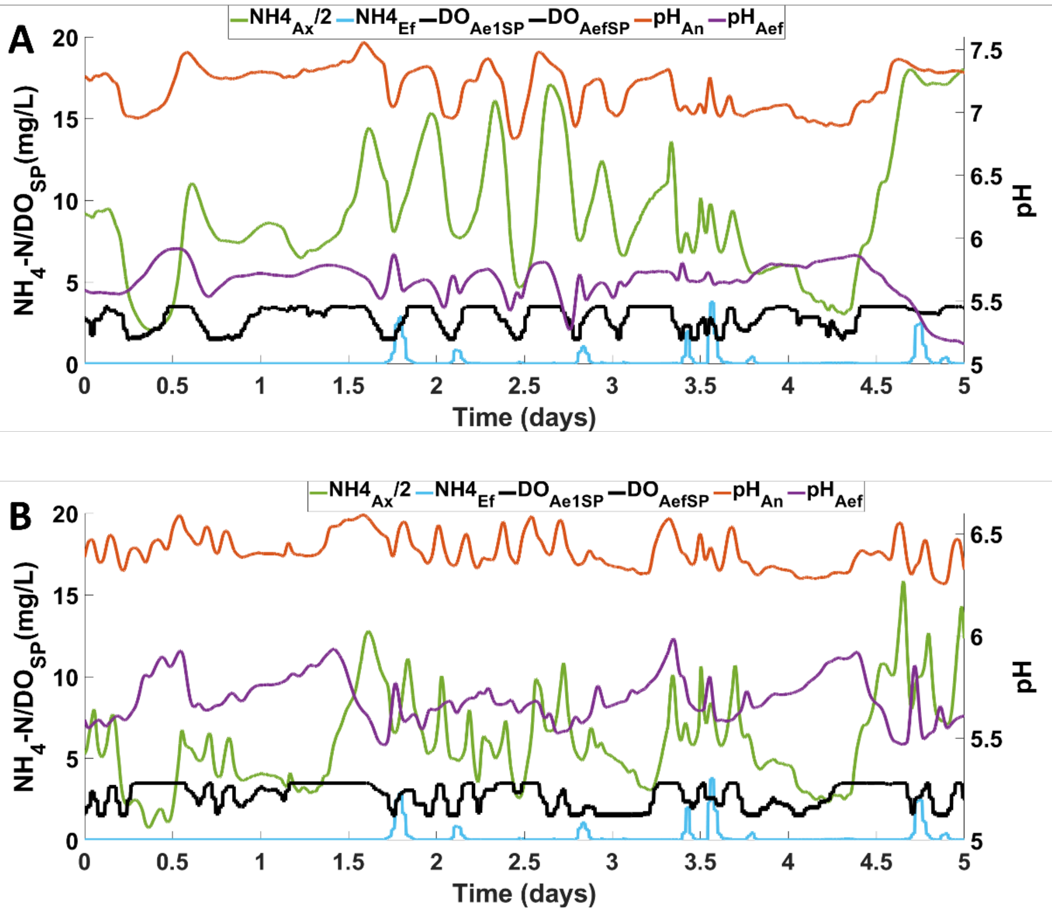

Figure 5. Nitrification controller performance in winter (January): A) Lane 1 and B) Lane 2. $NH4_{Ax}/2$: 0.5-h moving-average ammonium concentration in the anoxic chamber, divided by 2. $NH4_{Ef}$: 0.5-h moving-average ammonium concentration in the effluent of secondary settler. DO_{Ae1_SP} and DO_{Aef_SP}: DO set points in the first and second aerobic chambers. pH_{An}: 0.5-h moving-average pH in the anaerobic chamber. pH_{Aef}: 0.5-h moving-average pH in the last aerobic chamber.

Figure 6 shows the performance of the nitrification control system in WWTP#1 in summertime (same period illustrated in Figure 2 for ACS performance), when the average temperature was 22.3 ºC and the minimum DO set points (DO_{Ae1_SP} and DO_{Aef_SP}) were fixed at lower values than those set for the winter period (see Table 1).

As previously discussed, the nitrification control system increased the set points for the DO concentrations in the aerobic chambers when an increase in the system load and nitrification capacity were detected by the pH measurements. Figure 6 also shows that from day 3.5 of operation, the nitrification degree of both lanes increased, as revealed by the decreasing trend of $pH_{Aef,}$ regardless of the pH_{An} trend. This performance is also observed by the increase in the influent ammonium load as the $NH4_{Ax}$ trend illustrates. Overall, the control system commanded lower DO set points in the last aerobic chambers during this period than in winter conditions (see Figure 5).

