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Enhancing aerobic digestion of full-scale waste activated sludge using free nitrous acid pre-treatment

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Aerobic digestion is one of the mainstream technologies for waste activated sludge (WAS) reduction and stabilization prior to disposal, but its effectiveness is limited by the poor degradation of WAS. This study presents a novel strategy based on free nitrous acid (FNA *i.e.* HNO_2) pre-treatment to enhance full-scale WAS degradation in aerobic digestion. The full-scale WAS was subject to FNA treatment at 2.0 mg HNO_2–N per L for 24 h. The degradation of the FNA-treated WAS was then compared to that of the same WAS without FNA pre-treatment by aerobically digesting the WAS with a full-scale activated sludge for 14 days. Approximately 50% of the FNA-treated WAS was degraded during the 14 day aerobic digestion compared to 32% achieved with the untreated WAS. The inorganic nitrogen production (originating from breakdown of WAS) from the FNA-treated WAS was 43 mg N per g of mixed liquor volatile suspended solids (MLVSS) in the 14 day aerobic digestion, whereas its production from the untreated WAS was only 29 mg N per g of MLVSS, confirming the effectiveness of the FNA pre-treatment in enhancing aerobic digestion of full-scale WAS. Economic analysis showed that the FNA pre-treatment method was economically attractive, saving a cost of %-15 500–64 500 per year depending on WAS disposal cost in a treatment plant with a population equivalent of 80 000.

1. Introduction

Activated sludge processes produce substantial amounts of waste activated sludge (WAS), the treatment and disposal of which incur large costs.[1–4] Aerobic and anaerobic sludge digestion is the mainstream technology for sludge reduction and stabilization prior to disposal, but its effectiveness is limited by the poor degradation of WAS.[5] Various methods including mechanical, thermal, chemical and biological pre-treatment have been proposed to enhance WAS degradation during digestion.[6–15] For example, Uma Rani, *et al.*[13] enhanced biogas production by 80% during anaerobic digestion of WAS using a two-step sono-alkalization pre-treatment. Kavitha, *et al.*[14] achieved >100% increase in biogas production using phase-separated sludge disintegration method. However, the above approaches require either intensive energy input (*e.g.* high pressure or high temperature) or large chemical consumption (*e.g.* chlorine, ozone or alkali), incurring substantial economic costs.[6]

Free nitrous acid (FNA *i.e.* HNO_2) has been demonstrated to be biocidal to bacteria.[16] Subsequently, pre-treatment of WAS using FNA was shown to be effective in reducing sludge production and enhancing methane production during anaerobic digestion of WAS. For example, Wang *et al.*,[17] reported that sludge production in a laboratory reactor treating synthetic domestic wastewater was reduced by 28% by treating part of the return activated sludge with FNA at 2.0 mg N per L for 24 h. Recently, it has been demonstrated that methane production from a full-scale WAS, with FNA pre-treatment at 2.0 mg N per L for 24 h, was improved by approximately 30% at an anaerobic digestion time of 20 days in comparison with that from the WAS without FNA pre-treatment.[18] Also, the FNA pre-treatment method for enhancing methane production during anaerobic digestion was shown to be economically attractive.[18]

The above research discoveries led us to hypothesise that FNA pre-treatment on WAS can be used as a strategy to enhance WAS degradation during aerobic digestion. Aerobic digestion has been widely used for stabilising WAS and reducing WAS production, especially in the small-size wastewater treatment plants (WWTPs).[6] To verify this hypothesis, a full-scale WAS was subject to FNA treatment at 2.0 mg N per L for 24 h, with the WAS without FNA treatment as a control. The degradation of the FNA-treated WAS was then determined and compared to that of the untreated WAS by aerobically digesting these WAS with a full-scale activated sludge for 14 days. Economic analysis was also conducted to assess the economic potential of the FNA pre-treatment method. This is the first study to evaluate the feasibility of enhancing degradation of a full-scale WAS using FNA pre-treatment in aerobic digestion.

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2. Materials and methods

2.1. Sludge sources

Two types of sludge (*i.e.* full-scale WAS to be digested and digesting sludge) were used to carry out the experiments.

