

# When the smoke disappears: dealing with extinguishing chemicals in firefighting wastewater

E. N. P. Courtens, F. Meerburg, V. Mausen and S. E. Vlaeminck

## ABSTRACT

Water is not enough. Nowadays, numerous chemicals are used for fire extinction. After use, however, these may unintentionally enter sewerage systems. In order to safely treat firefighting wastewater (FFWW), knowledge of the potential effects of these chemicals on biological treatment processes is essential. This study characterized and mimicked the composition of FFWW containing two powders, three foams and one foam degrader. Nitrogen (162–370 mg  $\text{NH}_4^+\text{-N L}^{-1}$ ) and phosphorus (173–320 mg  $\text{PO}_4^{3-}\text{-P L}^{-1}$ ) concentrations exceeded discharge limits, whereas chemical and biological oxygen demand, suspended solids and detergent concentrations remained sufficiently low. Adequate nutrient removal could be obtained through  $\text{FeCl}_3$  addition and nitrification/denitrification with acetate as substrate. In batch tests, residual nitrifying activities of 84, 81, 89, 95 and 93% were observed in the presence of powders, foams, foam degrader, synthetic and real FFWW, respectively. All categories showed higher denitrification rates than the control. Although the powders at first seemed to inhibit anammox activity at 82%, after pH correction anammox was fully feasible, allowing nitrogen removal through oxygen-limited nitrification/denitrification (OLAND). Detailed cost calculations indicated that OLAND could save 11% of capital and 68% of operational costs compared to nitrification/denitrification, identifying OLAND as the most recommendable process for nitrogen removal from firefighting wastewaters.

**Key words** | feasibility study, firewater, nitrification/denitrification, partial nitrification/anammox, toxicity

## INTRODUCTION

The destructive power of fire is responsible for human, economic and ecological losses of immense scale. Technological progress has made it possible to combat fire more quickly and more efficiently than ever before, using not only water but also a range of retardants, foams and wetting agents (Kalabokidis 2000). After being used, however, these firefighting chemicals (FFCs) may enter the natural environment where they can cause adverse effects, or enter the sewerage system and possibly disrupt biological processes during wastewater treatment. To limit such harmful effects of firefighting wastewater (FFWW), environmental safety policies of governmental organizations and private corporations often specify water containment scenarios to limit the spread of FFWW to water bodies and sewerage systems. Firewater containment is a key requirement for companies to comply with the EU Environmental Liability Directive (Directive 2004/35/CE) or to

obtain an ISO 14001 certification (ISO 14001:2004). Yet, with the need to safely dispose of large volumes of FFWW comes the need to understand to what extent biological processes are affected by FFCs.

Adverse effects of FFCs on biological life depend on their mode of action. FFCs include fire retardants, which mainly consist of a mixture of water, inorganic fertilizer salts and additives, and they have limited effects on natural ecosystems apart from potential eutrophication of water bodies. The toxicity of ammonium-based fire retardants (e.g. ammonium sulfate, mono- and diammonium phosphate, ammonium polyphosphate) is mainly due to their pH-dependent release of un-ionized (free) ammonia ( $\text{NH}_3$ ), which is highly toxic to aquatic organisms and can cause eutrophication. Indeed, adverse effects of fire retardants to small freshwater crustaceans and algae have been linked to free ammonia concentrations (McDonald *et al.*

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1996, 1997). Other classes of FFCs such as foams, wetting agents, solvents and certain additives may be more toxic but are typically administered in low concentrations. Apart from the disruptive effect of surfactants on the integrity of cell membranes, these FFCs may contain perfluorinated surfactants or quaternary ammonium salts with toxic effects (Moody & Field 2000; Zaggia *et al.* 2010). When present in high concentrations, surfactants may disrupt the performance of wastewater treatment plants (Moody & Field 2000). Several review papers summarize research performed on the adverse effects caused by FFCs in forest, soil and aquatic ecosystems (Adams & Simmons 1999; Kalabokidis 2000; Giménez *et al.* 2004; Barreiro *et al.* 2010).