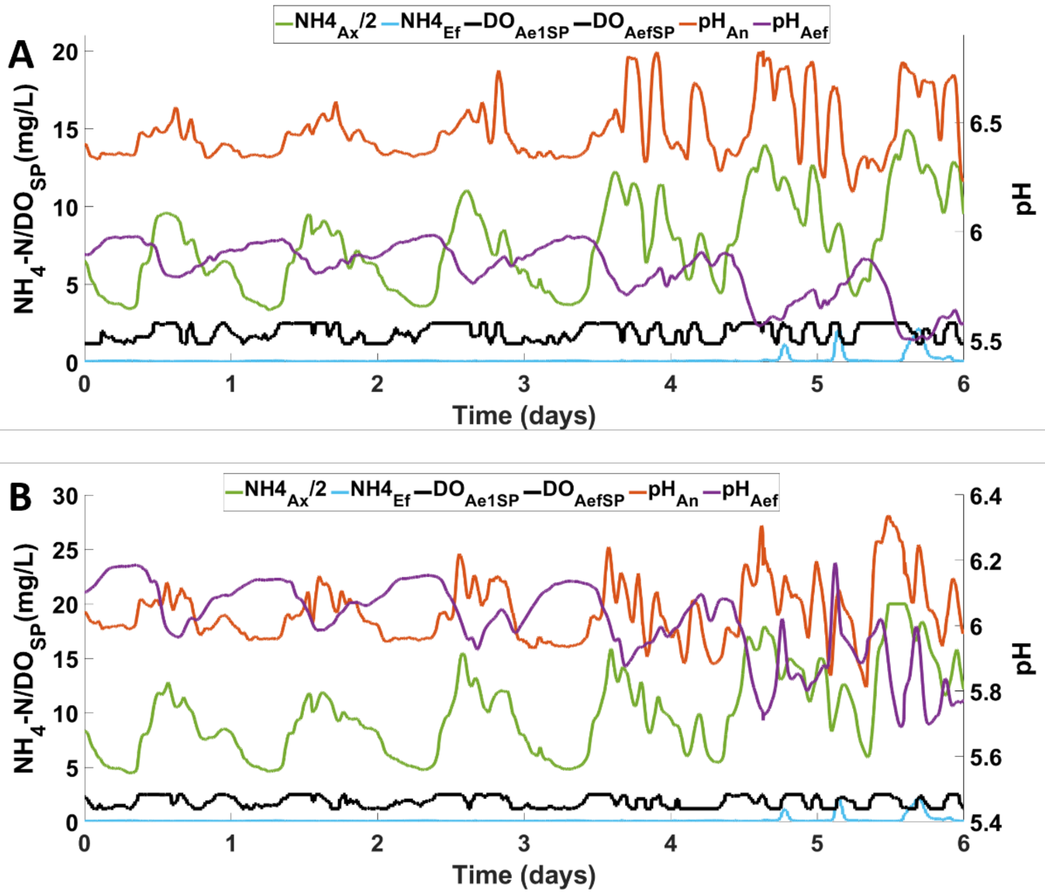

Figure 6. Nitrification controller performance in summer (June): A) Lane 1 and B) Lane 2. $NH4_{Ax}/5$: 0.5-h moving-average ammonium concentration in the anoxic chamber, divided by 5. $NH4_{Ef}$: 0.5-h moving-average ammonium concentration in the effluent of the secondary settler. DO_{Ae1_SP} and DO_{Aef_SP}: DO set points in the first and second aerobic chambers. pH_{An}: 0.5-h moving-average pH in the anaerobic chamber. pH_{Aef}: 0.5-h moving-average pH in the last aerobic chamber.

3.2.2 SND controller

Figure 7 shows the DO_{Fac_SP} and the 0.6-h and 0.5-h moving-average values of ORP_{An} and pH_{An}, respectively, as well as the 0.5-h moving-average ammonium concentration in the anoxic chamber ($NH4_{Ax}$) of each lane. Similar to the nitrification controller, the different location between pH_{An}/ORP_{An} and $NH4_{Ax}$ sensors must be taken into account for proper comparison of the measurements provided by this equipment, i.e., the hydraulic retention time in the system results in a delay for comparison between measurements. Figure 7A and Figure 7B illustrate the performance of the SND controller in winter (January), with an average temperature of 15.0 ºC, whereas Figure 7C and Figure 7D illustrate the performance in summertime (June), with an average temperature of 22.2 ºC. As Figure 7 shows, the control system increased DO_{Fac_SP} when ORP_{An} decreased, and pH_{An} increased. Under this situation, an increase in the ammonium load entering the system was happening, thus making it necessary to increase the nitrification capacity of the system. In contrast, when the nitrogen load decreased (i.e., ORP_{An} increased and pH_{An} decreased), DO_{Fac_SP} was decreased. As a result of establishing a low DO set point range, it was possible to favor the SND process by keeping DO concentrations low enough to favor denitrification process, and thus making nitrate available to denitrify simultaneously to the nitrification process. In general, DO set points during summer were lower than in winter since nitrification process rate was favored in the former.

During the calibration process, maximum and minimum absolute values were defined for ORP_{An} to define a normal operating range (which was different during winter and summer periods). When the measured ORP_{An} values lied outside this range, faster control actions were allowed (i.e., drastic increase or decrease in DO_{Fac_SP}) with the aim to bring this parameter back to their defined normal range (data not shown).