The full-scale WAS to be digested was collected from the secondary settler of a local biological nutrient removal wastewater treatment plant (WWTP) with a sludge retention time of 10–15 days in Queensland, Australia. The plant receives primarily domestic wastewater, achieving high-levels of chemical oxygen demand and nitrogen removal with an effluent total nitrogen level consistently below 8 mg N per L. The WAS was settled by gravity for 24 h to increase the concentration before the aerobic digestion tests (see Section 2.3). Its sludge concentration (with standard errors obtained from triplicate measurements) after gravity settling was: mixed liquor suspended solids (MLSS) 18.4 ± 0.2 g L^{-1}, mixed liquor volatile suspended solids (MLVSS) 15.3 ± 0.2 g L^{-1}.

Digesting sludge was collected from the aeration tank of the WWTP from which WAS was collected. This sludge was used to aerobically degrade the WAS (see Section 2.3). The concentration of digesting sludge (with standard errors obtained from triplicate measurements) was: MLSS 4.6 ± 0.2 g L^{-1}, MLVSS 3.8 ± 0.2 g L^{-1}.

2.2. FNA pre-treatment of full-scale WAS

Batch tests were performed to treat the full-scale WAS using FNA. Two batch reactors each with 0.2 L of full-scale WAS were used. One served as a control, with the other as the experimental reactor. For the experimental reactor, a nitrite stock solutions (40 g N per L) was added to achieve the designed level of 250 mg N per L. pH was controlled at 5.5 ± 0.1 throughout the 24 h treatment period *via* a programmable logic controller (PLC) that dosed 1 M HCl. The FNA concentration achieved was estimated to be 2.0 mg HNO_2–N per L using the formula with $S_{NO_2^- - N}/(K_a \times 10^{pH})$ the K_a value determined as a function of temperature T (°C) by $K_a = e^{-2300/(273+T)}$ (22 °C in this study).[19] Previous studies have revealed that FNA pre-treatment at 2.0 mg HNO_2–N per L for 24 h was effective in enhancing anaerobic digestion of the full-scale WAS.[18] These conditions were therefore selected in this study. In the control reactor, pH was not controlled and varied in the range of 6.6–6.8 in the 24 h treatment/storage period. No nitrite was added to the control reactor. It should be noted that pH pre-treatment at 5.0–6.0 has no effect on the sludge biodegradability[20] and therefore the pH in the control reactor was not adjusted to 5.5.

2.3. Aerobic digestion tests

The aerobic digestion tests were conducted to assess if the degradation of the full-scale WAS in aerobic digestion could be enhanced by FNA pre-treatment. Three lab-scale aerobic digestion reactors (R1, R2 and R3) were set up, with each seeded with 1.8 L digesting sludge. 0.2 L of FNA-treated full-scale WAS was added to R1 (digesting sludge/WAS = 2.2 on a dry MLVSS basis), which served as the experimental reactor. The use of more digesting sludge was to avoid the overload of the digesting sludge, thereby ensuring that the digesting sludge was not the limiting factor for the aerobic digestion of WAS; 0.2 L of full-scale WAS that was not subject to FNA pre-treatment was added to R2, which was used as the control reactor; 0.2 L of autoclaved effluent from the WWTP (where sludge was sourced) with an MLSS concentration below 10 mg L^{-1} was added to R3, which was a blank. The addition of 0.2 L of FNA treated WAS (which contained 250 mg NO_2^-–N per L) in R1 resulted in an initial nitrite concentration of 25 mg N per L (250 mg N per L × 0.2 L/2 L). To ensure the similar nitrite concentration in the other two reactors, a nitrite stock solution (40 g N per L) was dosed to R2 and R3, resulting in 25 mg NO_2^-–N per L in both reactors. pH was controlled at 7.0 ± 0.1 throughout the aerobic digestion period *via* a PLC that dosed 1 M NaOH in all reactors. This is the commonly used pH in the aerobic digesters. DO was maintained at above 4 mg L^{-1}. The aerobic digestion tests lasted for around 14 days, which was consistent with the hydraulic retention time (HRT) that commonly used at the full-scale aerobic digester.[4] Due to evaporation (mainly caused by air stripping) during the aerobic digestion period, tap water was added to the aerobic digestion reactors to ensure a working volume of 2 L. Samples from each reactor were taken every 1–4 days during the 14 day aerobic digestion for the analysis of ammonium (NH_4^+–N) nitrite (NO_2^-–N), nitrate (NO_3^-–N), MLSS and MLVSS. The MLSS and MLVSS concentrations were measured in triplicate. The degradation fraction of WAS (on an MLVSS basis) and the biomass specific production of inorganic nitrogen (*i.e.* NH_4^+–N + NO_2^-–N + NO_3^-–N; NO_3^-–N came from the oxidation of produced NH_4^+–N and added NO_2^-–N during aerobic digestion) from WAS were determined.

