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Detecting the end of nitrification in small and decentralised wastewater treatment systems using low-resource real-time control methods.

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ABSTRACT

There is increasing demand on operators of small-scale wastewater treatment plants (WWTPs) to improve biological nutrient removal and energy efficiency while being subject to unique challenges including reduced resources. Automated monitoring and control strategies of WWTPs can provide the necessary tools to improve plant performance and energy efficiency. However, online sensors for key parameters such as ammonium can require excessive maintenance, are unreliable unless frequently maintained and are often not affordable. In addition, control techniques such as machine learning may not be financially or technically compatible within the constraints of small-scale WWTPs. This study analyses the use of low cost, reliable surrogate sensors in association with inexpensive and robust programmable logistic controllers to improve WWTP performance and energy efficiency through automation. The paper presents three novel methodologies for control of batch WWTPs using pH and oxidation reduction potential (ORP) trends. Applying and optimising these methodologies enabled an average reduction in cycle time and energy consumption of 60% and 43% respectively when compared to the fixed-time treatment cycle and an average effluent ammonium concentration of 1.9 mg/l. The automated system proposed has significant potential to enhance the performance of small-scale WWTPs in terms of environmental compliance and energy consumption.

KEYWORDS

Real time control; regulatory compliance; small scale wastewater treatment, energy efficiency

Introduction

Approximately 80% of European wastewater treatment plants (WWTPs) are less than 5000 population equivalent (PE) (EPA 2013), (García 2009). In Ireland 94% of WWTPs operated by Irish Water (Ireland's sole water utility) have a PE of less than 10,000; 83% of which serve urban areas of less than 2000 PE (EPA 2014). Similar situations exist worldwide, for example, 57% of China's population live in 2.79 million villages accounting for 768.8 million people (Guo et al. 2014). Small WWTPs, however, have design and operational challenges that can impact performance including; (i) lack of permanent operators and local expertise, (ii) relatively high energy cost, (iii) sludge handling, (iv) complying with strict discharge licences, (v) non-consistent influent hydraulic or organic loads and (vi) inflexible operating regimes (Fox et al., 2016; Norton, 2009). In general approximately 33% of the total operating cost of a WWTP is attributed to energy requirements (Fernández et al., 2011). Energy consumed for aeration alone can represent up to 65% of the total energy consumption of WWTPs (Fernández et al. 2011).

The Water Framework Directive (WFD) (2000/60/EC) and the Urban Wastewater Treatment Directive (UWWTD) (91/271/EEC) are the key regulations in Europe related to WWTP discharges. However for many smaller WWTPs, particularly those with PEs < 2,000; biochemical oxygen demand (BOD), chemical oxygen demand (COD), total suspended solids (TSS) and ammonium-nitrogen (NH_4^+-N) are of most concern. Typically additional parameters including total phosphorus and total nitrogen (TN) of concern are limited to WWTPs in sensitive areas. For example, in Ireland 49% of WWTPs with a PE loading of < 2000 have an NH_4^+-N discharge limitation and only 3.5% have a TN discharge limit. Meeting NH_4^+-N limits can be challenging for many types of WWTP technologies (Toppett Mosby 2015). Removal of NH_4^+-N is the most important energy consumer, responsible for 50% of a WWTPs energy consumption (Hernández-del-Olmo et al. 2016).

Automated monitoring and automation of WWTPs has significant potential to improve facility operation, reducing manpower and energy (Aguado et al., 2009), and enable desired effluent standards be met efficiently. However automated monitoring and control is generally limited in small and decentralised WWTPs (Luccarini et al. 2010) and models (Santín et al., 2015). Online sensors can provide data on the operation of the WWTP while also allowing the application of real time control (RTC) strategies that can improve effluent quality and reduce energy consumption (Zanetti et al. 2012). However, online sensors for key parameters such as NH_4^+-N require extensive maintenance and can be unreliable (Hong et al., 2007) and are often not affordable to small WWTPs (Aguado et al. 2009). Thus the implementation of robust and low cost on-line process measurement systems is required (Marsili-Libelli 2006). Numerous studies have shown that sensors measuring variables such as oxidation reduction potential (ORP) and pH can act as surrogates for NH_4^+-N (Won & Ra, 2011; Ga & Ra, 2009; Guo et al., 2009; Tanwar et al., 2008; Akın & Ugurlu, 2005; Holman & Wareham, 2003). However, the implementation of such strategies at small and decentralised WWTPs, where there are significant limitations in terms of computational power in controlling systems has, to-date, been limited. Previous studies have identified useful termination points which indicate the end of nitrification including the sudden increase in pH (known as the "ammonium valley") which is related to CO_2 stripping (Akın & Ugurlu 2005) and a kick point in the ORP profile, known as the "ammonia elbow" (Akın & Ugurlu 2005). Within these continuously aerated systems this occurs as oxygen is no longer acting as an electron acceptor for NH_4^+-N and thus dissolved oxygen concentrations can increase rapidly (Holman, 2004).

Intelligent software sensor based systems have been developed, which utilise sensors such as pH and ORP as surrogates for NH_4^+-N sensors. Examples of intelligent software sensor based systems include neural networks (NN) (Corominas et al. 2017; Han et al. 2016; Bagheri et al. 2015; Luccarini et al. 2010), Gaussian-Process regression (Kocijan & Hvala 2013) and various fuzzy techniques (Huang et al. 2015; Li et al. 2016; Ruano et al. 2012; Mingzhi et al. 2009). Alternating peaks and troughs (characteristic of systems with intermittent aeration) are a challenge when trying to automatically terminate the aerobic phase of a treatment cycle. Intelligent softsensors generally use advanced algorithms such as filtration wave techniques, wavelet de-noising, regularisation algorithms and episode representations to smooth out noise from the raw data and allow for the detection of reaction termination points (Luccarini et al. 2010; Li et al. 2008; Puig et al. 2006). Intelligent systems have been successfully adapted for real time control of sequencing batch reactor (SBR) treatment plants (Cho et al., 2001; M. Huang et al., 2015; Luccarini et al., 2010; Marsili-Libelli, 2006; Ruano et al., 2012; Yang et al., 2007); however, they require expensive control equipment and technical knowledge to operate and have seen limited application to smaller WWTPs. It has been noted that advanced methods cannot be applied until control systems improve greatly and are more accessible for low cost programmable logic controllers (PLCs) (Yang et al., 2010). Thus new control methods are required to enhance the performance and energy efficiency of small wastewater SBR treatment systems (which are traditionally operated using fixed time cycles; Wimberger & Verde 2008).

This research aims to identify suitable control architecture for the development of an automated low resource real time control strategy incorporating data from pH and ORP sensors that can be implemented in readily available low cost PLCs. Three data mining and data analytic methods are presented, based on data generated during on-site pilot scale trial. The paper analyses the efficiency of each method in optimising SBR cycle time using a number of novel metrics. The results of this study are applicable to control systems and environmental engineers and researchers working in the water/wastewater industry.

Material and methods

A 6 PE domestic scale SBR was deployed for this study (Figure 1). The SBR tank (2 m diameter and 2 m tall) comprised a precast concrete tank with two chambers (a primary chamber and a reaction chamber), with working volumes of 2.42 m^3 and 1.56 m^3 respectively. The system received 900 litres of wastewater per day (150 l/PE-day) and was mechanically aerated. A 464 minute cycle controlled by a Siemens LOGO! PLC comprised the following phases; 2 minute fill phase, 400 minute aeration phase, a 60 minute settling phase and a 2 minute discharge phase. Figure 1 illustrates the cycle sequence. The aeration phase consisted of repeating periods, each 20 minutes in length, during which the aeration was switched on for a 5 minute period ("aeration on"), followed by 15 minute quiescent period. Intermittent aeration was leveraged in order to reduce energy consumption. It was found that intermittent aeration was sufficient to maintain dissolved oxygen concentrations at desired levels (between about 1 and 4 mg O_2/L).

Wastewater characteristics

The SBR was constructed adjacent to an existing large WWTP that received wastewater from a housing development. The large WWTP comprised; a foul water pump station, a primary settlement tank, a buffer tank, a SBR reaction chamber, a clear water pump station and a percolation system. A submersible foul water pump, placed in the primary tank was used to feed the primary tank of the SBR. This pump was programmed to mimic the typical diurnal flow pattern of a domestic house (Table 1) as per the European Standards for domestic wastewater treatment systems (CEN 12566-3 2006). The influent characteristics of the wastewater are repesented in Table S1 (supplementary information).

Equipment/flow pattern

Aeration in the SBR was achieved using a submersible mechanical aerator (DAB Novair 200). A feed pump installed in the reactor tank filled the reactor chamber by syphoning from the primary chamber. The feed pump was switched on for 5 seconds, creating a syphon which moved liquid from the primary chamber into the reaction chamber. Syphoning terminated when the liquid level in the primary chamber went below the inlet level of the feed pipe or when the two chambers had equalised (a technique commonly used in domestic scale SBR units). This technique resulted in a dynamic feed volume, as only the volume available over the feed pipe was transferred for treatment. A submersible pump housed in the reaction tank was utilised to remove treated wastewater during the discharge phase.

Monitoring

Throughout the study, influent wastewater samples were taken from the primary tank and effluent samples were taken from a collection vessel placed on the discharge line of the SBR. Filtered chemical oxygen demand (COD) and total suspended solids (TSS) were tested in accordance with standard methods (APHA, AWWA 2005). Total nitrogen (TN) was measured using a Biotector (total organic carbon (TOC), TN and total phosphorous (TP)) Analyser (Biotector, Cork, Ireland). NH_4^+-N and nitrate-nitrogen (NO_3-N) were measured using a Thermo Clinical Labsystem, Konelab 250 Nutrient Analyser (Serosep, Limerick, Ireland); samples were passed through 1.2 µm Whatman GF/C microfiber filters prior to measurement. Hach sc1000 multi-meters recorded data collected from pH, ORP and NH_4^+-N sensors, in the reactor chamber (Hach-Lange, Dublin, Ireland). pH and ORP was measured at 1 minute intervals while NH_4^+-N was measured at 5 minutes intervals on a 24 hour basis. Data from 41 treatment cycles (each cycle was 464 minutes long) were used in this study. All sensors were fitted approximately 500 mm below the lowest liquid level of the reaction chamber. All instruments were calibrated, maintained and operated in accordance with manufacturers' instructions.