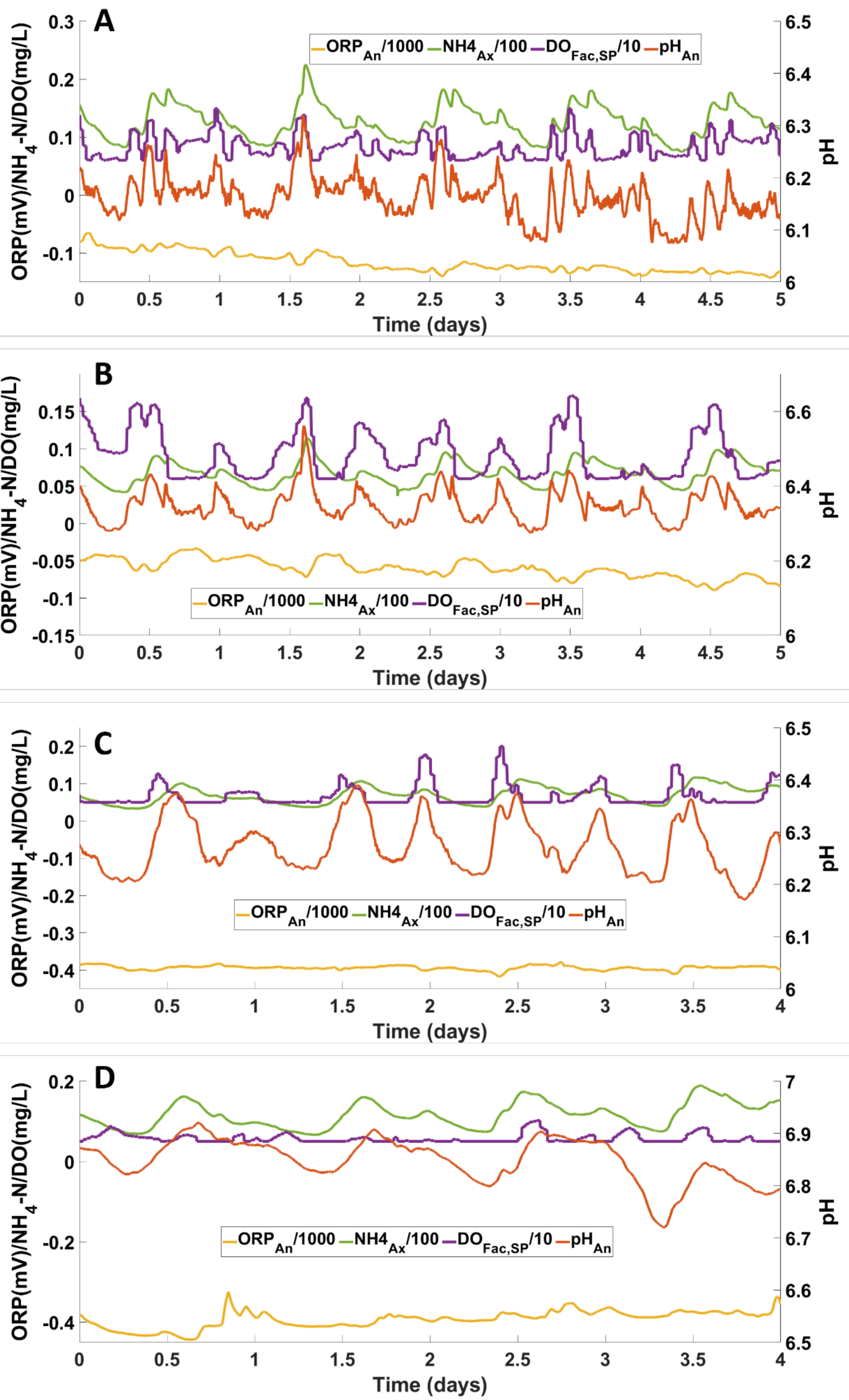
A
B
C
D
ORPAn/1000 NH4Ax/100 DOFac,SP/10 pHAn
ORP(mV)/NH4-N/DO(mg/L)
pH
Time (days)

Figure 7. SND controller performance: A) lane 1, winter; B) lane 2, winter; C) lane 1, summer; D) lane 2, summer. ORP_{An}/1000: 0.6-h moving-average ORP in the anaerobic chamber, divided by 1000. $NH4_{Ax}$/100: 0.5-h moving-average ammonium concentration in the anoxic chamber, divided by 100. DO_{Fac_SP}/10: DO set points in the facultative chamber, divided by 10. pH_{An}: 0.5-h moving-average pH in the anaerobic chamber.

3.2.3 Denitrification controller performance

Figure 8 shows the rotating speed of the nitrate recycling pumps, RP1 and RP2, and the 0.6-h and 0.5-h moving-average values of ORP_{Ax} and pH_{Ax}, respectively, as well as the 0.5-h moving-average nitrate concentration in the anoxic chamber ($NO3_{Ax}$) of each lane. Figure 8A and Figure 8B illustrate the performance of the denitrification controller in winter, with an average temperature of 15.7 ºC, whereas Figure 8C and Figure 8D illustrate the performance in October, with an average temperature of 22.5 ºC. As Figure 8 shows, the control system increased the pumps capacity when ORP_{Ax} decreased and pH_{Ax} increased. In this respect, the recirculation flow increased when the system showed a higher denitrification capacity: higher organic matter availability in relation to nitrate load in the anoxic chamber (i.e., higher pH levels and lower ORP levels).

By comparing Figure 8A and Figure 8B, it can be observed how the denitrification controller in lane 1 decreased the frequency of the recycling pumps as the ORP_{Ax} increased and the pH_{Ax} decreased (see, for instance, Figure 8A, days 4 to 7). In contrast, the main trend of ORP_{Ax} and pH_{Ax} in lane 2 (Figure 8B) was decreasing and increasing, respectively, maintaining the nitrate recycling flow rate at its maximum (the maximum frequency of the two RP), also due to the low ORP_{Ax} values, which were most of the period lower than the lower bound (-300 mV).

As per the SND controller, during the calibration period of the denitrification controller, maximum and minimum absolute values were set for ORP_{Ax} to define a normal operating range. When the measured ORP_{Ax} values lied outside this range, more abrupt control actions were allowed (i.e., drastic increase or decrease in the nitrate recycling flow rate) with the aim to bring this parameter back to their defined normal range. For instance, Figure 8B shows how ORP_{Ax} was lower than the lower bound during most of the period, and how that made the controller keep the two RP at their maximum capacity. On the other hand, Figure 8C (end of day 6) shows how the nitrate recirculation capacity was regulated to the lower boundary level by keeping only one recirculation pump to the minimum capacity (ORP_{Ax} values higher than the higher bound, -30 mV).

