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Knowledge-based system for automatic MBR control

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ABSTRACT

MBR technology is currently challenging traditional wastewater treatment systems and is increasingly selected for WWTP upgrading. MBR systems typically are constructed on a smaller footprint, and provide superior treated water quality. However, the main drawback of MBR technology is that the permeability of membranes declines during filtration due to membrane fouling, which for a large part causes the high aeration requirements of an MBR to counteract this fouling phenomenon. Due to the complex and still unknown mechanisms of membrane fouling it is neither possible to describe clearly its development by means of a deterministic model, nor to control it with a purely mathematical law. Consequently the majority of MBR applications are controlled in an "open-loop" way i.e. with predefined and fixed air scour and filtration/relaxation or backwashing cycles, and scheduled inline or offline chemical cleaning as a preventive measure, without taking into account the real needs of membrane cleaning based on its filtration performance. However, existing theoretical and empirical knowledge about potential cause-effect relations between a number of factors (influent characteristics, biomass characteristics and operational conditions) and MBR operation can be used to build a knowledge-based decision support system (KB-DSS) for the automatic control of MBRs. This KB-DSS contains a knowledge-based control module, which, based on real time comparison of the current permeability trend with "reference trends", aims at optimizing the operation and energy costs and decreasing fouling rates. In practice the automatic control system proposed regulates the set points of the key operational variables controlled in MBR systems (permeate flux, relaxation and backwash times, backwash flows and times, aeration flow rates, chemical cleaning frequency, waste sludge flow rate and recycle flow rates) and identifies its optimal value. This paper describes the concepts and the 3-level architecture of the knowledge-based DSS and details the knowledge-based control module. Preliminary results of the application of the control module to regulate the air flow rate of an MBR working with variable flux demonstrates the usefulness of this approach.

Key words | automatic control, energy saving, fouling, knowledge-based, membrane bioreactors

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INTRODUCTION

Membrane bioreactors (MBR) combine membrane technology and activated sludge biodegradation processes for the treatment of municipal and industrial wastewater. MBR technology is currently challenging traditional wastewater treatment systems and is increasingly selected for WWTP upgrading, e.g. as a result of increased influent flows, increased effluent quality requirements or when water scarcity requires its reuse. Further details about MBR technology can be found in Judd (2008). Filtration is achieved by drawing water to the inside of the membrane

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fibers under a vacuum applied across the membrane walls. Solids are rejected by the membranes and remain in the tank to be biologically or chemically treated or drained from the tank for recycle or further treatment. The main drawback of MBR technology is that the permeability of membranes declines during filtration due to membrane fouling. This phenomenon occurs when membrane pores are obstructed resulting in the loss of membrane permeability, i.e. the volume per unit of time of permeate that can be passed through a membrane surface per unit of pressure or vacuum applied.

MBR systems use air bubbled from under or between the membranes to scour the surface of the membranes to sustain the permeate flow rate. The airflow rate is typically constant for a particular installation when expressed as a volume of air per unit membrane area per unit of time. To increase air scour efficiency on fouling removal two different operational procedures are applied: relaxation or backwash. Relaxation is performed by eliminating the TMP, stopping permeate production and allowing the air bubbles to remove the sludge particles deposited on the membrane surface. The other operational procedure available for solids removal is backwash i.e. reversing the direction of the permeate flow, which allows for the removal of the sludge particles loosely deposited on the membrane pores and surface. Chemical cleaning may also be applied in order to remove foulants that accumulate on the membrane pores despite the routine application of bubbles, relaxation or backwash. Maintenance chemical cleaning, which requires a low concentrated chemical solution, may be applied to maintain or reduce a rate of decline in membrane permeability. Recovery chemical cleaning, which requires a more concentrated chemical solution, may be applied at a lower frequency to restore membrane permeability when it has decreased considerably. Thus membrane fouling causes an increase in energy and chemicals consumption. Furthermore, fouling mechanisms result in a reduction of the membrane lifetime, and thus in higher operational costs. Therefore, control of membrane fouling is one of the key issues in MBR operation.