Methodology development

Overall pH, ORP and NH_4^+-N trends

The aeration regime resulted in a cyclical rise and fall in both pH (Figure 2a) and ORP (Figure 3a) values as the aerator was switched on and off creating a peak (or apex) and trough (nadir) in each aeration period illustrated (Figure 2b and Figure 3b). The increase in pH – corresponding to the 5-minute periods where the aerator was switched on – was likely due to CO_2 stripping (Tanwar et al. 2008). It is likely the decrease in pH and ORP values between each 15 minute quiescent period were due to a reduction in microbial activity over the course of the aerobic phase as NH_4^+-N concentrations decreased (Chang & Hao 1996). The decrease in pH values was greatest immediately following the apex, and subsequently tailed off before a nadir was reached; a similar pattern was observed in the ORP profile.

A typical profile comprised an initial increase in NH_4^+-N concentrations as influent was mixed with the treated wastewater remaining in the reactor from the previous cycle. NH_4^+-N concentrations typically peaked soon after the fill phase.

Proposed cycle termination methods

Three novel methods, compatible with implementation on low-cost PLCs, were developed and analysed with a view to identifying the end of nitrification.

Method 1 – rate of change of pH and ORP values immediately following an "aeration-on" period

Method 1 (m1) examined the potential of utilising the initial rate of change in pH (pH_{m1}) or ORP (ORP_{m1}) values following each apex (Figures 2b and 3b) during an aeration cycle to determine the end of nitrification. Method 1 leveraged the observation that the rate of pH (or ORP) change following each apex tended to reduce over the course of an aeration period; and was expressed as follows (Eq. 1):

$$\boldsymbol{X_{m1(Pn)}} = \frac{[\boldsymbol{Apex_{(Pn)}} - \boldsymbol{Apex} + \boldsymbol{t_{(Pn)}}]}{\boldsymbol{t}} \qquad \textbf{Eq. 1}$$

where $X_{m1(Pn)}$ is the pH or ORP slope for method 1 during an aeration period n (Pn); $Apex_{(Pn)}$ is the apex pH (pH_{apex}) or ORP (ORP_{apex}) during aeration period n; $Apex+t_{(Pn)}$ is the pH or ORP value at a time t following the apex during aeration period n (typically set at about 25% of the aeration period).

Figure 4a shows the resulting $pH_{m1(Pn)}$ profile over the duration of a typical treatment cycle. It was observed that the rate of change in $pH_{m1(Pn)}$ was greatest at the beginning of the treatment cycle corresponding to periods of higher rates of NH_4^+-N removal and pH values generally decreased. When NH_4^+-N removal (via nitrification) ceased, $pH_{m1(Pn)}$ generally stabilised for the remainder of the cycle. The region where $pH_{m1(Pn)}$ decreases to relatively stable low values corresponds to the "ammonium valley" (Label A in Figure 4a). A similar trend was observed in the ORP_{m1} profile (illustrated in Figure 4b). The migration from high to low $pH_{m1(Pn)}$ and $OPR_{m1(Pn)}$ values form the basis of this method to predict when NH_4^+-N removal has ceased (Figures 4a and 4b contain thresholds).

Method 2 – average rate of change of pH and ORP values between aeration periods

Method 2 examined the potential of leveraging the change in pH (pH_{m2}) and ORP (ORP_{m2}) values between the apex and nadir of each aeration period. The method assessed whether the inclusion of the entire dataset for each aeration period would improve the prediction of when NH_4^+-N removal has ceased (m1 focused on the rate of change in pH and ORP only immediately after aeration stopped and thus required less data and processing time). Method 2 can be expressed as follows (Eq. 2).

$$\boldsymbol{X_{m2(Pn)}} = \frac{[\boldsymbol{Apex_{(Pn)}} - \boldsymbol{Nadir_{(Pn)}}]}{\boldsymbol{t}} \qquad \textbf{Eq. 2}$$

where $X_{m2(Pn)}$ is the pH or ORP slope for Method 2 (m2) during aeration period n; Apex $_{(Pn)}$ is apex the pH or ORP value during aeration period n, $Nadir_{(Pn)}$ is the nadir (lowest) pH (pH_{nadir}) or ORP (ORP_{nadir}) value during aeration period n and, t is the time in minutes between $Apex_{(Pn)}$ and $Nadir_{(Pn)}$.

It can be seen that $pH_{m2(Pn)}$ values initially increased (due to the initial fill and mixing) and thereafter decreased as NH_4^+-N removal proceeded (Figure 5a). As pH values increased following the end of nitrification, $pH_{m2(Pn)}$ stabilised for the remainder of the cycle; the region where $pH_{m2(Pn)}$ migrated from a high value to a stable low value corresponded to the "ammonium valley". A similar trend was observed in the ORP profile illustrated in Figure 5b. This general decrease and subsequent tailing off in $pH_{m2(Pn)}$ and $OPR_{m2(Pn)}$ values formed the basis of method 2.

Method 3 – rate of change of peak pH and ORP values between aeration periods

Method 3 examined the potential of utilising the rate of change of consecutive pH_{apex} or ORP_{apex} values over an aerobic cycle to identify the end of nitrification for pH (pH_{m3}) and ORP (ORP_{m3}) respectively. pH was examined over two sequential apex points (Eq. 3).

$$\boldsymbol{pH_{m3(Pn)}} = \boldsymbol{pH_{apex(Pn)}} - \boldsymbol{pH_{apex(Pn-1)}} \qquad \textbf{Eq. 3}$$
$$\forall\ \text{n}: n > 2$$

where $pH_{m3(Pn)}$ is the change in pH apex values between aeration period n and n-1 and $pH_{apex(Pn)}$ are the sequential pH_{apex} values from aeration periods 2 to n.

This point of accelerated change known as the “ammonium elbow” (Akın & Ugurlu 2005) has been linked to the end of nitrification, it occurs as oxygen no longer acts as an electron acceptor for NH_4^+-N resulting in increased dissolved oxygen (Holman 2004). To exaggerate the accelerated increase, or spike, of ORP; $ORP_{m3(Pn)}$ was examined over three sequential apex points (Eq. 4).

$$\boldsymbol{ORP_{m3(Pn)}} = \{(\boldsymbol{ORP_{apex(Pn+1)}}) - (\boldsymbol{ORP_{apex(Pn)}})\} - \{(\boldsymbol{ORP_{apex(Pn)}}) - (\boldsymbol{ORP_{apex(Pn-1)}})\} \quad \forall\, n: n > 2 \qquad \textbf{Eq. 4}$$

where $ORP_{m3(Pn)}$ is the change in ORP apex values between aeration period n and n-2 and $ORP_{apex(Pn)}$ are the sequential ORP_{apex} values from aeration periods 2 to n.

Figure 6a shows $pH_{m3(Pn)}$ and measured NH_4^+-N concentrations for a sample cycle. As can be seen $pH_{m3(Pn)}$ generally increased throughout the cycle before stabilising after a period of time. The point (Label A in Figure 6a) where $pH_{m3(Pn)}$ ascended above zero (i.e. the first $pH_{m3(Pn)}$ with a value greater than zero) was noted as generally corresponding to the end of nitrification. In Figure 6b, a spike (i.e. a sudden rise in the $ORP_{m3(Pn)}$ values) is apparent which was related to the end of nitrification.

Cycle termination rules

Following the development of each method associated rules were developed to predict the point where an aerobic phase should be terminated. Two rules were examined, namely; (i) threshold termination rule (TTR) and (ii) time delay termination rule (TDTR).

Threshold Termination rule (TTR)

The TTR comprised a threshold value for $X_{mz(Pn)}$ (where z refers to the method number 1, 2 or 3 and X refers to pH or ORP) which, when reached, would terminate the aerobic phase – i.e. once $X_{mz(Pn)}$

crossed the threshold value the aerobic phase would be terminated. TTR values were determined as follows:

i. Each $X_{mz(Pn)}$ value and associated time value at aeration period n was averaged across a group of treatment cycles (e.g. the values of $X_{mz(Pn)}$ for the first aeration period (n = 1) of every cycle analysed were averaged; this process was repeated for n = 2 … n).
ii. Three threshold values (T1, T2 and T3) were then calculated as follows (Supplementary Figures S2 and S3 present examples using data from this study):
    1. T1: average $X_{mz(Pn)}$ value plus two standard deviations,
    2. T2: average $X_{mz(Pn)}$ value plus one standard deviation and
    3. T3: average $X_{mz(Pn)}$ value

Figures 4a, 4b, 5a and 5b show an example of T1, T2 and T3 for $pH_{(m1Pn)}$. In the case of each threshold the cycle would be terminated when $pH_{(m1Pn)}$ crosses the horizontal line representing the threshold.

Method 3 ORP required a unique threshold identification technique as termination of the cycle was observed by a "spike" in the $ORP_{m3(Pn)}$ profile (Figure 6b) as opposed to a prolonged change as observed in method 1 and method 2 profiles. A database of $ORP_{m3(Pn)}$ spike values was prepared and the threshold values were calculated as follows;

- $ORP_{m3(T1)}$: A value which successfully identified the termination spike of 60% of the total number of cycles,
- $ORP_{m3(T3)}$: the threshold value that successfully identified the "termination spike" of all cycles and
- $ORP_{m3(T2)}$ was the median value between $ORP_{m3(T1)}$ and $ORP_{m3(T3)}$

It is appreciated that the selection of $ORP_{m3(T1)}$ impacts $ORP_{m3(T2)}$ and could be changed however for the purposes of this study the above values were used. In general it was hypothesised that where $X_{mz(Pn)}$ values decreased over time a higher threshold value would result in a shorter treatment cycle but increased NH_4^+-N concentrations when the threshold is reached. A lower threshold value would result in reduced NH_4^+-N concentrations on reaching the threshold value but a longer cycle time. The reverse would be true where $X_{mz(Pn)}$ values increased over time.

Time delay termination rule (TDTR)

The TDTR (i.e. rule that leveraged a time delay after a certain point was reached) was developed for pH_{m3} as it was observed that a cycle could be terminated when $pH_{m3(Pn)}$ increased above a value of 0 (Figure 6a) – i.e. for all cycles, termination was found to occur after $pH_{m3(Pn)}$ increased above a value of 0. Thus as $pH_{m3(Pn)}$ values rose above zero the cycle was terminated after a specified time (t) elapsed. For the purpose of this study three thresholds were analysed; namely (i) $pH_{m3(T1)}$ (TD1), (ii) $pH_{m3(T2)}$ (TD2) and (iii) $pH_{m3(T3)}$ (TD3) with values of 0, 20 and 40 minutes respectively (though these values were chosen based on experience and for any situation could easily be changed). In general a longer time should enhance NH_4^+-N removal, but negatively impact potential time/energy savings as the cycle would be terminated later.