The denitrification controller performance was quite different between summer and winter conditions due to the effect of process temperature on microorganisms' kinetics. Overall, although the nitrate recycling flow rate set in summer was lower than in winter, the nitrate concentration at the end of the anoxic chamber ($NO3_{Ax}$) was higher in summer than in winter. In this respect, temperature was a key factor affecting both process and control system performance, reaching situations in which the aeration demand was lower than the minimum capacity of the first aeration level (one regulated blower), resulting in DO concentrations in the last aerobic chamber that could even negatively affect the denitrification process.

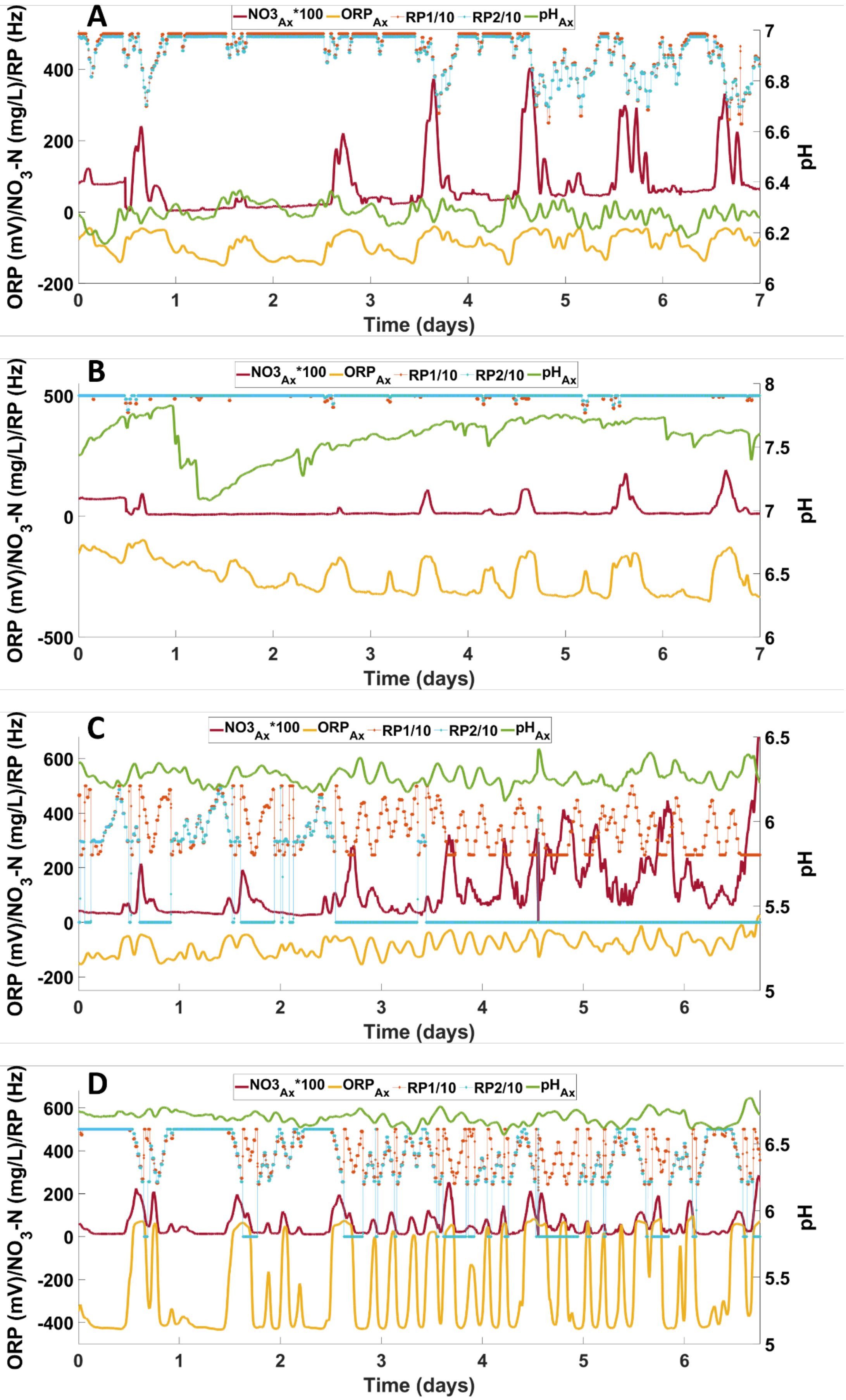
A
B
C
D
NO3Ax*100
ORPAx
RP1/10
RP2/10
pHAx
ORP (mV)/NO3-N (mg/L)/RP (Hz)
pH
Time (days)

Figure 8. Denitrification controller performance: A) lane 1, winter; B) lane 2, winter; C) lane 1, summer; D) lane 2, summer. $NO3_{Ax} \cdot 100$: 0.5-h moving-average nitrate concentration in the anoxic chamber, multiplied by 100. ORP_{Ax}: 0.6-h moving-average ORP in the anoxic chamber. RP1/10 and RP2/10: rotating speed of the recycling pumps 1 and 2, divided by 10. pH_{Ax}: 0.5-h moving-average pH in the anoxic chamber.

3.3. Overall performance

Table 2 shows the average energy consumption in the WWTPs before and after the implementation of the control system (BC and AC, respectively), expressed as kWh per m^3 of treated water, kWh per kg COD removed, and kWh per kg COD equivalent removed (considering the nitrified ammonium). As this table shows, energy consumption was reduced in all the facilities evaluated, highlighting the potential of the control system for energy optimization. Overall, between 14 % and 33 % energy savings were achieved (measured as kWh per kg COD equivalent removed).