Little information is known, however, of the effects of FFCs on engineered systems for wastewater treatment, which rely on good performance of several sensitive biological processes. Conventional domestic wastewater treatment plants typically employ chemical precipitation for the removal of phosphorus followed by activated sludge technology for the removal of organics and nitrogen. Nitrogen is typically removed by nitrification/denitrification, in which ammonium and organic nitrogen are oxidized first to nitrite and further to nitrate (nitrification), while in a subsequent stage, an organic carbon source is added to reduce nitrate to nitrogen gas (denitrification) (Metcalf & Eddy 2003). Several alternatives exist to this scheme, of which partial nitrification/anammox can be considered the most resource- and energy-efficient in the case of low biodegradable chemical oxygen demand (COD) to N ratio (Vlaeminck *et al.* 2012). In this process, also known as oxygen-limited autotrophic nitrification-denitrification (OLAND), careful monitoring of oxygen levels ensures that ammonia-oxidizing bacteria only oxidize part of the nitrogen to nitrite (nitritation), while no nitrate is formed. Anoxic ammonia-oxidizing bacteria then use the remaining ammonia-nitrogen to directly reduce nitrite to nitrogen gas (anammox). In order to treat FFWW in a similar way, it is necessary to understand to what extent the presence of FFCs affects the performance of each of these biological processes.

During urban fires, FFWW is polluted not only by FFCs but by a range of dissolved and particulate components originating from the combustion of building materials and other objects. In addition, water used for extinguishing industrial fires may become heavily polluted by combustion residues of plastics, toxic compounds and organic and inorganic chemicals. In contrast, municipal or industrial training centers for firefighters are of special interest for the study of FFCs in wastewater; such training facilities perform a large

number of fire exercises annually, the amounts of FFCs and combustion materials are well known and FFWW can be collected at relatively constant flow rates for further treatment. Therefore, the treatment of FFWW from these training facilities plays a key role in limiting the spread of FFCs into urban wastewater streams and, ultimately, the environment.

The purpose of this study was to identify the main FFCs used during standard fire training exercises at a fire training center and their individual contributions to the quality and characteristics of FFWW. After a chemical phosphorus removal test, the potential for biological nitrogen removal from FFWW was explored by testing the effects of individual and mixed FFCs on nitritation, nitrification, anammox and denitrification.

## METHODS

### FFWW, chemicals and synthetic wastewater

FFWW was sampled from a collection basin at a fire training facility for two time periods (10/2012 and 12/2012) after standard fire training exercises. The basin contained a lower fraction of sludge and settled materials, a middle fraction of wastewater containing dissolved and suspended materials, and a very thin top fraction consisting of a hydrophobic powder film. Samples were taken from the middle fraction. The FFCs used at the site are displayed in Table 1. A series of synthetic wastewaters was prepared containing (1) individual FFCs (two powders, three foams and a foam degrader), (2) combined powders or foams, and (3) all components combined (synthetic FFWW) in order to identify the FFCs that contributed to increased pollutant levels. The concentration of each FFC was calculated using monthly consumption rates and water usage at the facility (Table 1). Combustion products of magnesium flakes, industrial spirit and charred wood were suspended and analyzed after a 3-day stabilization period in order to quantify the contribution to the FFWW of combustion products used at the training center.

### Chemical phosphate removal

Ferric chloride ( $\text{FeCl}_3$ ) was dosed at a molar ratio of 2.5/1 Fe/P in both the real and synthetic FFWW to chemically precipitate the phosphate. The supernatant was also included for further biological nitrogen removal tests.