Due to the complex and still largely unknown mechanisms of membrane fouling it is neither possible to describe clearly its development by means of a deterministic model, nor to control it with a purely mathematical law. Consequently the majority of pilot or full-scale MBR applications operate in an "open-loop" way, i.e. with predefined and fixed filtration/relaxation or backwashing flow rates and cycle times, with constant air flow rate, and scheduled inline or offline chemical cleaning as a preventive measure, without taking into account the real needs based on the filtration performance.

To date very few MBR closed-loop control systems can be found in literature, however none of them estimates the loss of permeability in real time and aims at optimising both filtration and biological processes simultaneously (Fatone *et al.* 2008; Ginzburg *et al.* 2008; Vargas *et al.* 2008; Brauns *et al.* 2009; Choi *et al.* 2009). The current trend seems to perform an alternating aeration to both improve permeability and decrease aeration costs (WO/2007/006153). Existing theoretical and empirical knowledge about potential cause-effect relations between a number of factors and membrane fouling obtained from the literature (Cabassud *et al.* 2001; Pinnekamp & Friedrich 2006; Judd 2007) have been used to build a knowledge-based system for the automatic fouling control and prevention. A knowledge-based system is a computer program that emulates human expert reasoning processes when making decisions to confront problems. Its aim is to automatically and online detect fouling development and act consequently to counteract fouling when a deterioration of membrane performance is detected in real time. In this case the proposed knowledge-based control consists in a set of rules (knowledge base) that compare influent characteristics (e.g. influent flow rate or presence of high molecular weight compounds), biomass characteristics (e.g. MLSS, filamentous, etc.) and operational conditions (temperature, SRT, permeability, etc.) to theoretical and empirical information dealing with fouling issues to support early detection of membrane fouling and propose control actions to decrease fouling rates, save aeration energy or reduce the frequency of chemical cleaning. With this aim, the knowledge-based control system proposed will directly manipulate the control loop set points that regulate both the biological and the filtration processes.

The paper is structured as follows: first, the experimental systems where the knowledge-based control system has been developed and tested are presented. Second, the development and implementation of the knowledge-based system for the automatic control of MBRs. Finally, preliminary results obtained from two MBR pilot plants are discussed.

EXPERIMENTAL SYSTEM

The proposed control system has been developed and implemented in two semi-industrial UCT-MBR pilot plants, one working with a diurnal variable flux and the other with a constant flux, installed respectively in the full-scale WWTP of *El Vendrell* and *Castell-Platja d'Aro* (in Catalonia, NE Spain). Both pilot plants successfully removed C, N and P biologically from raw domestic wastewater (Ferrero *et al.* 2009; Monclús *et al.* 2010). These pilot plants are fully automated with pressure transducers, pH, ORP, dissolved oxygen, ammonium, mixed liquor suspended solids, conductivity and temperature sensors and have a programmable logic controller and a supervisory control and data acquisition system (SCADA) that regulate low-level control loops: aeration of the biological and membrane compartments, sludge age, permeate effluent flow rate, the backwashing or relaxation flux and time, chemical cleaning dose and frequency and the different recirculation flows. The knowledge-based control system will directly manipulate the set points of these control loops in order to optimise operational costs and effluent quality. Figure 1 illustrates the flow diagrams together with instruments and equipment of both pilot plants.

RESULTS AND DISCUSSION

Concepts of the proposed knowledge-based decision support system

The knowledge-based decision support system for the integrated control of MBRs performance consists of the following 3 hierarchical modules:

- Data acquisition and signal processing
- Knowledge-based control
- Knowledge-based supervision