In addition, by working with input control variables based on the dynamics of the measurements instead of absolute or average values, the control system showed robustness and tolerance towards sensor drifts and reduced sensor maintenance requirements. In this respect, manpower for maintenance purposes was estimated at 1, 0.9 and 0.9 hours work per month for the nitrification (2 pH sensors), SND (1 pH and 1 ORP sensor) and denitrification (1 pH and 1 ORP sensor) controllers, respectively. Moreover, the nitrification and SND controllers shared one pH sensor, resulting in an overall manpower for the BNR control system of 2.3 hours work per month. These manpower values were lower than those estimated in this work for the implementation of an equivalent control system based on ammonium and nitrate sensors: 1.3, 2.7 and 4.0 hours work per month for the nitrification (1 NH_4 sensor), SND (1 NH_4 and 1 NO_3 sensor) and denitrification (1 NO_3 sensor) controllers, respectively. Hence, overall manpower savings of 41.7 % were estimated in this work. Jointly with the above-mentioned energy saving, manpower saving also demonstrated that the proposed BNR control system allowed minimizing overall operating costs.

The performance of the BNR process improved after the implementation of the control system: effluent TN concentration decreased in all the evaluated facilities, highlighting the potential of the control system for enhancing both nitrification and denitrification processes (Table 3). Overall, between 14 % and 33 % energy savings were achieved (measured as kWh per kg COD equivalent removed) and total nitrogen concentration in the effluent decreased between 10 % and 30 %. This was due to an intensification in denitrification process of up to 46 %. In this sense, the controller allowed meeting effluent discharge criteria as well as increasing trust within operators through a reliable and improved process operation, which became more stable and therefore decreased vulnerability to process disturbances.

	WWTP#1		**WWTP#2**		**WWTP#3**	
	BC	**AC**	**BC**	**AC**	**BC**	**AC**
$kWh\cdot m^{-3}$	0.25±0.03	0.21±0.02	0.23±0.06	0.14±0.05	0.38±0.10	0.30±0.07
$kWh\cdot kg\ COD_{eq}^{-1}$	0.28±0.05	0.24±0.06	0.36±0.08	0.24±0.03	0.57±0.20	0.44±0.09
TN ($mg\ N\cdot L^{-1}$)	9.4±1.4	8.5±0.9	8.5±2.2	7.3±1.3	8.7±2.5	6.2±1.8
NH_4-N ($mg\ N\cdot L^{-1}$)	0.9±0.6	0.3±0.4	0.9±2.3	0.7±1.1	1.3±2.0	0.9±1.1
NO_3-N ($mg\ N\cdot L^{-1}$)	7.0±1.2	6.8±0.9	6.5±1.3	5.1±1.1	5.0±1.6	2.7±1.1

BC: before implementing the control system. AC: after implementing the control system.

Table 3. Energy consumption of the biological (kWh) treatment scheme within the facilities evaluated and nitrogen content in their effluent.

In summary, this study presents a comprehensive analysis of the practical implications of a low-cost-sensor-based control system for BNR processes in WWTPs. The effectiveness of the proposed control system has been thoroughly assessed in terms of cost, usability, and robustness from the results of the three full-scale implementations shown here. The cost analysis reveals that the proposed control system exhibits a substantial advantage over traditional ammonium and nitrate sensors/analyzers in terms of both capital and operating expenses. The cost effectiveness of the control system is particularly noteworthy in relation to the size of the WWTP, where significant cost savings are achieved.

In terms of usability and comprehensibility, these controllers were designed to be adaptable, emphasizing on simplifying the understanding of control loops. Although it is acknowledged that the fine-tuning of fuzzy logic-based controllers can be intricate, they exhibit a remarkable degree of adaptability to different operating conditions, efficiently catching process dynamics. Notably, prior knowledge-based adjustments, underpinned by systematic monitoring and historical data, it is possible to establish a set of control parameters values enabling the system to operate effectively within acceptable operating ranges. Furthermore, the flexibility and potential for broad applicability of this control system to different WWTPs is a key feature. This approach not only reduces sensor maintenance requirements but also enhances the overall resilience of the system, even in the face of sensor drifts. As shown in these three full-scale scenarios, the manpower required for sensor maintenance was significantly lower than that from equivalent control systems based on traditional ammonium and nitrate sensors. This is translated into significant operating cost savings, with an estimated reduction of 41.7%.

Beyond cost considerations, the implementation of the control system resulted in significant improvements in the performance of the BNR process, underscoring the potential of the system to improve both nitrification and denitrification processes. The practical applicability and significance of this controller in full-scale wastewater treatment scenarios is enhanced by meeting effluent discharge criteria while increasing operator confidence on reliable automated process performance and reducing vulnerability to process disturbances.

Hence, this study demonstrates the practical functionality of this low-cost-sensor-based BNR control system. By considering cost effectiveness, usability, and adaptability, this work underscores the significant potential of the proposed control system for cost savings while improving the overall performance of the BNR process.

4. Conclusions

The capability of a fuzzy-logic-based control system based on low-cost and low maintenance-requirement sensors for BNR process optimization has been validated in three municipal WWTPs. The control system, combining independent control loops (nitrification, SND and denitrification), allowed the average effluent total nitrogen concentration to be kept below the required discharge limits, responding properly to the strong dynamics in the influent load and flow and the variations on environmental and operating conditions within each facility. Controlled variables were kept around the corresponding flow set point value, achieving a reliable and improved process operation in terms of stability against disturbances. The set of knowledge-based rules included in the control system allowed to properly limit the response of the controllers under given operating conditions, avoiding unnecessary aeration and nitrate recycling pumping demands, while allowing the control system to be adapted to different WWTP characteristics. Overall, energy savings between 14 % and 33 % were achieved after the implementation of the control system in the three facilities evaluated.