**Table 1** | FFCs used at the training center, main components and final concentrations in the synthetic FFWW preparations

Type	Manufacturer	Name	Main components	Concentration
Powder 1	Caldic, Germany	Furex ABC-40	Ammonium sulfate (50%) monoammonium phosphate (40%)	0.833 g L <sup>-1</sup>
Powder 2	Saval, The Netherlands	PG	Ammonium sulfate (78%) monoammonium phosphate (20%) additives (2%)	0.833 g L <sup>-1</sup>
Foam 1	Solberg, Norway	TF5X	Water (80%) sodium lauryl ether sulfate (10–30%) 2-(2-butoxyethoxy)ethanol (5–10%) triethanolamine lauryl sulfate alkyl ethers sodium salts	0.666 mL L <sup>-1</sup>
Foam 2	Saval, The Netherlands	ABFFC ELGN	Water (>60%) sodium alkyl ether sulfate (1–5%) sodium octyl sulfate (1–5%)	0.177 mL L <sup>-1</sup>
Foam 3		Recycled foams of mixed origin		0.067 mL L <sup>-1</sup>
Foam degrader	TI Solutions, Belgium	Foam sorb	Alkyldimethylbenzylammonium chloride (2.5–10%)	0.013 mL L <sup>-1</sup>

## Biological activity tests

**Aerobic batch** experiments were performed in 250 mL open Erlenmeyer flasks with 100 mL working volume. Nitrifying biomass was used, harvested from an OLAND rotating biological contactor (RBC) (Pynaert *et al.* 2003). The flasks were supplied with the corresponding FFWW and a buffer solution (pH 7) with final concentrations of 1 g NaHCO<sub>3</sub> L<sup>-1</sup>, 3.7 g KH<sub>2</sub>PO<sub>4</sub> L<sup>-1</sup> and 6.5 g K<sub>2</sub>HPO<sub>4</sub> L<sup>-1</sup>. As the FFWW already contained the substrate ammonium, only ammonium was added to the three control treatments, covering the ammonium concentration range in the different categories (Table 2).

For the **anoxic batch** tests, 120 mL serum flasks were used, containing 80 mL of mixed liquor. OLAND biomass was used for the anammox activity test. For the denitrification test two types of sludge were used: activated sludge from an OLAND bioreactor for powders, foams and foam degrader; and denitrifying sludge from a mesophilic denitrifying reactor for synthetic and real FFWW. After the biomass, the concentrated buffering solution and either FFWW or FFCs were added and the flasks were closed with rubber stops and flushed with N<sub>2</sub> gas. The final concentrations of the anammox test buffer (pH 7.5) were 1 g NaHCO<sub>3</sub> L<sup>-1</sup>, 0.04 g KH<sub>2</sub>PO<sub>4</sub> L<sup>-1</sup> and 0.23 g K<sub>2</sub>HPO<sub>4</sub> L<sup>-1</sup>. The denitrification buffer (pH 8) had final concentrations of 0.6 g KH<sub>2</sub>PO<sub>4</sub> L<sup>-1</sup> and 10.5 g K<sub>2</sub>HPO<sub>4</sub> L<sup>-1</sup>. Flushed substrate solutions of NH<sub>4</sub>Cl and/or NaNO<sub>2</sub> for anammox and NaNO<sub>3</sub> and/or sodium acetate for denitrification (COD/N = 5) were supplemented by means of needled syringes to a final concentration equal to the nitrogen concentration

in the FFWW of 7–12 (see Table 2). Control flasks were prepared similarly without addition of FFWW or FFCs.

Aerobic and anoxic flasks were incubated on a shaker in a 34 °C controlled room. Liquid samples were taken over time for ammonium, nitrite and nitrate analysis and biomass-specific activities were calculated over the first 8 (nitrification, denitrification) or 24 (anammox) hours using volatile suspended solids (VSS) measurements of the biomass.