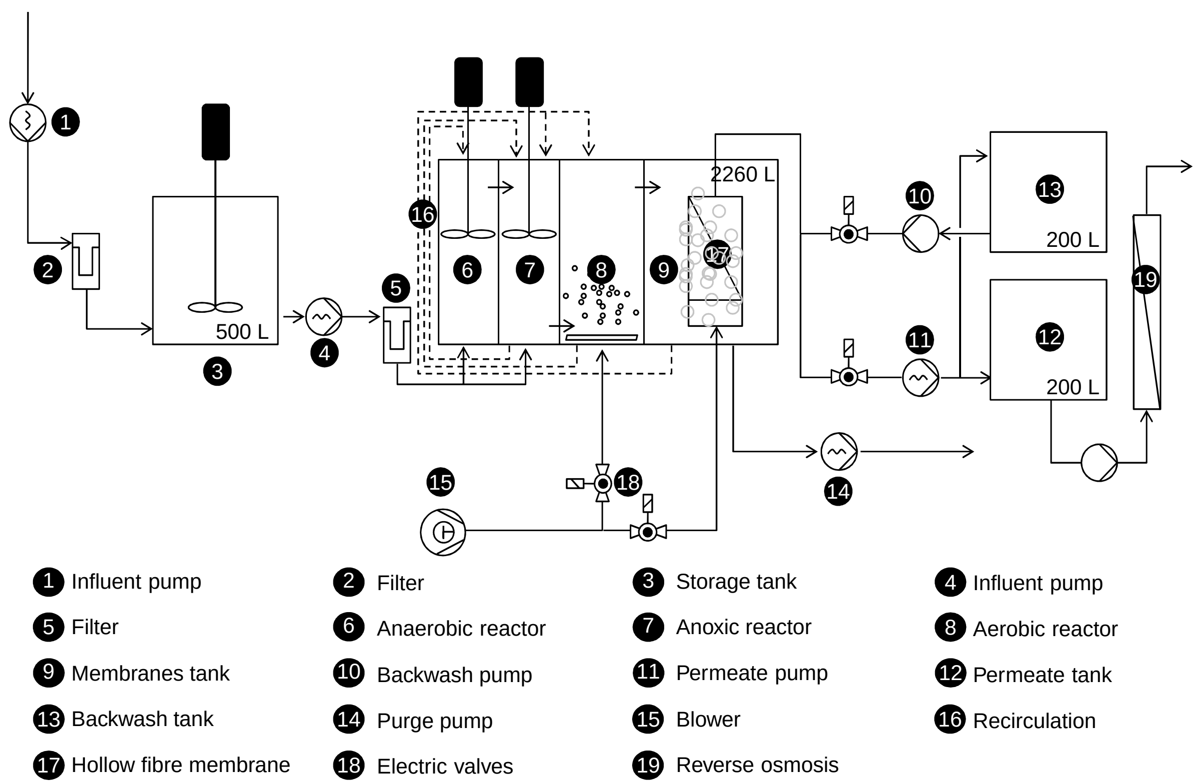

Figure 1 | Flow diagram of the two MBR pilot plants showing the different compartments, instruments and equipment.

Figure 2 illustrates the architecture of the knowledge-based control system. It is located hierarchically on top of the conventional supervisory control and data acquisition systems. This integrated control involves regulation of control set points for filtration, backwashing or relaxation flow rates and periods, for the air flow rate for biological conversions and filtration, for the sludge waste flow rate, for the sludge recycle flow rates and for the chemical cleaning dose and frequency, according to the needs of the operational mode in order to minimize membrane fouling while at the same time assure adequate biological nutrient removal. All operational and reference values of the 3 modules are suggested and can be modified by the user during the calibration of the KB-DSS.

Data acquisition and signal processing module

The lowest level of the KB-DSS is responsible for data acquisition and signal processing. SCADA systems typically carry out data acquisition and validation tasks; validated data are subsequently used within the automatic control loops. However, in this case, additional online data processing and data filtering for specific MBR monitoring parameters (e.g. temperature correction of permeability, noise reduction and removal of outliers) are necessary for the real-time control of the integrated operation of the MBR. The system does not only take the on-line data provided by the sensors and equipment, but also integrates additional qualitative and quantitative lab data (e.g. Extracellular Polymeric Substances (EPS), Chemical Oxygen Demand (COD), protozoa biodiversity, sludge viscosity, filterability, mixed liquor suspended solids (MLSS), NOx etc.).