Acknowledgments

This research did not receive any specific grant from public funding agencies. The authors would like to thank plant operators who collaborated in the control system implementations.

Appendix A.

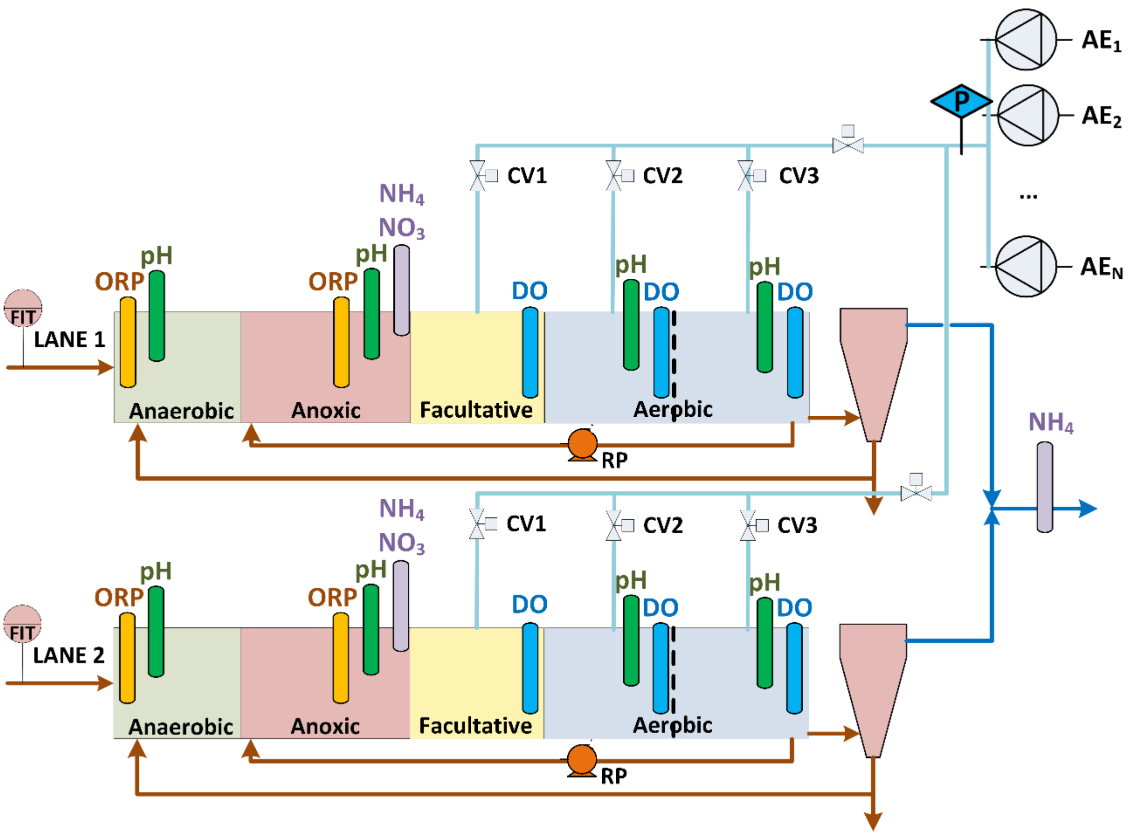

Figure A1. General lay-out of the three WWTPs evaluated. AE: aeration equipment, CV: control valve, RP: recycling pump, P: pressure.