The degradation fraction of WAS (on an MLVSS basis) was determined using eqn (1):

$$F(t) = \mathrm{MLVSS}(t_0)_{\mathrm{WAS}} - \mathrm{MLVSS}(t)_{\mathrm{WAS}} - (\mathrm{MLVSS}(t_0)_{\mathrm{Eff}} - \mathrm{MLVSS}(t)_{\mathrm{Eff}}) \times V_{\mathrm{R}}/V_{\mathrm{WAS}}/\mathrm{MLVSS}_{\mathrm{WAS}} \quad (1)$$

where $F(t)$ = degradation fraction of WAS (%); $\mathrm{MLVSS}(t_0)_{\mathrm{WAS}}$ = MLVSS concentration in R1 or R2 on Day 0 (g L^{-1}); $\mathrm{MLVSS}(t)_{\mathrm{WAS}}$ = MLVSS concentration in R1 or R2 at time t (g L^{-1}); $\mathrm{MLVSS}(t_0)_{\mathrm{Eff}}$ = MLVSS concentration in R3 on Day 0 (g L^{-1}); $\mathrm{MLVSS}(t)_{\mathrm{Eff}}$ = MLVSS concentration in R3 at time t (g L^{-1}); V_{R} = working volume of aerobic digestion reactors (*i.e.* 2 L in this study); V_{WAS} = volume of WAS that was added to the aerobic digestion reactors (*i.e.* 0.2 L in this study); $\mathrm{MLVSS}_{\mathrm{WAS}}$ = MLVSS concentration of WAS (*i.e.* 15.3 g L^{-1} in this study).

The biomass specific production of inorganic nitrogen (*i.e.* NH_4^+–N + NO_2^-–N + NO_3^-–N) from WAS was determined using eqn (2):

$$\mathrm{N}(t) = \mathrm{N}(t)_{\mathrm{WAS}} - \mathrm{N}(t_0)_{\mathrm{WAS}} - (\mathrm{N}(t)_{\mathrm{Eff}} - \mathrm{N}(t_0)_{\mathrm{Eff}}) \times V_{\mathrm{R}}/V_{\mathrm{WAS}}/\mathrm{MLVSS}_{\mathrm{WAS}} \quad (2)$$

where $\mathrm{N}(t)$ = biomass specific production of inorganic nitrogen from WAS (mg N per g MLVSS); $\mathrm{N}(t)_{\mathrm{WAS}}$ = inorganic nitrogen concentration in R1 or R2 at time t (mg N per L); $\mathrm{N}(t_0)_{\mathrm{WAS}}$ = inorganic nitrogen concentration in R1 or R2 on Day 0 (mg N per L); $\mathrm{N}(t)_{\mathrm{Eff}}$ = inorganic nitrogen concentration in R3 at time t

(mg N per L); $N(t_0)_{Eff}$ = inorganic nitrogen concentration in R3 on Day 0 (mg N per L).

2.4. Analysis

Samples were filtered through disposable Millipore filter units (0.45 μm pore size) for the analyses of NH_4^+–N, NO_2^-–N and NO_3^-–N. Their concentrations were analyzed using a Lachat QuikChem8000 Flow Injection Analyzer (Lachat Instrument, Milwaukee, Wisconsin). MLSS and MLVSS concentrations were analyzed according to the standard methods.[21]

3. Results and discussion

3.1. Effect of FNA pre-treatment on WAS degradation in aerobic digestion

The aerobic digestion tests were carried out to assess the degradation of the full-scale WAS with and without FNA pre-treatment. These experiments were done by adding the same amount of WAS with and without FNA pre-treatment, and an equivalent volume of autoclaved WWTP effluent to a full-scale digesting sludge. The degradation of the WAS was then assessed by evaluating the loss of MLVSS and the biomass specific production of inorganic nitrogen during the aerobic digestion period.