Minimum cycle time

With the initial application of TTR and TDTR it was noted that in some cycles threshold values were reached prior early in the SBR treatment cycle thus causing premature termination of cycle (i.e. termination before desired levels of NH_4^+-N removal had taken place). There were three separate causes of premature triggers; (i) the time required to mix influent with the bulk fluid impacted $X_{mz(Pn)}$

profiles in the initial period of the aerobic phase, (ii) $X_{mz(Pn)}$ profiles remained above or below the threshold value from the start of the cycle until the end of the cycle, and (iii), which applied to ORP_{m3} only, was caused by spikes after NH_4^+-N concentrations peaked at the start of the treatment cycle.

Thus to eliminate premature cycle termination a minimum cycle time was applied. The minimum cycle time for each individual subset was chosen by analysing the treatment cycles deemed to have a premature trigger and selecting the lowest value required to prevent a premature termination for the entire affected group. In general the minimum cycle time for an SBR system operating in a similar fashion to this one would be equal to the length of the fill phase and the anoxic phase and would allow for initial mixing during the aeration phase (which occurred during the first “aeration-on” period).

Methodology for comparing cycle optimisation methods

To compare the efficiency of each method in optimising the treatment cycles it was necessary to develop a set of performance criteria. For example, in some cases where discharge limits are not stringent energy efficiency may be a priority whereas other sites might prioritise discharge limits. Five criteria were used to enable comparison between each method (at each threshold value).

Criterion 1: Percentage of successful cycles

A successful cycle was defined as a cycle where $X_{mz(Pn)}$ crossed the given threshold value. For some cycles the $X_{mz(Pn)}$ value did not cross the threshold value and thus the cycle would not have been stopped before the allotted aeration phase time despite NH_4^+-N concentrations levelling off. Such cycles were considered as unsuccessful cycles (i.e. cycles in which the threshold analysed failed to shorten the length of the aerobic phase despite NH_4^+-N concentrations levelling off prior to the end of the cycle) and was calculated as per Eq. 5.

$$\% \; \boldsymbol{successful\ cycles} = \left(\frac{\boldsymbol{C_{Succ}}}{\boldsymbol{C_{Tot}}}\right) \times \mathbf{100} \qquad \textbf{Eq. 5}$$

where C_{succ} is the number cycles terminated early and C_{Tot} is the total number of cycles analysed

Criterion 2: Potential NH_4^+-N removal

This criterion was defined as the percentage NH_4^+-N removal achieved if a cycle were terminated divided by the NH_4^+-N removal achieved during the full treatment cycle (Eq. 6).

$$\boldsymbol{NH_{4\,rem}}(\%) = \left(\frac{\boldsymbol{NH_{4\,peak}} - \boldsymbol{NH_{4\,thres}}}{\boldsymbol{NH_{4\,peak}} - \boldsymbol{NH_{4\,final}}}\right) \times \mathbf{100} \qquad \textbf{Eq. 6}$$

where NH_{4rem} is the percentage of potential NH_4^+-N removal achieved; $NH_{4\ thres}$ is the NH_4^+-N concentration where the cycle was terminated NH_4^+-N (mg/l); $NH_{4\ final}$ is the final NH_4^+-N concentration at the end of a full cycle (mg/l) and $NH_{4\ peak}$ is the highest NH_4^+-N concentration (mg/l).

Criterion 3: Average effluent NH_4^+-N

This criterion calculated the average NH_4^+-N concentration at the termination of each cycle.

Criterion 4: Average time saving

The average time saving criterion was assessed as the percentage of the full treatment cycle saved by the early termination of a cycle (Eq. 7).

$$\boldsymbol{T_{save}} = \left(\mathbf{1} - \frac{\boldsymbol{T_{thres}}}{\boldsymbol{T_{fixed}}}\right) \times \mathbf{100} \qquad \textbf{Eq. 7}$$

where T_{save} is the time saving (%); T_{thres} is cycle time when the cycle was terminated (min) and T_{fixed} is the fixed time cycle length (min).

Criterion 5: Average energy saving

Energy savings were calculated as the percentage of the total energy consumed during a full treatment cycle saved by the early termination of a cycle (Eq. 8). Energy consumption for the SBR was calculated using the power rating of each pump and the aerator (these were the major electricity consumers).

$$\boldsymbol{E_{save} = (1 - \frac{E_{thres} + E_{dis}}{E_{fixed}})} \qquad \textbf{Eq. 8}$$

where E_{save} is the energy saved (%), E_{thres} is the energy consumed prior to termination of the cycle (kWh); E_{dis} is the energy consumed to discharge effluent (kWh) and E_{fixed} is the energy used by a full treatment cycle (kWh).

It should be noted that energy and time savings are likely to be correlated but both were considered in this case as the system deployed intermittent aeration.

Ranking system

A ranking system was then developed to evaluate which method was optimal based on the above criteria (Table 2). In consultation with WWTP operators weights were applied to the criteria outlined above. For indicative purposes the weights outlined in Table 2 were applied to this study. In general the overriding concern in WWTPs is to meet environmental regulations. As there were no regulatory discharge limits applied to this site (as it was a pilot study) a required effluent concentration of 2 mg NH_4^+-N /l was chosen for indicative purposes.

The applied weights can be altered to suit the operator's goals and may change which of methods 1, 2 and 3 (and subset) might be optimal for any given site. For example, if potential energy savings was given a higher weight (for example 4 to 10) methods that lead to higher energy savings but also higher effluent NH_4^+-N concentrations would be favoured.

Subsets were compared by multiplying the criterion weight by a score attributed to that subset to give an overall weighted value. As an example consider two subsets (A and B), achieving potential energy savings of 60% and 70% respectively and potential NH_4^+-N removals of 20% and 5% respectively. The scores for potential energy savings would be 1 and 2 for A and B respectively with weighted scores of 4 and 8 (see Table 2 for applied weights). While for potential NH_4^+-N removal the scores for A and B would be 2 and 1 respectively with associated weighted scores of 2 and 1. Thus the total weighted scores for subsets A and B would be 6 and 9 respectively and therefore B would be the preferred subset.

Results

pH based methods –thresholds and minimum cycle times

For context, overall influent and effluent results for the SBR during the study are summarised in the supplementary information (Table S1). Figures 7a and 7b summarise the results from each of the pH based methods.

The threshold values for method pH_{m1} (taken from Figure S2a) were; T1 ($pH_{m1(Pn)} < 0.0037$), T2 ($pH_{m1(Pn)} < 0.0026$), and T3 ($pH_{m1(Pn)} < 0.0015$) and are shown in Figure 4a. A minimum cycle time of 70 minutes was applied to pH_{m1}. The threshold values, for method pH_{m2} (taken from Figure S2b) were; T1 ($pH_{m2(Pn)} < 0.005$), T2 ($pH_{m2(Pn)} < 0.003$), and T3 ($pH_{m2(Pn)} < 0.002$) - shown in Figure 5a. A minimum cycle time of 70 minutes was applied to pH_{m2}. As discussed the pH_{m3} time delays analysed were 0, 20 and 40 minutes. Each time delay was applied from the point $pH_{m3(Pn)}$ trend rose above zero as illustrated in Figure 6a. A minimum cycle time of 60 minutes was applied to pH_{m3}.

ORP based methods – thresholds and minimum cycle times

The overall results for each ORP based method are presented in Figures 8a and 8b**.**

The three threshold values for method ORP_{m1} (taken from Figure S3a) were; T1 ($ORP_{m1(Pn)} < 1.02$), T2 ($ORP_{m1(Pn)} <0.68$), and T3 ($ORP_{m1(Pn)} <0.34$) - illustrated in Figure 4b. Minimum cycle times of 60, 60 and 50 minutes were applied to T1, T2 and T3 respectively. The three threshold values for method ORP_{m2} (taken from Figure S2b) were; T1 ($ORP_{m2(Pn)} < 1.57$), T2 ($ORP_{m1(Pn)} < 1.07$), and T3 ($ORP_{m1(Pn)} < 0.57$) and are shown in Figure 5b. Minimum cycle times of 75, 65 and 65 minutes were applied to T1, T2 and T3 respectively. The thresholds identified for ORP_{m3} were; T1 ($ORP_{m3(Pn)} < 0.0127$), T2 ($ORP_{m3(Pn)} < 0.0068$), and T3 ($ORP_{m3(Pn)} < 0.0009$) (Figure 6b). A minimum cycle time of 80 minutes was applied to all assessments in ORP_{m3}.

pH and ORP results discussion

The results from pH_{m1}, ORP_{m1}, pH_{m2}, ORP_{m2} and pH_{m3} demonstrated that, as was hypothesised, a higher threshold value returned increased energy and time saving; however, it also resulted in increased effluent NH_4^+-N concentrations. The inverse was true for ORP_{m3}, where a lower threshold value yielded higher effluent NH_4^+-N concentrations and reduced energy and time savings. ORP_{m3} was the only method to utilise a Spike in lieu of a trend line and this caused the difference in the relationship between threshold values and operational efficiencies.

Method 1 examined the initial change in pH or ORP values after they reached their maximum value (generally at the end of the “aeration-on” period) during each aeration period and method 2 studied the trend between this maximum value and the subsequent nadir (minimum value for pH or ORP). It was observed that in both pH and ORP studies method 2 proved to be more efficient in meeting effluent quality requirements while method 1 resulted in increased energy and time savings. For optimising final effluent quality pH_{m3} proved more suitable than both pH_{m1} and pH_{m2}, however this resulted in lower potential energy and time savings (a similar result was seen in ORP_{m3} when compared to methods 1 and 2).

Comparing pH and ORP subsets, ORP results were 17% and 13% more efficient in time and energy savings respectively; however, NH_4^+-N removals were less efficient when compared to the pH based methods.