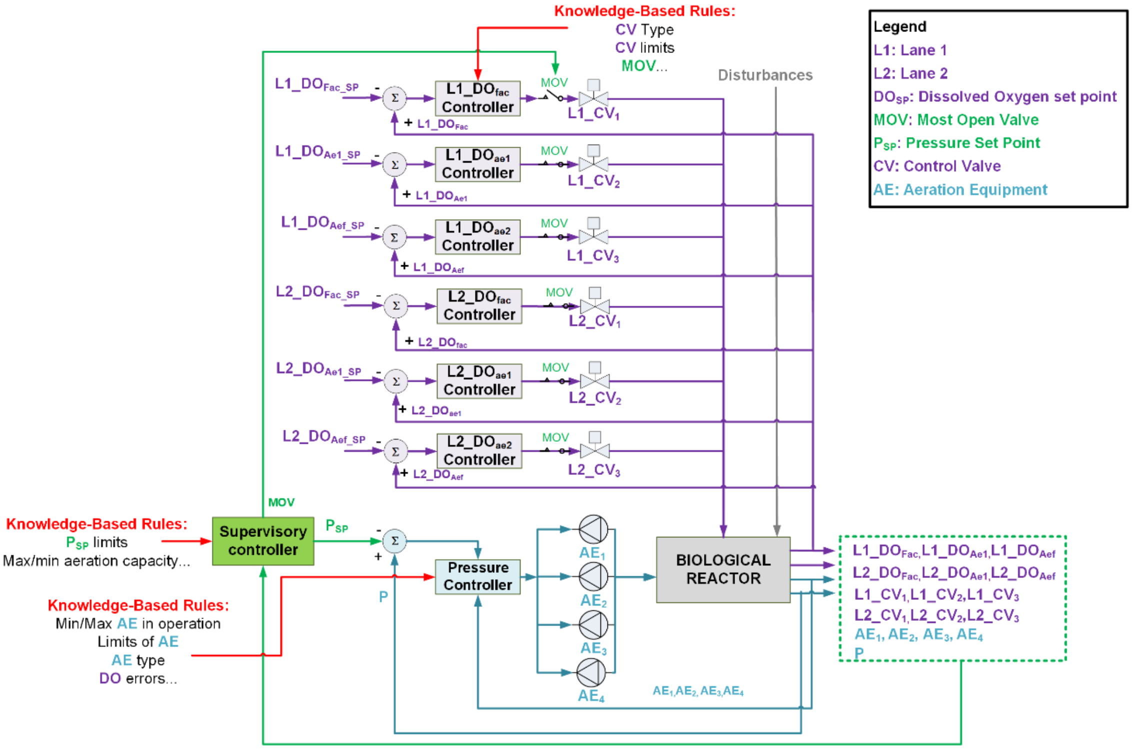

Figure A2. Architecture of the aeration control system in WWTP#1.

References

[1] Palatsi, J., Ripoll, F., Benzal, A., Pijuan, M., Romero-Güiza M.S., Enhancement of biological nutrient removal process with advanced process control tools in full-scale wastewater treatment plant, Water Res 200 (2021) 117212. https://doi.org/10.1016/j.watres.2021.117212.

[2] Stentoft P.A., Munk-Nielsen T., Moller J.K., Madsen H., Valverde-Pérez B., Mikkelsen P.S., Vezzaro L., Prioritize effluent quality, operational costs or global warming? –Using predictive control of wastewater aeration for flexible management of objectives in WRRFs, Water Res 196 (2021) 116960. https://doi.org/10.1016/j.watres.2021.116960.

[3] Rosso D., Larson L. E., Stenstrom M.K., Aeration of large-scale municipal wastewater treatment plants: state of the art, Water Sci Technol 57 (7) (2008) 973–978. https://doi.org/10.2166/wst.2008.218

[4] Haslinger J., Lindtner S., Krampe J., Operating costs and energy demand of wastewater treatment plants in Austria: benchmarking results of the last 10 years, Water Sci Technol 74 (11) (2016) 2620–2626. https://doi.org/10.2166/wst.2016.390.

[5] Bernardelli A., Marsili-Libelli S., Manzini A., Stancari S., Tardini G., Montanari D., Anceschi G., Gelli P., Venier S., Real-time model predictive control of a wastewater treatment plant based on machine learning, Water Sci Technol 81 (11) (2020) 2391–2400. https://doi.org/10.2166/wst.2020.298

[6] Ribes J., Serralta J., Ruano M.V., Robles A. and Ferrer J., Widening the applicability of most-open-valve (MOV) strategy for aeration control at full scale WWTPs by combining fuzzy-logic control and knowledge-based rules, J Water Process 53 (2023) 103689. https://doi.org/10.1016/j.jwpe.2023.103689

[7] Åmand L. and Carlsson B., Optimal aeration control in a nitrifying activated sludge process, Water Res 46 (2012) 2101-2110. https://doi.org/10.1016/j.watres.2012.01.023

[8] Third KA, Gibbs B., Newland M., Cord-Rubisch R, Long-term aeration management for improved N-removal via SND in a sequencing batch reactor, Water Res 39(15) (2005) 3523-3530. https://doi.org/10.1016/j.watres.2005.06.014

[9] Holenda, B.,Domokos, E.,Rédey, Á.,Fazakas, J., Aeration optimization of a wastewater treatment plant using genetic algorithm, Optim Control Appl Methods 28(3) (2007) 191–208. https://doi.org/10.1002/oca.796

[10] Martin de la Vega, P.T., Jaramillo, M.A., Martinez de Salazar, E., Upgrading the biological nutrient removal process in decentralized WWTPs based on the

intelligent control of alternating aeration cycles, Chem Eng J 232 (2013) 213-320. https://doi.org/10.1016/j.cej.2013.07.051.

[11] Serralta J., Ribes J., Seco A. and Ferrer J., A supervisory system for optimising nitrogen removal and aeration energy consumption in wastewater treatment plants, Water Sci Technol 45(4-5) (2002) 309-316. https://doi.org/10.2166/wst.2002.0612

[12] Vrecko D., Hvala N., Stare A., Burica O., Strazar M., Levstek M., Cerar P., Podbevsek S., Improvement of ammonia removal in activated sludge process with feedforward-feedback aeration controllers, Water Sci Technol 53(4-5) (2006) 125-132. https://doi.org/10.2166/wst.2006.098.

[13] Guerrero J., Guisasola A.,Vilanova R.,Baeza JA, Improving the performance of a WWTP control system by model-based setpoint optimization, Environ model softw 26(4) (2011) 492-497. https://doi.org/ 10.1016/j.envsoft.2010.10.012.

[14] Ruano M.V., Serralta J., Ribes J., Seco A. and Ferrer J., An advanced control strategy for biological nutrient removal in continuous systems based on pH and ORP sensors, Chem Eng J 183 (2012) 212-221. https://doi.org/ 10.1016/j.cej.2011.12.064.