Fig. 1 shows the degradation fraction of WAS (on an MLVSS basis) with and without FNA pre-treatment during the 14 day aerobic digestion period. A higher degradation of WAS with FNA pre-treatment was observed throughout the aerobic digestion period compared to that without FNA pre-treatment. 50% of the FNA-treated WAS was degraded during the aerobic digestion of 14 days, whereas only 32% of the untreated WAS was degraded over the same period. This suggests that FNA pre-treatment is effective in enhancing degradation of the full-scale WAS during aerobic digestion. Fig. 1 also shows that the enhanced WAS degradation mainly occurred in the first two days, after which the WAS degradation in the cases of FNA-treated and untreated WAS was similar ($p > 0.05$). This indicates that the improved WAS degradation was mainly derived from the rapidly biodegradable fraction rather than the slowly biodegradable fraction of WAS. This is consistent with the results of our previous studies,[18,22] in which it was found that the enhanced methane production in the *anaerobic* digestion of FNA-treated WAS was mainly related to the degradation of the rapidly biodegradable substrates in WAS. In addition, Fig. 1 shows that the degradation of FNA-treated WAS in the first two days was comparable ($p > 0.05$) to that of untreated WAS achieved in the 14 day aerobic digestion. This indicates that the volume of the aerobic digestion reactor with FNA pre-treatment would be much smaller compared with that without pre-treatment if the similar WAS degradation was desired.

Fig. 2 shows the concentrations of nitrogenous compound and FNA in R1, R2 and R3. All the nitrite and FNA were removed

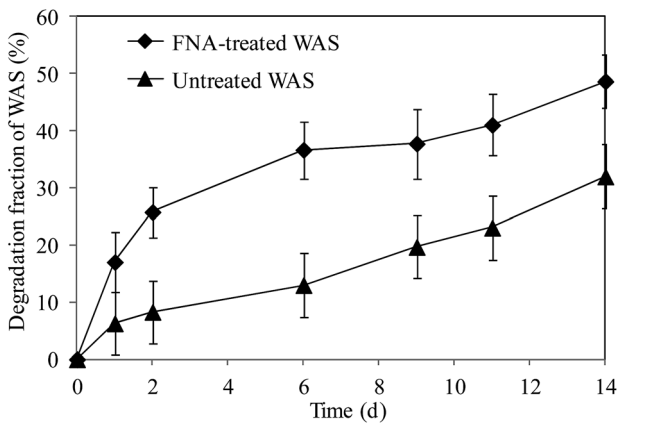

Fig. 1 Degradation fraction of WAS (on an MLVSS basis) with and without FNA pre-treatment during the 14 day aerobic digestion period. Error bars indicate the standard errors.