Ranking methods

A set of sample weights were applied which prioritised effluent quality over time and energy savings as per Table 2. With the application of these weights $pH_{m3(T1)}$ and $ORP_{m1(T1)}$ were the highest ranked pH and ORP methods respectively; with $pH_{m3(T1)}$ being the top ranked method (Figure 9). Application of $pH_{m3(T1)}$ to the cycles examined would have resulted in an average energy saving of 43% (maximum 87% time saving and minimum 39%) corresponding to an average time saving of 60% (maximum 86% and minimum 29%) of the fixed time cycle and an average effluent NH_4^+-N concentration of 1.9 mg/l (maximum 4.5 mg/l and minimum 0.9 mg/l). Further information on the application of the ranking method is given in supplementary information (See Tables S2 to S5 and Figure S1).

Application and discussion

The methods outlined are all readily applied to low cost PLCs typically used at small and decentralised WWTPs (or indeed can be applied to all SBR systems). In order to optimise these methods a short trial on a given site would be recommended. Initially the site would be operated using the existing or planned fixed time cycle and pH, ORP and NH_4^+-N sensors installed to collect data over a period; depending on the quality of the data this could vary but it is anticipated that two to four weeks would be sufficient. The collected data should be separated into individual cycles; at this point the ranking system can be applied to the data to determine the most suitable control method for that site. The weights applied within the ranking system will impact which method is likely to be most suitable and these should be modified to reflect the objectives of the operator/engineer or researcher at that site. The most suitable method can then be deployed using a low cost PLC.

Within this study, methods based on pH data were observed to result in more efficient operation when compared to those based on ORP data. Therefore, where the wastewater characteristics and SBR operation were similar to those in place during this study, the user could potentially limit the study to a pH sensor only and in particular method 3.

When comparing methods 1 and 2, method 2 doubled the effort of the PLC when compared to method 1 as the identification of both the apex and nadir are required; though it did result in improved overall results; again this could be a consideration depending on the PLC deployed and the sensitivity of the site to discharge limits or energy/time savings.

The ORP and pH strategies described above were developed for use with low cost basic PLCs. For this purpose the Siemens LOGO! was selected as a test unit. The PLC's compatible software LOGO! Soft Comfort V7.1 has a variety of function blocks which control the overall SBR cycle and can interpret the analogue values from the pH and ORP sensors and thus terminate the SBR cycle when conditions are appropriate. The analogue values can be input directly into a function block that can determine maximum values during treatment cycles. The change between subsequent maximum values can then be determined using an instruction function block. The input from this block can be connected into an analogue “threshold” trigger. When this trigger receives a specified value, for example zero or greater for pH_{m3}, a signal can be sent to the SBR programme to terminate the aeration phase. The technology’s application would result in some additional maintenance in terms of cleaning and calibration of sensors; however, day to day maintenance of the WWTP would remain unchanged. However the significant benefits include improved compliance and enhanced energy savings and increase the flexibility of the SBR when treating variable influent volumes or wastewater characteristics.

The methods can be adapted for SBR systems that operate continuous aeration but would be less effective without significant change if applied to typical activated sludge treatment systems. The methods would prove most effective when applied to batch treatment systems that operate intermittent aeration.

Conclusions

This research outlines a procedure to develop a low resource real time control architecture for small WWTPs using pH and ORP sensors. Three control methodologies each with three subset analyses were developed and applied to data collected from a domestic scale SBR unit. Results from each subset were separated in 5 criteria and ranked to determine the best subset. It was determined for a typical treatment cycle the most optimal subset would achieve an average overall cycle time savings of 60% with a corresponding energy saving of 43%. NH_4^+-N removal was 78% of the NH_4^+-N removal achieved in the fixed time treatment cycle with a corresponding NH_4^+-N concentration of 1.9 mg/l (which was within the self-imposed discharge limit thus further treatment was not necessary).

All methods were readily applicable to low cost PLCs thus potentially making practical solutions for aiding control systems and Environmental Engineers operating small wastewater treatment systems Limited maintenance, apart from occasional sensor cleaning was required. When operating SBR systems in a similar context to this study it may be possible, when ascertaining the optimal methods, to limit the study to using a pH sensor. However, this may depend on the ranking criteria determined by the operative. Further research on this subject should include the application of the developed control methodology (at site scale) and monitoring of the impacts (on biomass etc.) of prolonged deployment of these methods. The use of such methods on other technologies should also be explored.

Acknowledgments

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Notation

The following symbols are used in this paper:

C_{Succ}	Number successful cycles
C_{Tot}	Total number of available cycles
E_{dis}	Energy consumed to discharge effluent (kWh)
E_{fixed}	energy used by a full treatment cycle (kWh)
E_{save}	Percentage of energy saved
E_{thres}	Energy consumed prior to threshold (kWh)
NH_4^+-N	Ammonium nitrogen
$NH_{4\ final}$	Final NH_4^+-N concentration at the end of a full cycle (mg/l)
$NH_{4\ peak}$	Highest NH_4^+-N concentration (mg/l)
NH_{4rem}	Percentage of potential NH_4^+-N removal achieved
$NH_{4\ thres}$	NH_4^+-N concentration where the cycle was terminated automatically (mg/l)

NH_4-N	NH_4^+-N nitrogen
NO_2-N	Nitrite nitrogen
NO_3-N	Nitrate nitrogen
ORP_{apex}	Individual ORP apex value
$ORP_{apex(Pn)}$	sequential ORP_{apex} values from aeration periods 2 to n
$ORP_{apex(Pn-1)}$	Previous aeration period to $ORP_{apex(Pn)}$
ORP_{m1}	ORP method 1, method 1 examined the potential of utilising the initial rate of ORP (ORP_{m1}) change
$ORP_{m1(Pn)}$	ORP method 1 values between aeration period n and n-1
$ORP_{m1(T1)}$	ORP method 1 threshold 1
$ORP_{m1(T2)}$	ORP method 1 threshold 2
$ORP_{m1(T3)}$	ORP method 1 threshold 3
ORP_{m1Tr}	ORP method 1 threshold r (r is threshold number 1,2 or 3)
ORP_{m2}	ORP method 2, method 2 examines the potential of utilising the entire change in ORP (ORP_{m2}) values
$ORP_{m2(Pn)}$	ORP method 2 values between aeration period n and n-1
$ORP_{m2(T1)}$	ORP method 2 threshold 1
$ORP_{m2(T2)}$	ORP method 2 threshold 2
$ORP_{m2(T3)}$	ORP method 2 threshold 3
ORP_{m2Tr}	ORP method 2 threshold r (r is threshold number 1,2 or 3)
ORP_{m3}	ORP method 3, method 3 examines the potential of utilising the rate of change of consecutive ORP_{apex} values over an aerobic phase
$ORP_{m3(Pn)}$	ORP method 3 values between aeration period n and n-1
$ORP_{m3(T1)}$	ORP method 3 threshold 1
$ORP_{m3(T2)}$	ORP method 3 threshold 2
$ORP_{m3(T3)}$	ORP method 3 threshold 3
ORP_{m3Tr}	ORP method 3 threshold r (r is threshold number 1,2 or 3)
$ORP_{mz(Pn)}$	ORP value for tethod z between aeration period n and n-1 (z is method number 1, 2 or 3)
ORP_{nadir}	Individual ORP nadir value
pH_{apex}	Individual pH apex value
$pH_{apex(Pn)}$	sequential pH_{apex} values from aeration periods 2 to n
$pH_{apex(Pn-1)}$	Previous aeration period to $pH_{apex(Pn)}$
pH_{m1}	pH method 1, method 1 examined the potential of utilising the initial rate of pH (pH_{m1}) change
$pH_{m1(Pn)}$	pH method 1 apex values between aeration period n and n-1
$pH_{m1(T1)}$	pH method 3 threshold 1
$pH_{m1(T2)}$	pH method 3 threshold 2
$pH_{m1(T3)}$	pH method 3 threshold 3
pH_{m1Tr}	pH method 1 threshold r (r is threshold number 1,2 or 3)
pH_{m2}	pH method 2, method 2 examines the potential of utilising the entire change in pH (pH_{m2}) values between the apex and nadir of each aeration period over an aerobic cycle
$pH_{m2(Pn)}$	pH method 2 apex values between aeration period n and n-1
$pH_{m2(T1)}$	pH method 2 threshold 1
$pH_{m2(T2)}$	pH method 2 threshold 2
$pH_{m2(T3)}$	pH method 2 threshold 3
pH_{m2Tr}	pH Method 2 threshold r (R is threshold number 1,2 or 3)
pH_{m3}	pH method 3, method 3 examines the potential of utilising the rate of change of consecutive pH_{apex}
$pH_{m3(Pn)}$	pH method 3 apex values between aeration period n and n-1

$pH_{m3(T1)}$	pH method 3 threshold 1
$pH_{m3(T2)}$	pH method 3 threshold 2
$pH_{m3(T3)}$	pH method 3 threshold 3
pH_{m3Tr}	pH method 3 threshold r (r is threshold number 1,2 or 3)
$pH_{mz(Pn)}$	pH apex values for method z (z is method number 1, 2 or 3)
pH_{nadir}	Individual pH nadir value
T_{fixed}	Fixed time cycle length (min)
T_{save}	Percentage of time saving
T_{thres}	Time at the threshold (min)
$X_{apex(Pn)}$	pH or ORP value at the nth aeration period apex
$X_{apex+t(Pn)}$	pH or ORP value t min after the nth aeration period apex
$X_{m1(Pb)}$	pH or ORP values for method 1 at the nth aeration period
$X_{m2(Pn)}$	pH or ORP apex values for method 2 at the nth aeration period
X_{mz}	pH or ORP method 1,2 or 3
$X_{mz(Pn)}$	pH or ORP values for method z (z is method number 1, 2 or 3)
$X_{mz(T1)}$	Threshold value 1 for method z (z is method number 1, 2 or 3)
$X_{mz(T2)}$	Threshold value 2 for method z (z is method number 1, 2 or 3)
$X_{mz(T3)}$	Threshold value 3 for method z (z is method number 1, 2 or 3)
$X_{nadir(Pn)}$	pH or ORP nadir value at the nth aeration period apex

Supplementary data

Tables S1-S5 and Figures S1–S3 are available online in the ASCE Library (ascelibrary.org).