## Analytical procedures

Ammonium (Nessler method and steam distillation method), total Kjeldahl nitrogen, total suspended solids (TSS), VSS, alkalinity, biochemical oxygen demand (BOD<sub>5</sub>) and dissolved magnesium were measured according to *Standard Methods* (Greenberg *et al.* 1992). Nitrite and nitrate were determined on a 761 Compact Ion Chromatograph (Metrohm, Switzerland) equipped with a conductivity detector. Chemical oxygen demand (COD), orthophosphate, total phosphorus and anionic, cationic and non-ionic surfactants were measured by photometric methods using Nanocolor test tubes (Macherey–Nagel, Germany) with detection limits of 15 mg L<sup>-1</sup> for COD (Tube test 0–26), 0.05 mg-P L<sup>-1</sup> for phosphorus (Tube test 0–76), 0.20 mg L<sup>-1</sup> for anionic and cationic surfactants (Tube tests 0–32 and 0–34) and 0.3 mg L<sup>-1</sup> for non-ionic surfactants (Tube test 0–47). Dissolved oxygen (DO) and pH were measured with an HQ30d DO meter (Hach Lange, Germany) and an SP10 T pH electrode installed on an R305 pH-controller (Consort, Belgium), respectively.

**Table 2** | Characteristics of real FFWW, synthetic FFWW and their constituent chemicals, combustion products used at the firefighting training center and FFWW supernatant after chemical precipitation of phosphorus. Comparison is made with Flemish discharge limits for industrial wastewater, general or sectoral

Sample	pH	Alkalinity (meq L <sup>-1</sup> )	TSS (mg L <sup>-1</sup> )	COD (mg L <sup>-1</sup> )	BOD <sub>5</sub> (mg L <sup>-1</sup> )	NH <sub>4</sub> <sup>+</sup> -N (mg L <sup>-1</sup> )	Mg diss (mg L <sup>-1</sup> )	Ortho-P (mg L <sup>-1</sup> )	Total P (mg L <sup>-1</sup> )	Cationic detergents (mg L <sup>-1</sup> )	Other detergents <sup>a</sup> (mg L <sup>-1</sup> )
Real FFWW 23-10	6.06	2	44	30	0	370		314	320		
Real FFWW 7-12	6.12	1.48	44	96	4	162	5.24	167	173		
Synthetic FFWW	5.46	0.336	92	35	2	277	4.24	203	212		
Powder 1	6.19	0								0.21	<0.5
Powder 2	5.7	0								0.23	<0.5
All powders	5.65	0.358	8	15	1	291		144	147		
Foam 1	6.56	0								0.48	1.4
Foam 2	6.88	0								<0.2	<0.5
Foam 3	7.01	0								<0.2	<0.5
All foams	6.76	0.298	0	19	2	0		2.7	2.9		
Foam degrader	6.56	0.248	0	0	0	0		0.13	0.12	<0.2	<0.5
Water + industrial spirit				0							
Water + charred wood				168							
Water + Mg flakes				24			12.6				
FeCl <sub>3</sub> supernatant real FFWW	8.01		24	81		137		3.3	3.5	<0.2	<0.5
FeCl <sub>3</sub> supernatant synthetic FFWW	7.45		16	206		239		0.69	1.07	0.38	<0.56
Discharge limit	6.5 <sup>b</sup>		60 <sup>b</sup>	125 <sup>b</sup>	25 <sup>b</sup>	15 (Total N) <sup>b</sup>	50 <sup>c</sup>		2 <sup>d</sup>	3 (Total detergents) <sup>b</sup>	

<sup>a</sup>Other detergents constitute the sum of anionic and non-ionic detergents.<sup>b</sup>Vlarem II article 4.2.2.1.1.<sup>c</sup>Vlarem II attachment 2.4.1, indicative.<sup>d</sup>Vlarem II attachment 5.3.1.