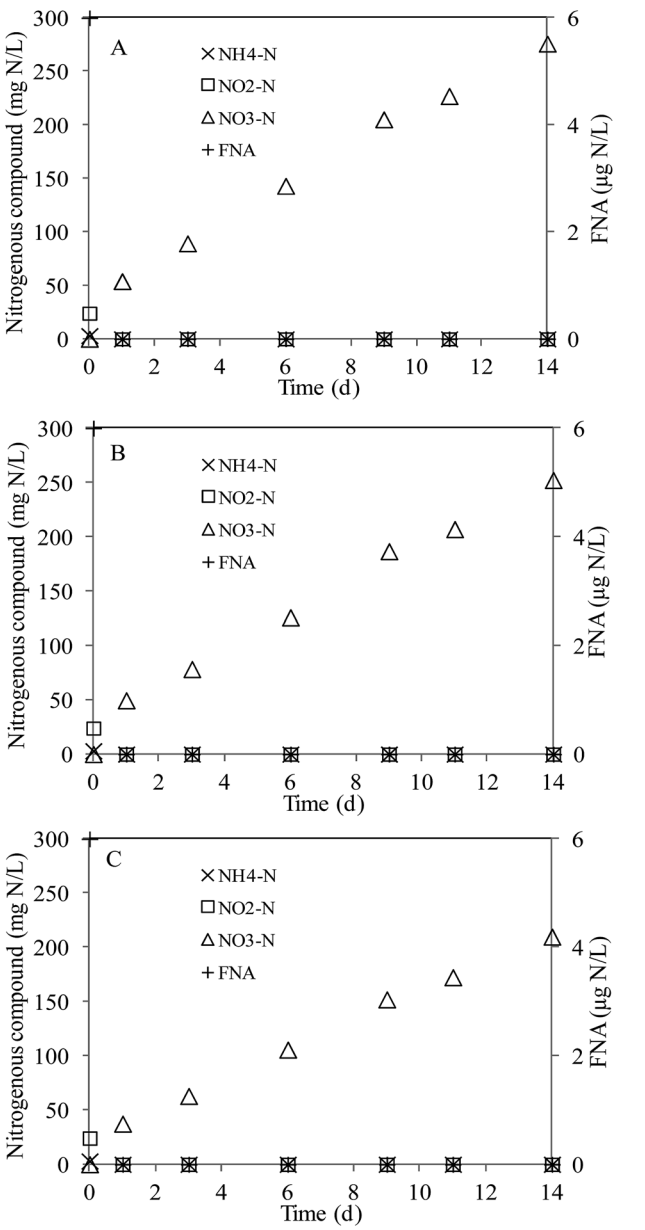

Fig. 2 Concentrations of nitrogenous compound and FNA in the 14 day aerobic digestion period. (A) R1; (B) R2; (C) R3.

very quickly (in one day) in R1, R2 and R3. Based on the nitrogenous compound concentration, the biomass specific production of inorganic nitrogen during the aerobic digestion period was calculated (using eqn (2)) and shown in Fig. 3. It is clear that the inorganic nitrogen production from the FNA-treated WAS was higher than that from the untreated WAS. The inorganic nitrogen production was 43 mg N per g MLVSS in the case of FNA-treated full-scale WAS in the 14 day aerobic digestion. In comparison, the inorganic nitrogen production was only 29 mg N per g MLVSS for the untreated WAS. As the inorganic nitrogen originates from the breakdown of the WAS (*i.e.* hydrolysis of dead cells and/or extracellular polymeric substances), more inorganic nitrogen production implies higher WAS degradation. This is consistent with the MLVSS-based WAS degradation results, confirming the effectiveness of the FNA pre-treatment in enhancing full-scale WAS degradation in aerobic digestion.

3.2. FNA pre-treatment as a potential method for enhancing full-scale WAS degradation in aerobic digestion

This study reveals for the first time that enhanced degradation of full-scale WAS can be achieved using FNA treatment prior to aerobic digestion of WAS. This was experimentally demonstrated by lab-scale aerobic digestion tests using full-scale WAS.

Importantly, the FNA pre-treatment reactor is expected to be a very simple vessel with simple mixing devices, as opposed to most of the thermal, mechanical and chemical methods currently available, which require specialised vessels and equipment to cope with the high temperature, high pressure or high mechanical forces. In the aerobic digester, FNA contained in the FNA-treated WAS can be diluted and quickly removed *via* nitratation without negatively affecting the aerobic digestion performance. Although the FNA-based pre-treatment method would introduce an extra nitrogen load *via* nitrite, the additional nitrogen load to the WWTPs would be negligible (<1%) compared with the nitrogen load in the influent of the WWTPs. This is because that the hydraulic load of the digestion liquor is typically only 1% of the hydraulic load of the WWTPs.[23]

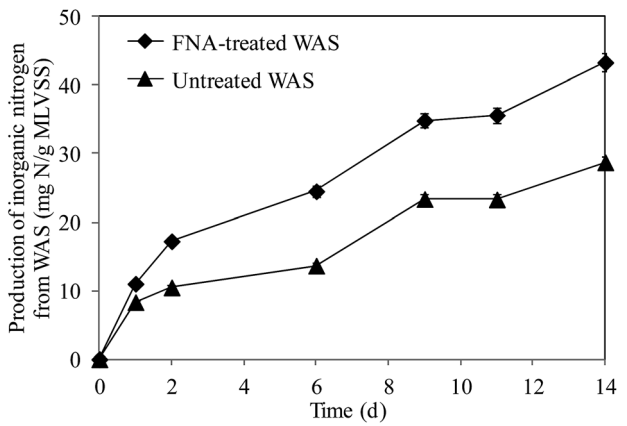

Fig. 3 Biomass specific production of inorganic nitrogen from WAS with and without FNA pre-treatment during the 14 day aerobic digestion period. Error bars indicate the standard errors.

To evaluate the potential economic benefit of the FNA pre-treatment method, a desktop scaling-up study on a full-scale WWTP with a population equivalent of 80 000 was conducted. Two types of economic evaluation were performed. The first one was done by assuming that the aerobic digestion reactors with and without FNA pre-treatment had the same aerobic digestion time. Therefore, the two aerobic digestion reactors would have different WAS degradation fractions, and hence have different oxygen consumptions and different WAS disposal costs. The second one was done by assuming that the aerobic digestion reactors with and without FNA pre-treatment had the same WAS degradation fraction. Therefore, the two aerobic digestion reactors would need different aerobic digestion time, and thus have different volumes and different capital costs.