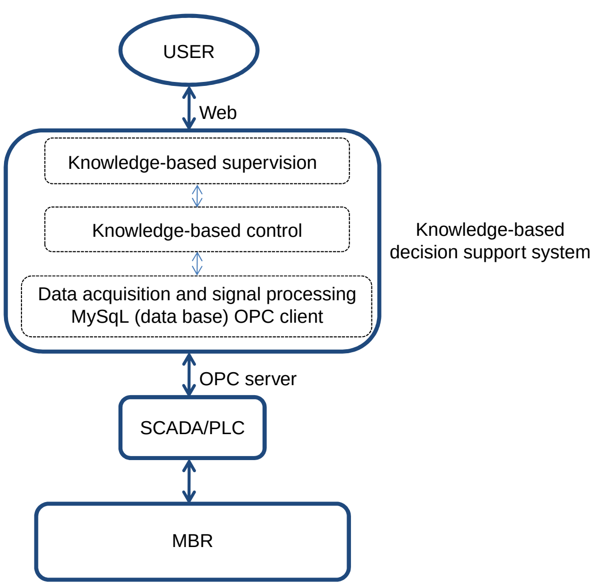

Figure 2 | Architecture of the proposed knowledge-based control system.

Raw signals of instantaneous permeability values, calculated from the temporal evolution of the TMP and flux along the sequential filtration cycles and registered every 10 seconds in a dynamic database (MySQL), are corrected by temperature, filtered and then hourly and daily averaged. Different mathematical algorithms are applied for the signal filtering of online data. First, a median is calculated for all the values of each cycle, gathered every 10 seconds, then a filter excludes values within a significant range around the median (e.g. values $>$ or $<$ of the 50% of the median), and finally a new average of the filtered values is recalculated for each cycle. After that, an hourly and daily averaged value can be obtained for TMP and permeability. The system provides automatic fault detection in real-time: the user is warned when the permeate flow is zero during more than one filtration/relaxation (or backwash) cycle and such values are excluded while calculating hourly and daily average values.

Regarding the filtration process, changes in permeability values and permeability trends have been selected as monitoring parameters to provide online and real time information about the membrane performance. They are used as early warning signals of fouling development or incorrect operation of the installation. A deeper study of the permeability signal during short periods of time (e.g. a few days) enables to detect the performance tendency of membrane permeability (increasing: positive slope, decreasing: negative slope). These slope values, that present the tendency of the membrane permeability, are calculated as the slope of a linear regression of the hourly averaged permeability values during a certain period of operational time, normally 4 days. Figure 3A shows the evolution of the daily averaged permeability of the *Castell-Platja d'Aro* MBR pilot plant during the experimental period.

When the start up phase of the MBR is completed, i.e. MLSS within an appropriate range and good filterability, a "reference" permeability trend (REF) is identified as well as every day a current or "working" permeability trend