## Cost calculation

A detailed cost calculation was performed focusing on the different nitrogen removal technologies. All civil engineering work was accounted for at current prices, including installation; and calculated at the detail level of, for instance, concrete, rebar, shutters, pumps and valves for the aeration basin and sludge thickener. The costs for detailed engineering were separately added as 20% of the equipment capital expenditure. All capital costs were amortized at 3.5% over 10 years. Operating costs for heating were derived from a heating price of  $0.05 \text{ € kWh}^{-1}$  of thermal energy. Acetic acid (80%) at  $450 \text{ € ton}^{-1}$  was used as the carbon source for denitrification, dosed at 120% of its stoichiometric requirement to account for 20% degraded aerobically. For the base addition,  $\text{NaHCO}_3$  was used at  $150 \text{ € ton}^{-1}$ . Aeration requirements were calculated based on a sludge retention time of 40 days, biomass yields of  $0.4 \text{ g VSS g}^{-1} \text{ COD}$  and  $0.1 \text{ g VSS g}^{-1} \text{ N}$  for heterotrophs and autotrophs, respectively, an endogenous decay coefficient of  $0.1 \text{ g VSS g}^{-1} \text{ VSS d}^{-1}$ , a fraction of biomass that remains as cell debris of  $0.2 \text{ g VSS g}^{-1} \text{ VSS}$ , an efficiency of  $1 \text{ kg O}_2 \text{ kWh}^{-1}$ , and an electricity price of  $0.1 \text{ € kWh}^{-1}$ . The sludge thickener was assumed to concentrate incoming sludge at 1 to 3% DW. Thickened sludge was disposed of at  $50 \text{ € m}^{-3}$ .

## RESULTS AND DISCUSSION

### FFWW characterization and simulation

In order to identify the sources of the organic and inorganic constituents of the wastewater, analytical characterization was performed for real FFWW, synthetic FFWW and a series of waters containing individual FFCs used at the training center. As demonstrated in Table 2, the synthetic FFWW closely resembled real FFWW and consisted mainly of nutrients (ammonium-N and ortho-P) with minor contaminations of COD and detergents. The small difference between ortho-P and total P indicated that the amount of organic phosphorus was negligible. This was also the case for organic nitrogen (data not shown). Nearly all nitrogen and phosphorus in the synthetic FFWW originated from the powders. Furthermore, the powders raised alkalinity and lowered the pH of the wastewater. Powders and foaming agents both contributed to the raised COD and cationic detergent concentrations in the final FFWW, while foaming agents also contributed to other

detergents (anionic and non-ionic). As indicated by the low  $\text{BOD}_5$  concentrations, the COD present in the FFCs was not rapidly biodegradable. Subsequently, the combustion products of fire stimulants (Mg flakes, industrial spirit and charred wood) used at the training center were mixed with water and analyzed to quantify their contribution to the FFWW. Charred wood raised COD levels five times more than FFCs did, and combusted Mg flakes raised dissolved  $\text{Mg}^{2+}$  three times more than FFCs.

Comparison of these characteristics to effluent standards in Flanders (Vlarem II 2005) reveals that TSS, COD,  $\text{BOD}_5$ ,  $\text{Mg}^{2+}$  and detergents in the FFWW remain below discharge limits and do not require further treatment, while pH values are slightly too low (Table 2). Nitrogen and phosphorus levels exceed limits by an order of magnitude, indicating that further chemical or biological treatment is required before discharge of this FFWW.