For the first type of economic evaluation, an HRT of 14 days was assumed for the two aerobic digestion reactors with and without FNA pre-treatment. A system with FNA pre-treatment at 2.0 mg N per L for 24 h was designed to achieve a WAS degradation (on an MLVSS basis) of 50%. A system with a WAS degradation of 32% was used as a control. The cost/benefit caused by the FNA pre-treatment method is summarized in Table 1. As shown in Table 1, the net economic benefit of the FNA pre-treatment method is estimated to be %-15 500–64 500 per annum compared with the system without FNA pre-treatment (positive saving can be achieved when the WAS transport and disposal cost was above %50 per wet tonne). The net benefit arises from the enhanced WAS degradation (*i.e.* decreased WAS transport and disposal costs) (%20 000–100 000 per year) subtracting the additional cost for WAS pre-treatment (%35 500 per year). For the second type of economic evaluation, the aerobic digestion reactor with FNA pre-treatment was assumed to have an HRT of 2 days. In comparison, the aerobic digestion reactor without FNA pre-treatment had an HRT of 14 days to achieve a similar WAS degradation to that achieved in the aerobic digestion reactor with pre-treatment. The cost/benefit caused by the FNA pre-treatment method in this case is also summarized in Table 1. As shown in Table 1, the net economic benefit of the FNA pre-treatment method is estimated to be up to %37 500 per annum compared with the system without FNA pre-treatment. The net benefit arises from the decreased capital cost of the aerobic digestion reactor (%60 000 per year) overweighing the additional cost for WAS pre-treatment (%22 500 per year). Therefore, the FNA pre-treatment method is economically attractive for enhancing aerobic digestion of full-scale WAS. However, it should be noted that this is only a proof-of-concept study and is the first step to investigate the proposed strategy for enhancing aerobic digestion of full-scale WAS. Therefore, the benefit and cost values presented should be considered as preliminary and indicative only. In particular, they may vary from region to region and from country to country, depending on the local conditions (particularly the cost for WAS transport and disposal). In addition, the economic analysis also needs to be carried out again to better evaluate the economic feasibility of the proposed strategy after performing full-scale trials. It should also be highlighted that technology optimisation (*e.g.* optimization of the FNA concentration and FNA pre-treatment time) would be needed to

Table 1 Economic analysis of FNA pre-treatment method for enhancing aerobic digestion of full-scale WAS