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Table 1 - Diurnal flow pattern used to feed the primary chamber of the SBR pilot unit (CEN 2006)

Time of day	% of total volume	Volume (litres)	Time of day	% of total volume	Volume (litres)
0:00-6:00	0	0	14:00-15:00	0	0
6:00-7:00	10	60	15:00-16:00	0	0
7:00-8:00	10	60	16:00-17:00	0	0
8:00-9:00	10	60	17:00-18:00	0	0
9:00-10:00	5	30	18:00-19:00	20	120
10:00-11:00	5	30	19:00-20:00	20	120
11:00-12:00	5	30	20:00-21:00	5	30
12:00-13:00	0	0	21:00-22:00	5	30
13:00-14:00	0	0	22:00-23:00	5	30

Table 2 - applied weights

Criteria	Weight	Comments
Meet discharge limit <2 mg/l	5	Ranked most important as facilities must achieve regulatory compliance
Potential energy saving (%)	4	If compliance has been achieved energy efficiency was seen as a priority
Successful cycles (%)	3	The greater the number of cycles a method successfully impacts the greater the potential energy saving
Potential time saving (%)	2	Savings in cycle time can result in energy efficiency and also mean the system is available to handle larger volumes
Potential NH_4^+-N removal (%)	1	NH_4^+-N removal beyond the discharge limit may be seen as inefficient and thus least important

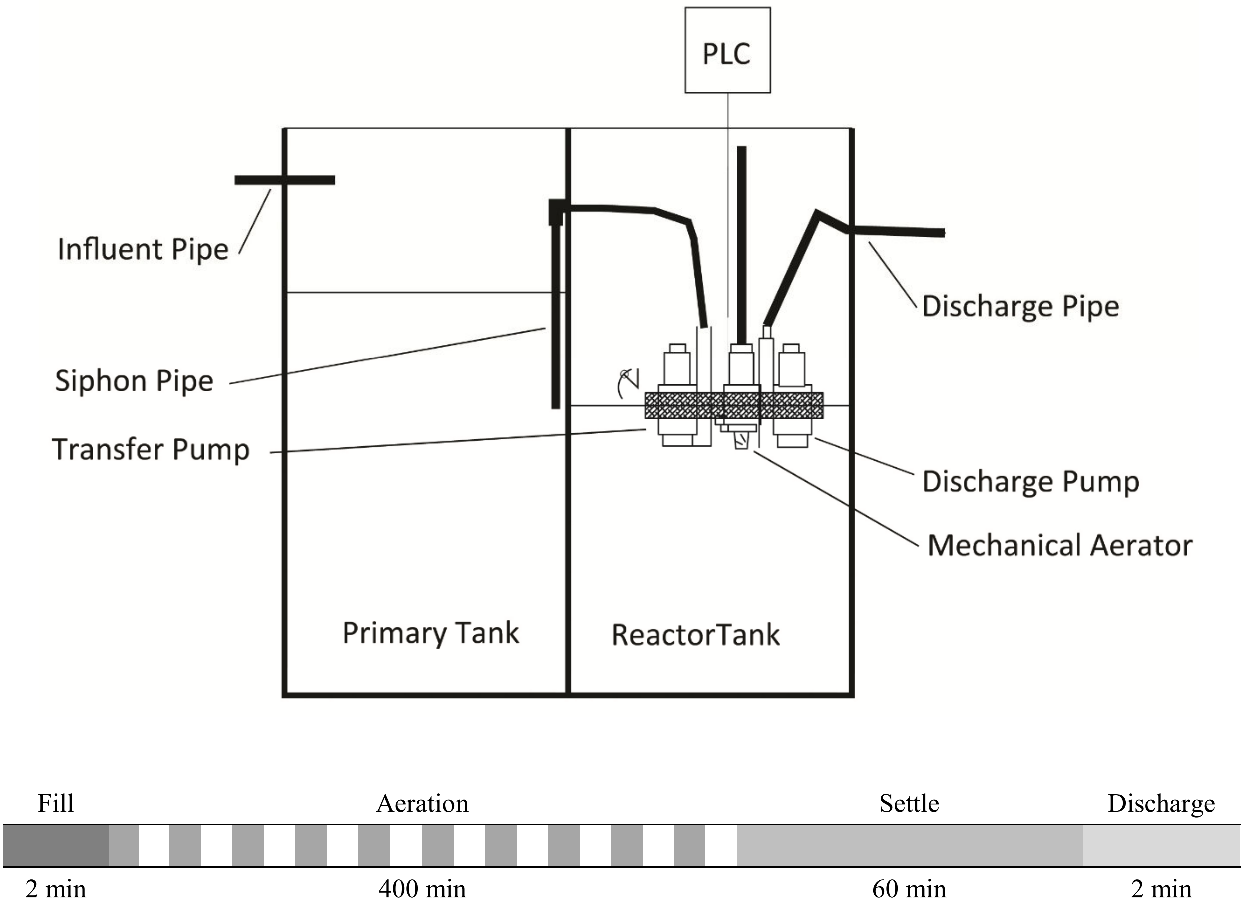

Figure 1 - Schematic of pilot SBR unit and the cycle sequence

a)

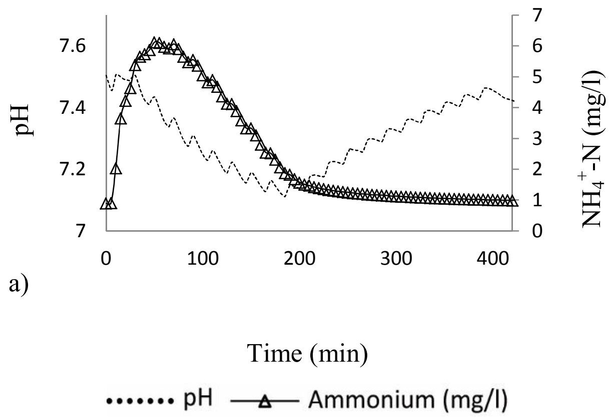

Figure 2a - pH and NH_4-N profiles for a typical cycle

b)

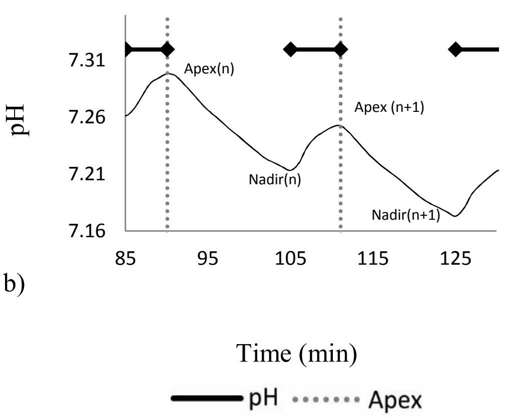

Figure 2b - Example of two aeration periods for a typical cycle with a pH profile (black lines indicate "aeration-on" periods)

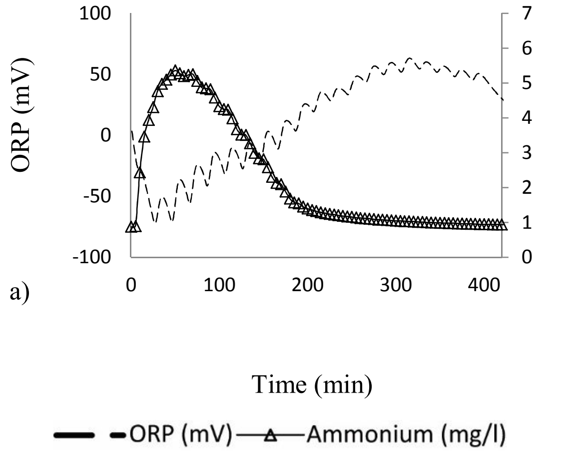

Figure 3a - ORP and NH_4^+-N profiles for a typical cycle

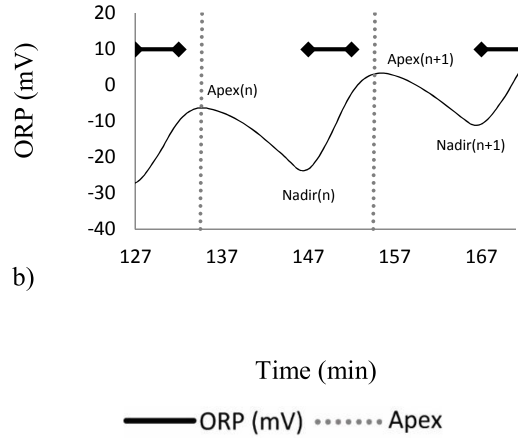

Figure 3b - Example of two aeration periods for a typical cycle with an ORP profile (black lines indicate "aeration-on" periods)