### Chemical phosphorus removal with $\text{FeCl}_3$

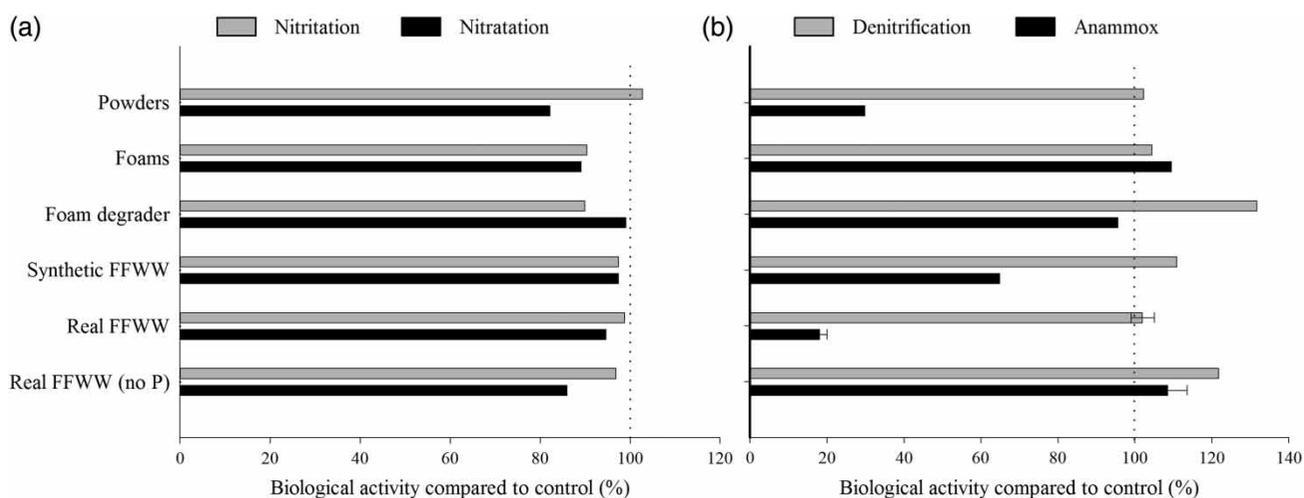
As chemical precipitation of phosphorus with  $\text{FeCl}_3$  is a relatively easy and widely applied technology, the phosphorus removal potential for real FFWW was tested. The obtained phosphorus levels in the FFWW supernatant were sufficiently low to meet discharge limits. A removal level of 99% was reached, achieving  $1.7 \text{ mg P L}^{-1}$ . Before implementation of this process, it is advisable to fine-tune the required Fe/P ratio in order to render the technology cost effective.

### Biological nitrogen removal options for FFWW

The potential for biological nitrogen removal from FFWW was explored in toxicity batch tests, investigating the effects of individual and mixed FFCs on nitrification, denitrification, anammox and denitrification.

For nitrification, i.e. nitrification and nitratation, aerobic activity batch tests revealed that the ammonium present in the FFWW could successfully be nitrified to nitrate (Figure 1(a)). Some of the individual product categories slightly inhibited the oxidation rates, but both the synthetic as well as the real FFWW showed more than 90% biological activity compared with the control treatment.

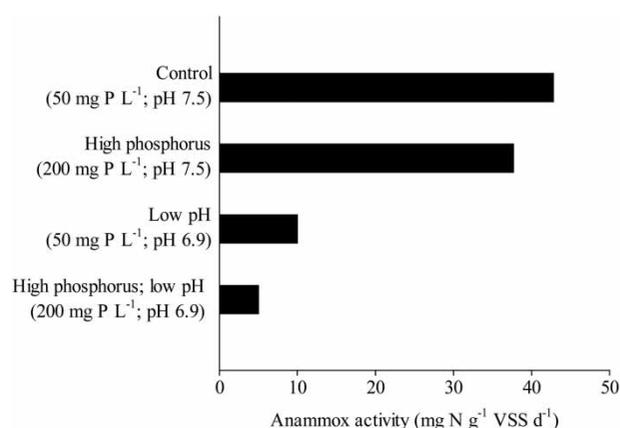
For denitrification, anoxic batch tests showed that the formed nitrate could be denitrified with acetate as added carbon source in all FFWW categories (Figure 1(b)). Note that the different denitrifying activities in the control flasks resulted from the use of two types of control sludge. However, in all of the treatments, denitrification activities were slightly higher than those for the control treatment.