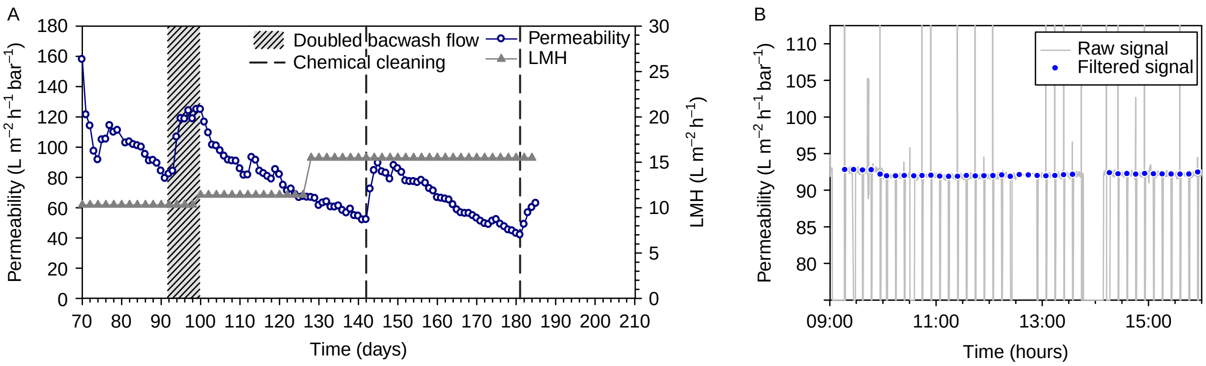

Figure 3 | Results of Castell-Platja d'Aro MBR pilot plant (A) Evolution of the permeability, LMH, and the days of different control actions (doubling the backwashing flow on day 91 and chemical cleaning on days 142 and 181. (B) Raw and filtered data for the on line permeability.

(CURRENT) is calculated, estimated as the slope of the last 4 daily averaged permeability values. The reference value is automatically adjusted depending on the evolution of the control parameters without the need for manual intervention of operators; it is also recalculated operating in 'safe mode' (initial conditions suggested by membrane suppliers) and after each recovery chemical cleaning.

Simultaneously, the data acquisition and signal processing module estimate the time (days) to reach the recovery chemical cleaning (t_1) and the maintenance chemical cleaning (t_2). Membrane suppliers always set the recovery chemical cleaning when TMP reaches the maximum permitted value (TMP_{max}); such values change depending on membrane configuration, model, material, producer, etc. Maintenance chemical cleaning is not fixed, but is usually suggested to be carried out every six months. The herewith proposed invention suggests to carry out a maintenance chemical cleaning when meeting a TMP value of TMP_{max}–30% (absolute values). All these data, once processed, are sent to the upper level of the KB-DSS.

Knowledge-based control module

This level implements the necessary knowledge reasoning to compare once a day the CURRENT or "working" permeability trend with respect to the REF value, which represents the normal temporal evolution of the permeability in "standard" MBR operation. Significant differences with respect to this reference value and projections to reach warning values of TMP may launch appropriate rules to apply preventive (e.g. suggest a chemical cleaning), corrective (e.g. increase backwash flow rate) or saving control actions (e.g. decrease air flow rate). Specifically, if the "working" permeability trend value is lower than the "reference" value the system automatically takes a hierarchy of control actions that tend to minimize energy consumption (saving actions):

1. Air scour to the membrane is gradually reduced until a limit value inferior to the value recommended by membrane suppliers.
2. Back pulse (or relaxation) duration is reduced until a limit value inferior to the length recommended by membrane suppliers.
3. Back pulse flow (just in case of hollow fibre MBRs) is reduced until a limit value inferior to the flow recommended by membrane suppliers.

In case the "working" permeability trend value is greater than the "reference" value the system automatically takes control actions that tend to restore a correct operation (corrective actions):

1. Back pulse flow (just in case of hollow fibre MBRs) is increased until reaching the flow recommended by membrane suppliers.
2. Back pulse (or relaxation) duration is increased until reaching the length recommended by membrane suppliers.
3. Air scour to the membrane is gradually increased until the value recommended by membrane suppliers.

Both the saving and corrective actions are proportional to the positive quotient of CURRENT/REF multiplied by a safety factor (set by the user during the calibration of the DSS). For example, if the "working" permeability trend

Table 1 | Reference or set-point values for the air scour modification control action

Current or "working" permeability trend/"reference" permeability trend	Control action (Hz in air supplier)
Negative	Decrease 3 Hz
From 0 to 0.2	Decrease 2 Hz
From 0.2 to 0.5	Decrease 1 Hz
From 0.5 to 0.9	Decrease 0.5 Hz
From 0.9 to 1.1	No change
From 1.1 to 1.4	Increase 0.5 Hz
From 1.4 to 1.7	Increase 1 Hz
From 1.7 to 1.9	Increase 2 Hz
Higher than 1.9	Increase 3 Hz

would be higher than the reference value, then an increase of the back pulse flow proportional to the quotient CURRENT/REF would be the first corrective action to be taken. Table 1 summarizes the reference or set-point values that a user must set during the calibration for the air scour modification control action.