General parameter	Values
Size of the WWTP (population equivalent – PE)	80 000
Decay coefficient of the heterotrophic biomass (per day)	0.2[a]
Decay coefficient of the nitrifying biomass (per day)	0.1[a]
Yield coefficient of the heterotrophic biomass (g COD/g COD)	0.625[a]
Yield coefficient of the nitrifying biomass (g COD/g N)	0.24[a]
Fraction of inert COD generated in biomass decay (g COD/g COD)	0.2[a]
Mixed liquor suspended solid concentration in the bioreactor (mg L^{-1})	4000
Mixed liquor volatile suspended solid concentration in the bioreactor (mg L^{-1})	3200
Sludge retention time (SRT) in the bioreactor of the WWTP (day)	10
Solids content in thickened WAS	6%
Solids content in dewatered WAS	15%
Mixing energy of the reactor (kW h per m^3 per day)	0.12
Power price (% per kW per h)	0.1
Cost of WAS transport and disposal (% per wet tonne)	30–150[b]
Price of HCl (32%) (% per tonne)	150[c]
Price of $NaNO_2$ (% per tonne)	400[c]
Period over which capital costs are annualised (*i.e.* lifetime) (year)	20
Interest applied for initial capital expenditure	8.5%
Control system (without FNA pre-treatment)	
WAS degradation (MLVSS basis)	32%
HRT in the aerobic digestion reactor (day)	14
Capital cost of the aerobic digestion reactor (%)	660 000
Annualised cost of aerobic digestion reactor (% per year)	70 000
System with FNA pre-treatment (same HRT)	
WAS degradation (MLVSS basis)	50%
HRT in the aerobic digestion reactor (day)	14
Capital cost of the aerobic digestion reactor (%)	660 000
Annualised cost of aerobic digestion reactor (% per year)	70 000
WAS pre-treatment time by FNA (day)	1
pH used in the FNA pre-treatment reactor	5.5
Concentration of NO_2^- in the FNA pre-treatment reactor (mg N per L)	250
Capital cost of FNA pre-treatment reactor (%)	42 000
Annualised cost of FNA pre-treatment reactor (% per year)	4500
Annualised mixing cost of FNA pre-treatment reactor (% per year)	100
Annual cost of HCl (% per year)	1800
Storage time of HCl (day)	30
Capital cost of HCl storage reactor (%)	1700
Annualised cost of HCl storage reactor (% per year)	200
Annual cost of $NaNO_2$ (% per year)	5600
Storage time of $NaNO_2$ (day)	30
Capital cost of $NaNO_2$ storage reactor (%)	2600
Annualised cost of $NaNO_2$ storage reactor (% per year)	300
Extra energy cost associated with oxygen consumption (compared to the control system) due to enhanced WAS degradation (% per year)	13 000[d]
Labour cost (% per year)	10 000
Annual cost associated with WAS pre-treatment (% per year)	**35 500**
Annual reduced WAS transport and disposal cost (compared to the control system) (% per year)	**20 000–100 000**
Annual saving (% per year)	**−15 500–64 500[e]**
System with FNA pre-treatment (same WAS degradation)	
WAS degradation (MLVSS basis)	32%
HRT in the anaerobic digestion reactor (day)	2
Capital cost of the aerobic digestion reactor (%)	94 000
Annualised cost of aerobic digestion reactor (% per year)	10 000
WAS pre-treatment time by FNA (day)	1
pH used in the FNA pre-treatment reactor	5.5
Concentration of NO_2^- in the FNA pre-treatment reactor (mg N per L)	250
Capital cost of FNA pre-treatment reactor (%)	42 000
Annualised cost of FNA pre-treatment reactor (% per year)	4500

Table 1 (*Contd.*)

General parameter	Values
Annualised mixing cost of FNA pre-treatment reactor (% per year)	100
Annual cost of HCl (% per year)	1800
Storage time of HCl (day)	30
Capital cost of HCl storage reactor (%)	1700
Annualised cost of HCl storage reactor (% per year)	200
Annual cost of $NaNO_2$ (% per year)	5600
Storage time of $NaNO_2$ (day)	30
Capital cost of $NaNO_2$ storage reactor (%)	2600
Annualised cost of $NaNO_2$ storage reactor (% per year)	300
Labour cost (% per year)	10 000
Annual cost associated with WAS pre-treatment (% per year)	**22 500**
Reduced annualised cost of aerobic digestion reactor (compared to the control system) (% per year)	**60 000**
Annual saving (% per year)	**37 500**

[a] Ref. 24. [b] Ref. 6 and 25. [c] http://www.alibaba.com/. [d] Oxygen consumption was calculated based on nitrogen and organic carbon balance.[24] [e] Positive saving can be achieved when the WAS transport and disposal cost was above %50 per wet tonne.

achieve an even higher WAS degradation. A more detailed understanding of the mechanisms involved in FNA pre-treatment of WAS will help identify the optimal treatment conditions, and require further research. Also, more parameters (*e.g.* proteins and carbohydrates) need to be measured during the aerobic digestion to better understand the proposed technology in the future.

The WAS degradation in aerobic digestion was enhanced by 56% (from 32% to 50%) using FNA pre-treatment. This is lower than that achieved in the study of *e.g.* Kavitha, *et al.*[26] in which WAS degradation was enhanced by more than two times (from 15% to 50%) using enzyme secreting bacterial pre-treatment. However, it should be noted that the direct quantitative economic comparison between FNA pre-treatment and other available technologies are difficult at this stage since the results depend on many factors including the WAS characteristics, among others. The comparison could and should be done in future studies by performing experiments using the same WAS and under similar operating conditions.

4. Conclusions

The feasibility of enhancing full-scale waste activated sludge degradation during aerobic digestion based on FNA pre-treatment was investigated through lab-scale aerobic digestion tests. The main conclusions are:

- FNA pre-treatment is effective in enhancing full-scale waste activated sludge degradation in aerobic digestion.
- FNA pre-treatment is an economically attractive method for enhancing aerobic digestion of full-scale waste activated sludge. However, full-scale studies are required to better evaluate this proposed method.

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