[15] Beltrán, S., Irizar, I., Ayesa, E., Instrumentation, monitoring and real-time control strategies for efficient sewage treatment plant operation, in: K. Katerina Stamatelatou, K. P. Tsagarakis, (Eds.), Sewage Treatment Plants: Economic Evaluation of Innovative Technologies for Energy Efficiency, IWA Publishing, London, 2015. https://www.iwapublishing.com/books/9781780405018/sewage-treatment-plants-economicevaluation-innovative-technologies-energy

[16] Schraa, O., Rieger, L., Alex J., Miletic, I., Ammonia-based aeration control with optimal SRT control: improved performance and lower energy consumption, Water Sci Technol 79(1) (2019) 63-72. https://doi.org/10.2166/wst.2019.032

[17] Wan, X., Baeten, J.E., Laureni, M., Volcke, E.I.P., Ammonium-based aeration control improves nitrogen removal efficiency and reduces N2O emissions for partial nitritation-anammox reactors, Chemosphere 274 (2021) 129720. https://doi.org/10.1016/j.chemosphere.2021.129720.

[18] Liu Y., Shi H., Xia L., Shi H., Shen T., Wang Z., Wang G., Wang Y, Study of operational conditions of simultaneous nitrification and denitrification in a Carrousel oxidation ditch for domestic wastewater treatment, Biores Technol 101(3) (2010) 901-906. https://doi.org/10.1016/j.biortech.2009.09.015.

[19] Regmi, P., Sturm, B., Hiripitiyage, D., Keller, N., Murthy, S., Jimenez, J., Combining continuous flow aerobic granulation using an external selector and carbon-efficient nutrient removal with AvN control in a full-scale simultaneous nitrification-denitrification process, Water Res 210 (2022) 117991. https://doi.org/10.1016/j.watres.2021.117991.

[20] Åmand L., Olsson G. and Carlsson B., Aeration control – a review, Water Sci Technol 67 (11) (2013) 2374-2398. https://doi.org/10.2166/wst.2013.139.

[21] Ayesa E., De la Sota A., Grau P., Sagarna J.M., Salterain A. and Suescun J., Supervisory control strategies for the new WWTP of Galindo-Bilbao: the long run from the conceptual design to the full-scale experimental validation, Water Sci Technol 53 (4–5) (2006) 193–201. https://doi.org/10.2166/wst.2006.124.

[22] Olsson G., Carlsson B., Comas J., Copp J., Gernaey K. V., Ingildsen P., Jeppsson U., Kim C., Rieger L., Rodríguez-Roda I., Steyer J.-P., Takács I., Vanrolleghem P. A., Vargas A., Yuan Z. and Åmand L., Instrumentation, control and automation in wastewater – from London 1973 to Narbonne 2013, Water Sci Technol 69(7) (2014) 1373-1385. https://doi.org/10.2166/wst.2014.057.

[23] Tanwar P., Nandy T., Ukeya P. and Manekara P., Correlating on-line monitoring parameters, pH, DO and ORP with nutrient removal in an intermittent cyclic process, Biores Technol 99 (2008) 7630-7365. https://doi.org/10.1016/j.biortech.2008.02.004.

[24] Fox S., Clifford E. Detecting the End of Nitrification in Small and Decentralized Wastewater Treatment Systems Using Low-Resource Real-Time Control Methods, Journal of Environmental Engineering 144 (8), (2018). 10.1061/(ASCE)EE.1943-7870.0001404.

[25] Ruano M.V., Robles A., Medrano D., Hermosilla P., Usoz R., Jiménez E., Casao M., Ribes J., Serralta J., Seco A. and Ferrer J., Advanced control system based on pH, ORP and DO sensors for optimisation of full-scale WWTPs, in: proceedings of the 12th IWA conference on instrumentation control and automation, 2017.

[26] Ruano M.V., Ribes J., Seco A. and Ferrer J., Low cost-sensors as a real alternative to on-line nitrogen analysers in continuous systems, Water Sci Technol 60(2) (2009) 3261-3268. https://doi.org/10.2166/wst.2009.607.

[27] Thürlimann C.M., Dürrenmatt D. J., Villez K., Soft-sensing with qualitative trend analysis for wastewater treatment plant control, Control Eng Pract 70 (2018) 121-133. https://doi.org/10.1016/j.conengprac.2017.09.015.

[28] Gaffar A., Murali S., Seshagiri A., Chapter 25 - Fuzzy Logic Control of Active Sludge–Based Wastewater Treatment Plants, Soft Computing Techniques in Solid Waste and Wastewater Management, Elsevier, (2021), 409-422, ISBN 9780128244630. https://doi.org/10.1016/B978-0-12-824463-0.00028-8.

[29] Boiocchi R., Mauricio-Iglesias M., Vangsgaard A.K., Gernaey K.V., Sin G., Aeration control by monitoring the microbiological activity using fuzzy logic diagnosis and control. Application to a complete autotrophic nitrogen removal

reactor, Journal of Process Control 30 (2015) 22-33. https://doi.org/10.1016/j.jprocont.2014.10.011.

[30] Robles A., Capson-Tojo G., Ruano M.V., Latrille E., Steyer J.-P., Development and pilot-scale validation of a fuzzy-logic control system for optimization of methane production in fixed-bed reactors, Journal of Process Control, 68, (2018), 96-104.https://doi.org/10.1016/j.jprocont.2018.05.007.

[31] Estaben M., Polit M., Steyer J.P., Fuzzy control for an anaerobic digester, Control Engineering Practice, 5(9), (1997), 1303-1310. https://doi.org/10.1016/S0967-0661(97)84369-9.

[32] Jenkins, T.E. (2013) Aeration Control System Design. A Practical Guide to Energy and Process Optimization. John Wiley & Sons Inc., Hoboken, New Jersey.

[33] Lazić, A.; Larsson, V.; Nordenborg, Å. (2012) Energy savings potential of new aeration system: Full scale trials. Water Practice and Technology, 7 (4) https://doi.org/10.2166/wpt.2012.098