Moreover, the knowledge-based control module also takes preventive control actions depending on the time projections to reach the user-set warning values of TMP for recovery chemical cleaning (t_1) and maintenance chemical cleaning (t_2). When $10 < t_1 < 30$ the control system launches an alarm and automatically switches the current operational mode to a *safe mode*, a mode that implies the standard operational conditions suggested by the membrane suppliers (e.g. membrane air scour flow rate, filtration relaxation/backwash times, MLSS concentration, filterability values, etc.). If $t_1 < 10$ the system launches an alarm and suggests carrying out an urgent recovery chemical cleaning (or realizes it automatically if the installation allows to). When $t_1 > 30$ the system considers the time to the maintenance chemical cleaning (t_2): if $t_2 < 10$ the control system launches an alarm and suggests carrying out a maintenance chemical cleaning (or realizes it automatically if the installation allows to); and if $t_2 > 10$ no alarm is launched and the MBR keeps working following the current operational mode. If t_2 is checked more than 3 times within a 7 days time frame, the system will warn the user and automatically switch to safe mode.

After any maintenance chemical cleaning the system will wait for the double of the time frame chosen for the calculation of permeability slopes before calculating a new 'current' slope. During this period the system will work in the same operational conditions of 2 days prior to the chemical cleaning, with the last control action that was taken and that might have affected membranes performance.

Knowledge-based supervision module

The rule-based supervision module supervises the control actions proposed by the knowledge-based control module. Based on all processed data received from the data acquisition and signal processing module, it will warn the user and deactivate the knowledge-based control or propose an alternative strategy to the user when encountering one of the following operational 'anomalies': flux or TMP gradient higher than a fixed value during a specified time frame, temperature out of range, start-up phase,

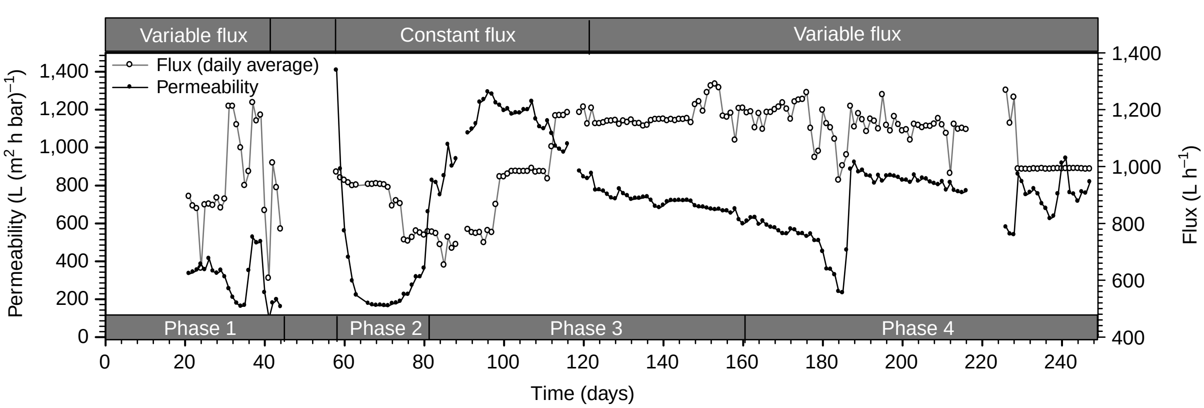

Figure 4 | Evolution of the permeability and permeate flux during the entire experimental period in El Vendrell MBR pilot plant.

instrumentation or mechanical malfunction, poor biological nutrient removal, microbiology-related problems or bad sludge filterability.

Thus the identification of these operational modes may require additional set point changes of the automatic MBR control loops. The proposed KB-DSS will ultimately perform a real time *integrated* control of the biological and filtration processes, i.e. the design of advanced supervision and control strategies for MBRs should consider any potential effect on the biological processes due to the control actions for the filtration processes and vice versa. When required, interaction with the user is done through a remote application with web-oriented graphical user interface (www.colmatar.es).