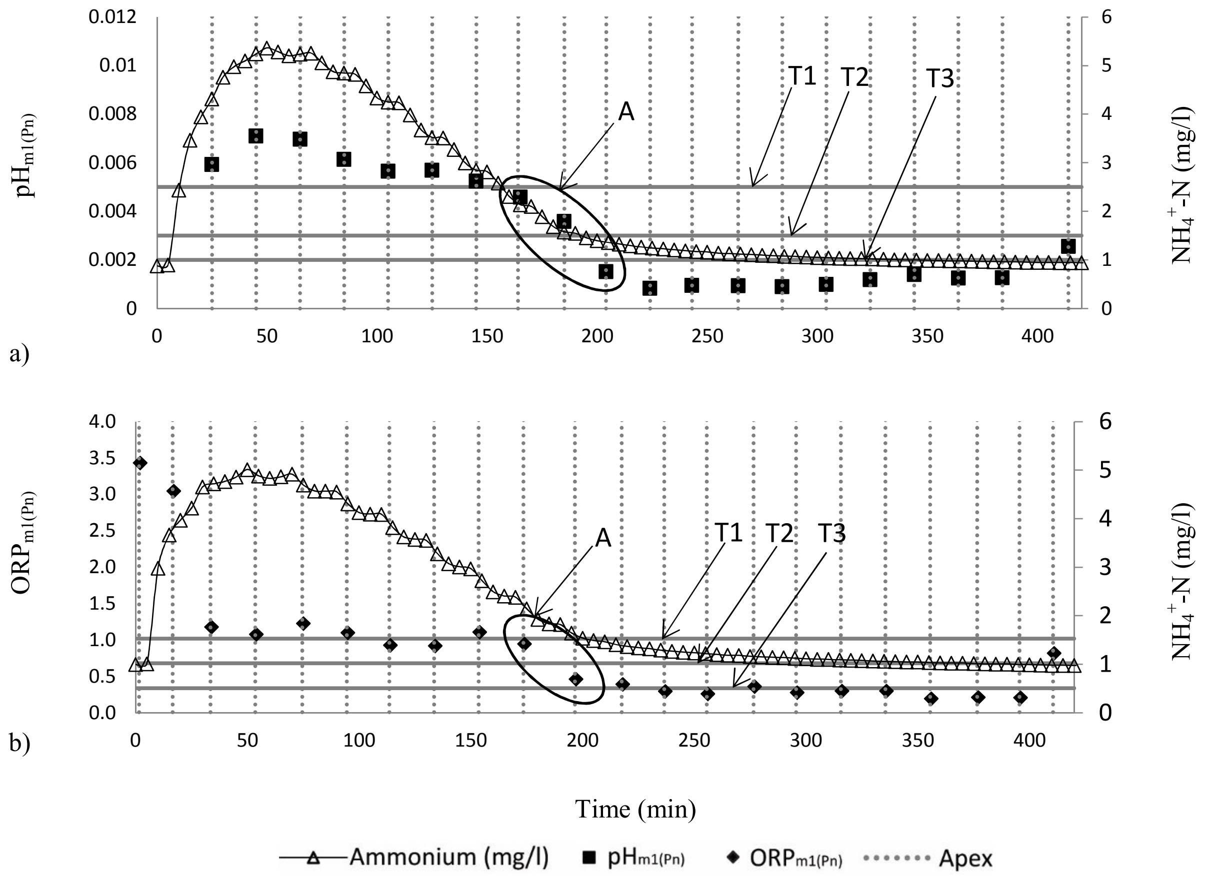

Figure 4a - $pH_{m1(Pn)}$ and NH_4^+-N profiles (vertical lines indicate each identified pH_{apex} and horizontal lines indicate threshold values); 4b - $ORP_{m1(Pn)}$ and NH_4^+-N profiles (vertical lines indicate each identified ORP_{apex} and horizontal lines indicate threshold values).

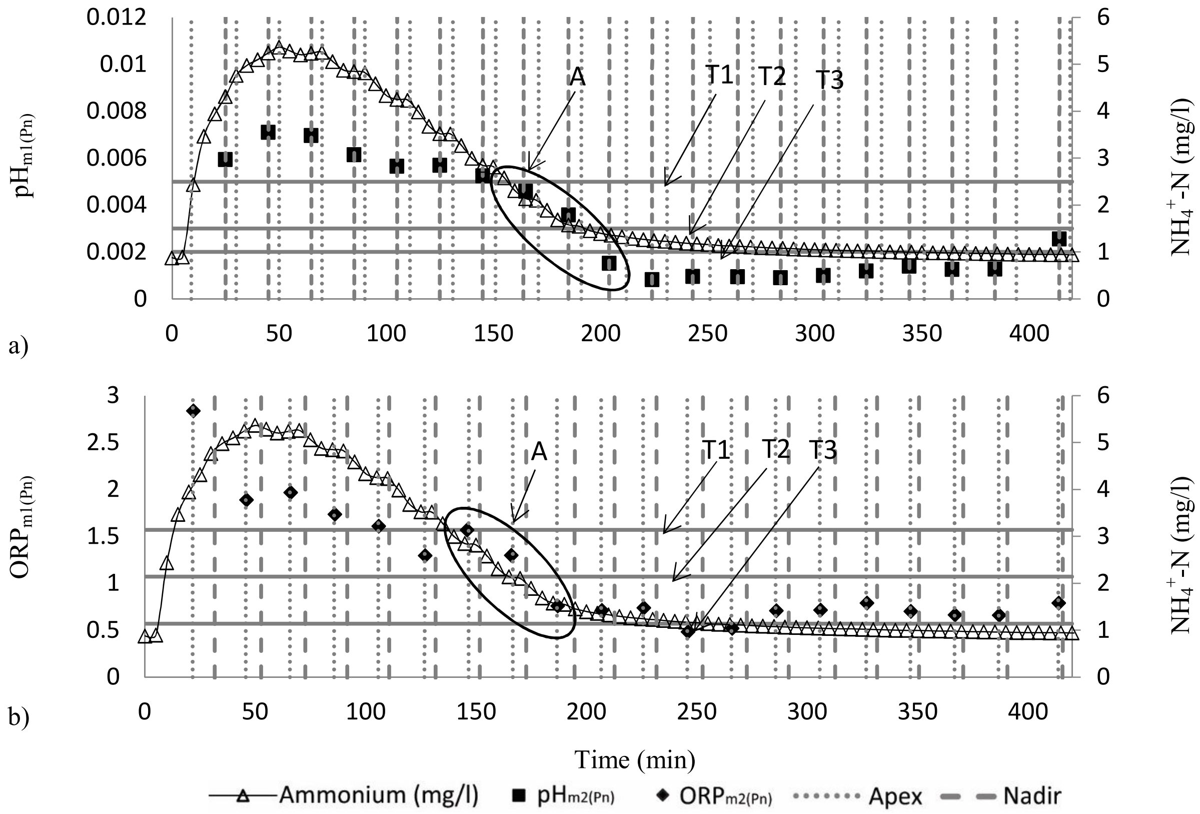

Figure 5a - pH$_{m2(Pn)}$ and NH$_4^+$-N profiles (vertical lines indicate each identified pH$_{apex}$ and horizontal lines indicate threshold values); 5b - ORP$_{m2(Pn)}$ and NH$_4^+$-N profiles (vertical lines indicate each identified ORP$_{apex}$ and horizontal lines indicate threshold values).

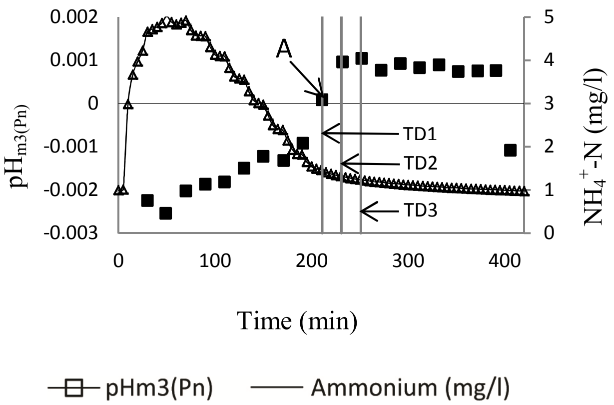

Figure 6a - A typical $pH_{m3(Pn)}$ and associated NH_4^+-N profile.

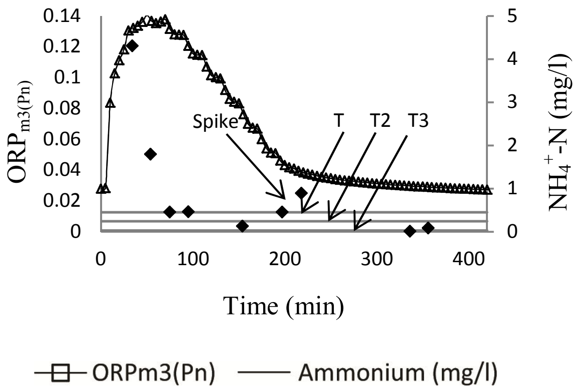

Figure 6b - A typical $ORP_{m3(Pn)}$ and associated NH_4^+-N profile.

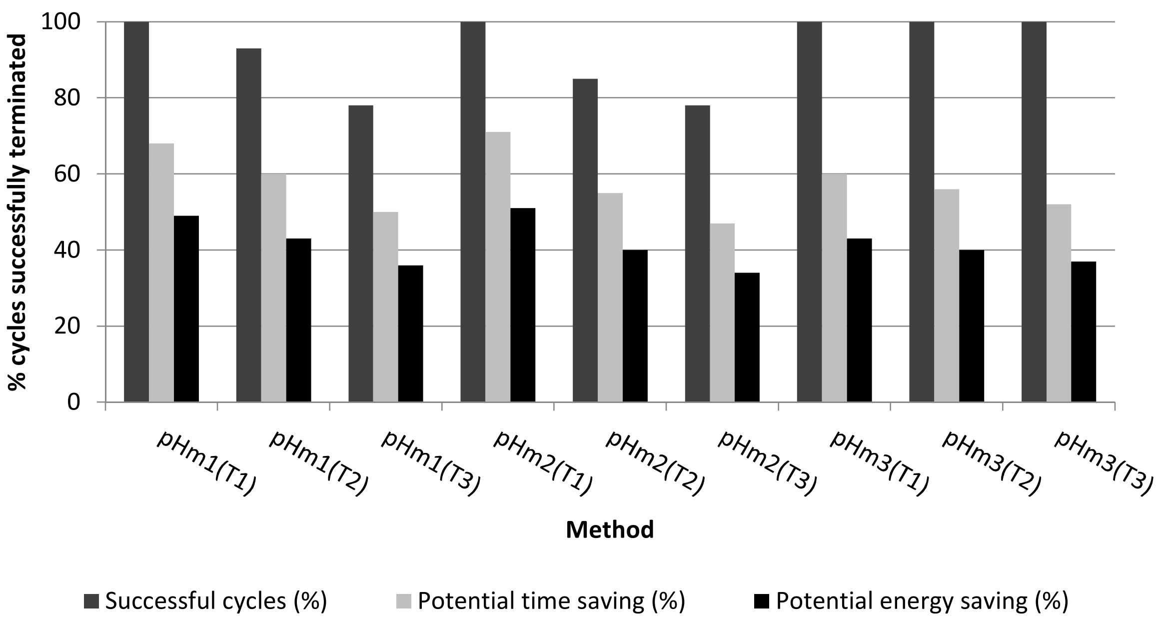

Figure 7a – The percentage of cycles successfully terminated, potential time saving and potential energy saving for each pH based method