Application and validation of the knowledge-based control module

Figure 3A illustrates the results of a control action of the knowledge-based control module in the *Castell-Platja d'Aro* MBR pilot plant. Specifically this is a case where the permeability is clearly positively affected by the effect of increasing the backwash flow rate (in this case increased by a factor of 2 during 7 days, from day 91), with a first high increase of the permeability (from 80 to 123 $\mathrm{L\,m^{-2}\,h^{-1}\,bar^{-1}}$ or LMH $\mathrm{bar^{-1}}$), followed by a slight increase once the permeability value is more stabilized. However, if permeability trends of each 10 minutes cycle are studied in detail, the variability resulted too high to extract any interesting conclusion (See Figure 3B). Figure 3A also illustrates the positive effect of two chemical cleanings at days 142 and 181.

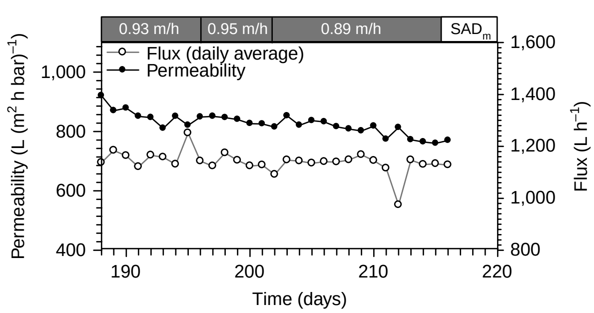

Figure 5 | Evolution of permeability and permeate flux while applying different control actions (saving energy) in El Vendrell MBR pilot plant.

Table 2 | Automatic control parameters

Day	Air flow (m^3/h)	SADm (m/h)	PTM (bar)
188	37.1	0.93	−0.0398
196	37.8	0.95	−0.0427
202	35.6	0.89	−0.0420

Figure 4 illustrates the evolution of the permeability and permeate flux along the entire experimental period in *El Vendrell* MBR pilot plant. During this period, the permeate flux was first variable in accordance with the receiving wastewater flow to emulate real conditions in full scale plants, then constant during 60 days and again variable during the rest of the experimental period.

Figure 5 and Table 2 illustrate the successful application of this control system to regulate the air flow rate of the *El Vendrell* MBR plant working with variable permeate flux. The closed-loop control system operated automatically starting from day 188; it applied the changes reported in Figure 5 and Table 2. It can be observed that the air scour was first increased from 0.93 m/h to 0.95 m/h and subsequently lowered until 0.89 m/h without any significant change in transmembrane pressure values nor in nutrient removal efficiency. As the air scour flow recommended from the membrane suppliers for a FS50 Kubota module is 0.95 m/h, the control actions resulted in an optimization of the process that led to save up to 6% of the air flow required.

These results reveal the potential benefits of this knowledge-based approach with respect to an open loop control (constant air flow rate, flows and cycle durations), as typically suggested by manufacturers and operated in current MBRs.

CONCLUSIONS

In this article, a knowledge-based control system has been presented to optimize the operation and energy costs of MBRs. The main achievements are:

- Development of an automatic knowledge-based control system for decreasing fouling rates, saving energy and reducing operational costs at the same time that treatment efficiency is maintained or improved.

- The architecture of the proposed control system includes 3 hierarchical modules: the data acquisition and signal processing module, the knowledge-based control module and the knowledge-based supervision module.
- The reasoning of the knowledge-based control module is based on a real time comparison of the current permeability trend with respect to a "reference trend" in order to identify the real needs for aeration and chemical cleaning of membranes.
- The proposed automatic control system has been successfully validated under certain operational conditions in two different MBR pilot plants, one with hollow fibre, the other one with flat sheet membranes.

Comparison with other non-controlled full-scale MBR plants and validation under a complete range of operational conditions are required to prove the efficiency and usefulness of the proposed system and therefore, full-scale validation of the whole KD-DSS becomes the main issue for future research.

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