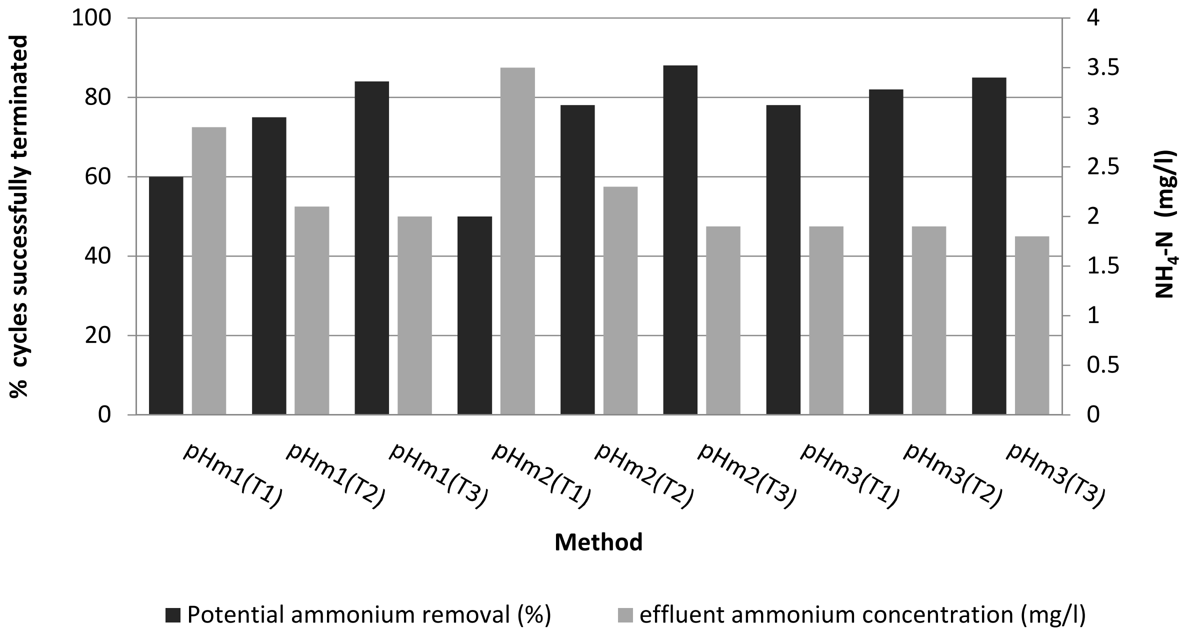

Figure 7b – The potential NH_4^+-N removal (%) and effluent NH_4^+-N concentration (mg/l) results for each pH based method

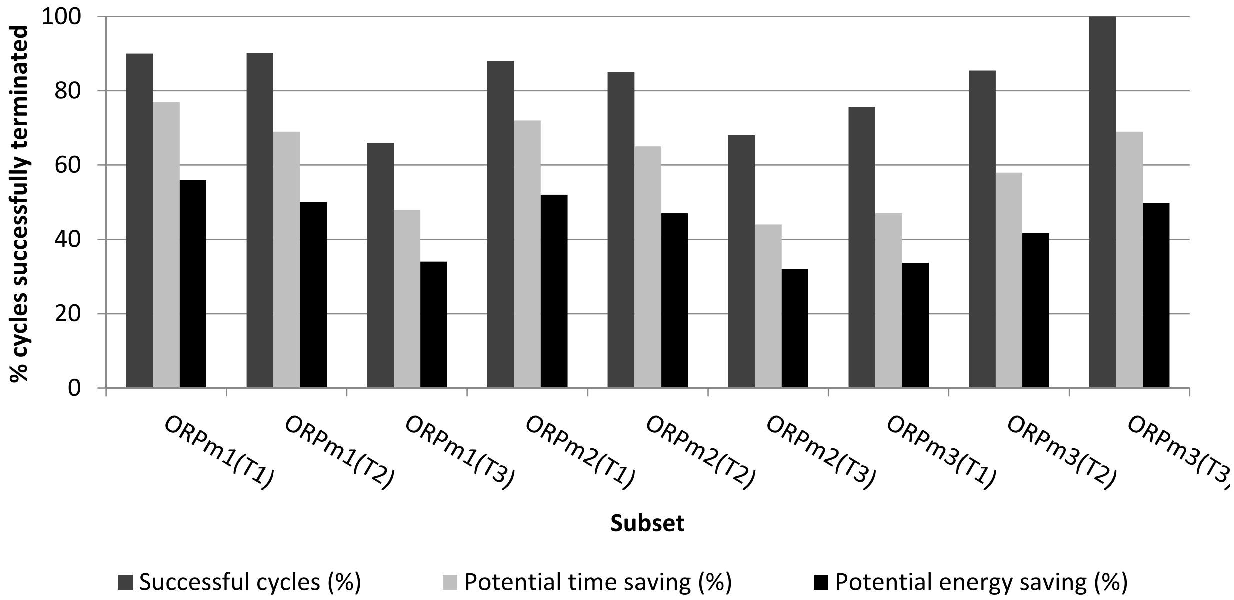

Figure 8a - The percentage of cycles successfully terminated, potential time saving and potential energy saving for each ORP based method

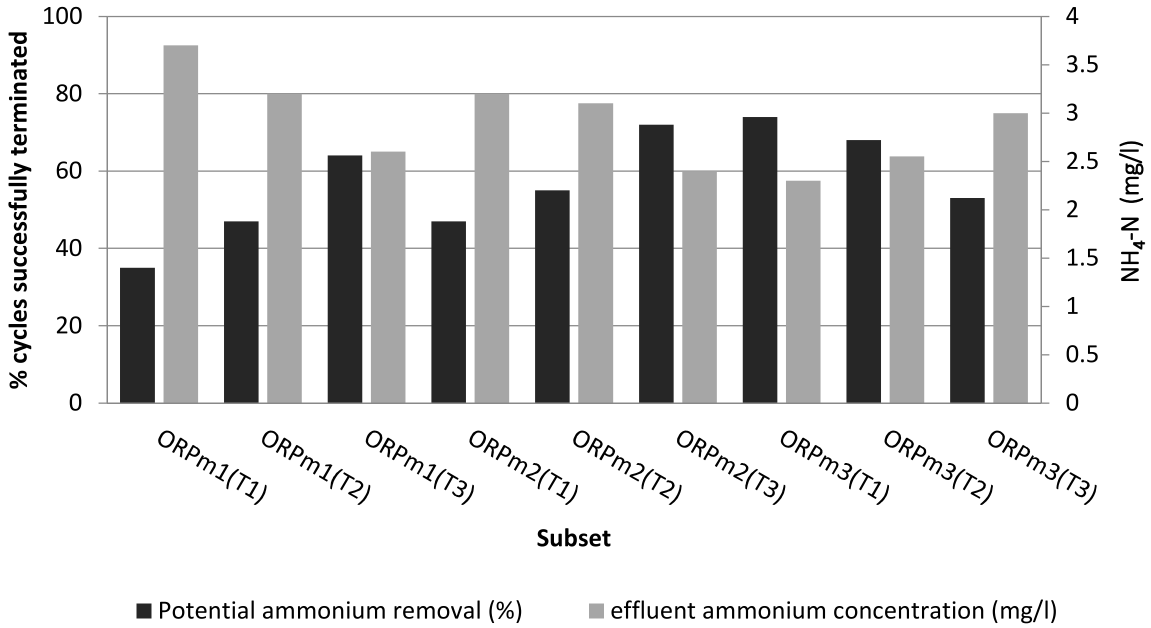

Figure 8b – The potential NH_4-N removal (%) and effluent NH_4-N concentration (mg/l) results for each ORP based method

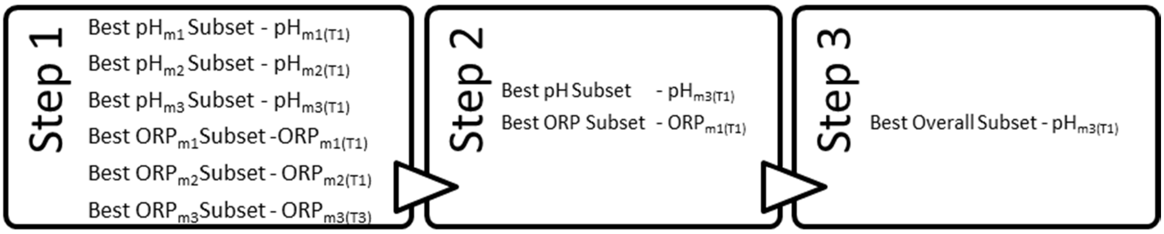

Figure 9 - Overall Ranking results

Figure 1 - Schematic of pilot SBR unit and the cycle sequence

Figure 2a - pH and NH_4-N profiles for a typical cycle

Figure 2b - Example of two aeration periods for a typical cycle with a pH profile (black lines indicate "aeration-on" periods)

Figure 3a - ORP and NH_4^+-N profiles for a typical cycle

Figure 3b - Example of two aeration periods for a typical cycle with an ORP profile (black lines indicate "aeration-on" periods

Figure 4a - $pH_{m1(Pn)}$ and NH_4^+-N profiles (vertical lines indicate each identified pH_{apex} and horizontal lines indicate threshold values); 4b - $ORP_{m1(Pn)}$ and NH_4^+-N profiles (vertical lines indicate each identified ORP_{apex} and horizontal lines indicate threshold values).

Figure 5a - $pH_{m2(Pn)}$ and NH_4^+-N profiles (vertical lines indicate each identified pH_{apex} and horizontal lines indicate threshold values); 5b - $ORP_{m2(Pn)}$ and NH_4^+-N profiles (vertical lines indicate each identified ORP_{apex} and horizontal lines indicate threshold values).

Figure 6a - A typical $pH_{m3(Pn)}$ and associated NH_4^+-N profile.

Figure 6b - A typical $ORP_{m3(Pn)}$ and associated NH_4^+-N profile.

Figure 7a – The percentage of cycles successfully terminated, potential time saving and potential energy saving for each pH based method

Figure 7b – The potential NH_4^+-N removal (%) and effluent NH_4^+-N concentration (mg/l) results for each pH based method

Figure 8a - The percentage of cycles successfully terminated, potential time saving and potential energy saving for each ORP based method

Figure 8b – The potential NH_4-N removal (%) and effluent NH_4-N concentration (mg/l) results for each ORP based method

Figure 9 - Overall ranking results

Supplementary information

Table S1 - Average influent and effluent results

Parameter	**Average influent**	**Influent st.dev.**	**Average effluent**	**Influent st.dev.**	**% removal**	**n**
	mg/l	mg/l	mg/l	mg/l		**Inf/Eff**
COD_f	405	126	120	85	70.3	9/14
TN	87.4	36	16.2	7.9	81.5	12/18
NH_4^+-N	49.6	20	1.1	1.2	97.8	17/28
NO_3-N	-	-	2.5	4.3	-	-/27

n is number of samples; Inf – Influent; Eff - Effluent

Table S2 - Step 1 pH

			T1		T2		T3	
		Weight	**Score**	**Weighted**	**Score**	**Weighted**	**Score**	**Weighted**
pH_{m1}	Successful cycles (%)	3	3	9	2	6	1	3
	NH_4^+-N removal (%)	1	1	1	2	2	3	3
	Meet discharge limit	5	0	0	0	0	0	0
	Potential time saving	2	3	6	2	4	1	2
	Potential energy saving	4	3	12	2	8	1	4
	Total weighted values			28		20		12
	Rank			3		2		1
pH_{m2}	Successful cycles (%)	3	3	9	2	6	1	3
	NH_4^+-N removal (%)	1	1	1	2	2	3	3
	Meet discharge limit	5	0	0	0	0	3	15
	Potential time saving	2	3	6	2	4	1	2
	Potential energy saving	4	3	12	2	8	1	4
	Total weighted values			28		20		27
	Rank			3		2		1
pH_{m3}	Successful cycles (%)	3	3	9	3	9	3	9
	NH_4^+-N removal (%)	1	1	1	2	2	3	3
	Meet discharge limit	5	3	15	3	15	2	10
	Potential time saving	2	3	6	2	4	1	2
	Potential energy saving	4	3	12	2	8	1	4
	Total weighted values			43		38		28
	Rank			3		2		1

Table S3 - Step 1 ORP

			T1		T2		T3	
		Weight	**Score**	**Weighted**	**Score**	**Weighted**	**Score**	**Weighted**
ORP_{m1}	Successful cycles (%)	3	3	9	3	9	2	6
	NH_4^+-N removal (%)	1	1	1	2	2	3	3
	Meet discharge limit	5	0	0	0	0	0	0
	Potential time saving	2	3	6	2	4	1	2
	Potential energy saving	4	3	12	2	8	1	4
	Total weighted values			28		23		15
	Rank			1		2		3
ORP_{m2}	Successful cycles (%)	3	3	9	2	6	1	3
	NH_4^+-N removal (%)	1	1	2	2	2	3	3
	Meet discharge limit	5	0	0	0	0	0	0
	Potential time saving	2	3	6	2	4	1	2
	Potential energy saving	4	3	12	2	8	1	4
	Total weighted values			29		20		12
	Rank			1		2		3
ORP_{m3}	Successful cycles (%)	3	1	3	2	6	3	9
	NH_4^+-N removal (%)	1	3	3	2	2	1	1
	Meet discharge limit	5	0	0	0	0	0	0
	Potential time saving	2	1	2	2	4	3	6
	Potential energy saving	4	1	4	2	8	3	12
	Total weighted values			12		20		28
	Rank			3		2		1

Table S4 - Step 2

			$pH_{m1(T1)}$		$pH_{m2(T1)}$		$pH_{m3(T1)}$	
		Weight	**Score**	**Weighted**	**Score**	**Weighted**	**Score**	**Weighted**
pH	Successful cycles (%)	3	3	9	3	9	3	9
	NH_4^+-N removal (%)	1	2	2	1	1	3	3
	Meet discharge limit	5	0	0	0	0	3	15
	Potential time saving	2	2	4	3	6	1	2
	Potential energy saving	4	2	8	3	12	1	4
	Total weighted values			23		28		33
	Rank			3		2		1
			$ORP_{m1(T1)}$		$ORP_{m2(T1)}$		$ORP_{m3(T3)}$	
ORP	Successful cycles (%)	3	2	6	1	3	3	9
	NH_4^+-N removal (%)	1	1	1	2	2	3	3
	Meet discharge limit	5	0	0	0	0	0	0
	Potential time saving	2	3	6	2	4	1	2
	Potential energy saving	4	3	12	2	8	1	4
	Total weighted values			25		17		18
	Rank			1		3		2

Table S5 - Step 3

		$pH_{m3(T1)}$		$ORP_{m1(T1)}$	
	Weight	**Score**	**Weighted**	**Score**	**Weighted**
Successful cycles (%)	3	2	6	1	3
NH_4^+-N removal (%)	1	2	2	1	1
Meet discharge limit	5	2	10	0	0
Potential time saving (%)	2	1	2	2	4
Potential energy saving (%)	4	1	4	2	8
Total weighted values			24		16
Rank			1		2

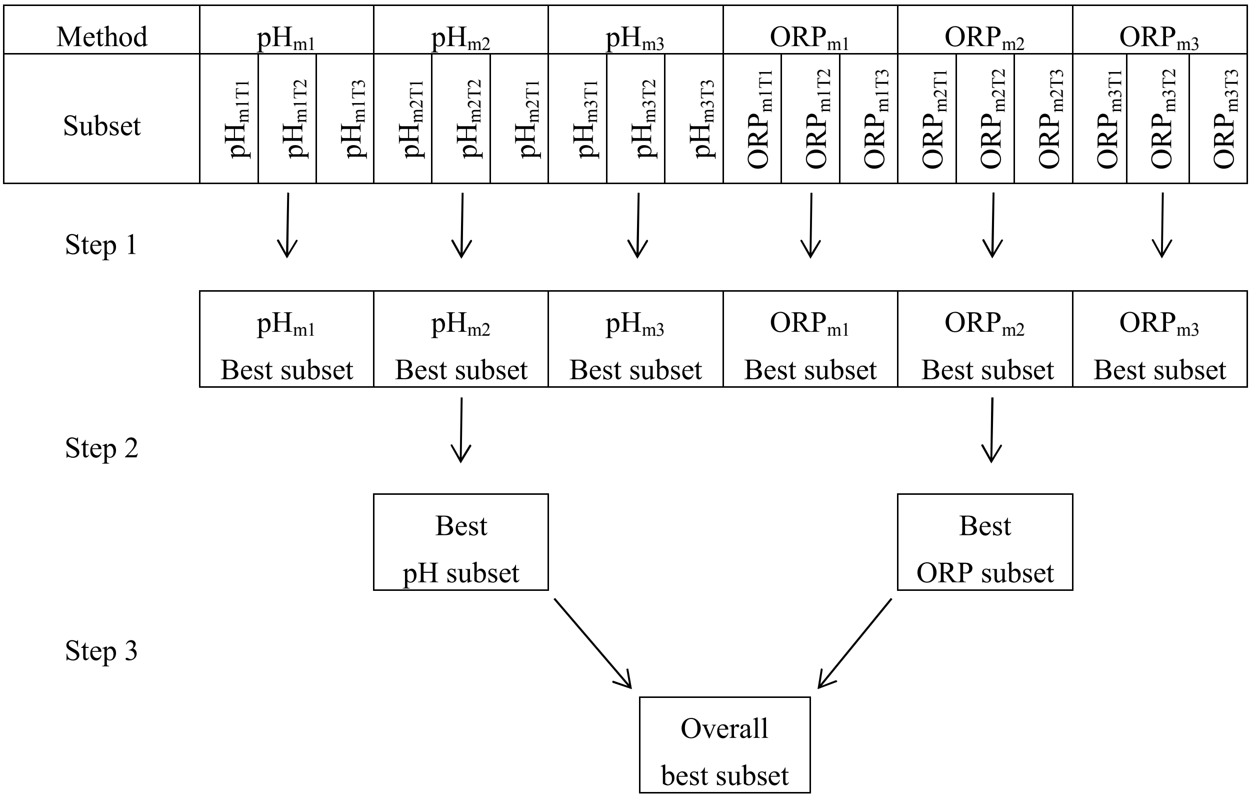

Figure S1 - Weighting and ranking procedure

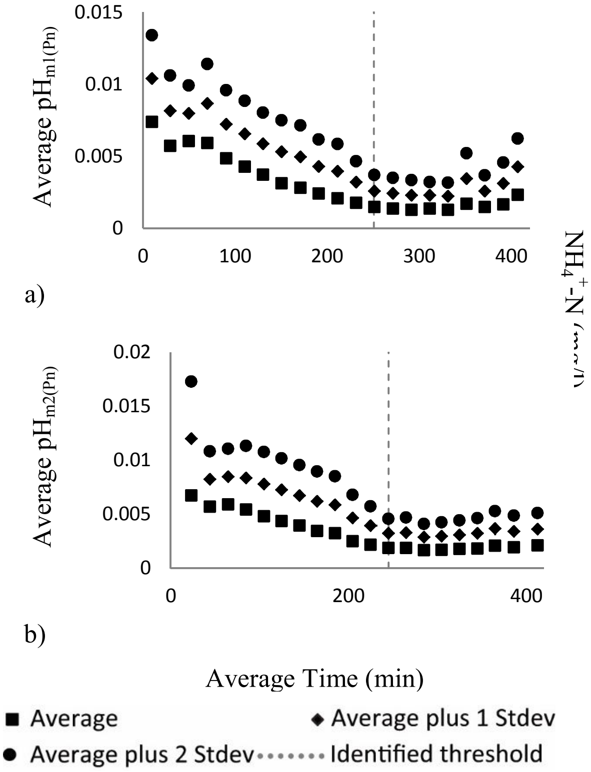

Figure S2a – pH_{m1}, threshold selection; b – pH_{m2}, threshold selection

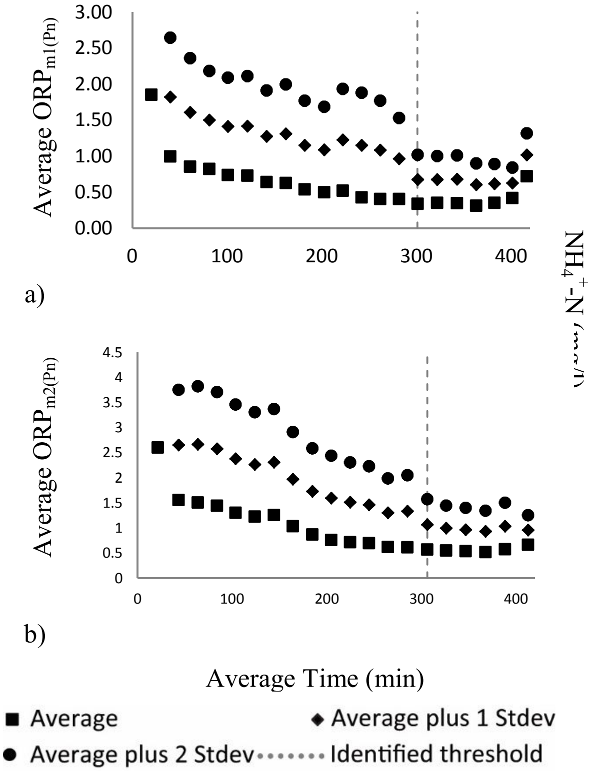

Figure S3a – ORP_{m1}, threshold selection; b – ORP_{m2}, threshold selection