**Figure 1** | Relative nitritation and nitratation (a) and denitrification and anammox (b) activities for the different FFWs (powders, foams and foam degrader, synthetic and real FFW) and real FFW after phosphorus removal through  $\text{FeCl}_3$  precipitation. Activities of the control treatments were  $39 \text{ mg N g}^{-1} \text{ VSS d}^{-1}$  for nitritation;  $12 \text{ mg N g}^{-1} \text{ VSS d}^{-1}$  for nitratation;  $57 \text{ mg N g}^{-1} \text{ VSS d}^{-1}$  (powders, foams and foam degrader) or  $8,341 \text{ mg N g}^{-1} \text{ VSS d}^{-1}$  (synthetic and real FFW) for denitrification; and  $23 \text{ mg N g}^{-1} \text{ VSS d}^{-1}$  (foams, foam degrader and synthetic FFW) or  $43 \text{ mg N g}^{-1} \text{ VSS d}^{-1}$  (powders and real FFW) for anammox.

In contrast to nitritation, nitratation and denitrification, anammox activities were inhibited in the presence of powders and real FFW, resulting in an inhibition of up to 75% in the real FFW. Since the firefighting powders were responsible for relatively high concentrations of phosphorus ( $147 \text{ mg P L}^{-1}$ , Table 2) and the anammox activity could be restored after chemical phosphorus removal, the observed inhibition of anammox could, at first sight, be attributed to the high P content of the powders. Depending on the dominant anammox species and the operating conditions, phosphorus is known to be toxic at concentrations of  $50 \text{ mg P L}^{-1}$  or higher (Dapena-Mora *et al.* 2007; Jin *et al.* 2012). However, apart from increasing the phosphorus content, the powders also lowered the pH to 5.65. The light pH buffer ( $50 \text{ mg P L}^{-1}$ ) used in the anammox activity batch tests was only able to correct this low pH to a value of 6.9. Therefore, an extra experiment was performed to compare anammox activities at control phosphate concentrations ( $50 \text{ mg P L}^{-1}$ ) versus elevated concentrations ( $200 \text{ mg P L}^{-1}$ ) and at control pH (7.5) versus lowered pH (6.9). As shown in Figure 2, higher phosphorus concentrations still resulted in 88% anammox activity compared to the control treatment, while the activity dropped to 23% at a pH of 6.5.

These results demonstrate that the anammox inhibition in the FFW was not due to high phosphorus concentrations but to the low pH caused by the powders. Indeed, the optimal pH for anammox is pH 7.5–8 (Strous *et al.* 1999). Egli *et al.* (2001) have already observed inhibition of 57% at pH 7 and complete inhibition at pH 6.5 and 6.



**Figure 2** | Anammox activities at different phosphorus concentrations and pH.

### Nitrogen removal economy for FFW

As the experiments revealed that nitrogen removal from FFW is feasible through conventional nitrification/denitrification and OLAND, the costs of both technologies were assessed. One of the challenges for implementation of OLAND is the low average temperature of the FFW ( $11 \pm 5.6 \text{ }^\circ\text{C}$ ). However, the latest OLAND developments on pretreated sewage indicate that reasonably high nitrogen removal rates of at least  $250 \text{ mg N L}^{-1} \text{ d}^{-1}$  can be reached at  $15 \text{ }^\circ\text{C}$  (De Clippeleir *et al.* 2013). Assuming maximum biomass concentrations of about  $10 \text{ g VSS L}^{-1}$  in the RBC of this study, specific removal rates of  $25 \text{ mg N g}^{-1} \text{ VSS d}^{-1}$  can be realistically expected and hence can serve as a design basis for the OLAND cost calculation. Taking into

**Table 3** | Capital and operational costs (CAPEX and OPEX) for nitrogen removal from FFWW through nitrification/denitrification and OLAND

		Nitrification/denitrification		OLAND	
		€	€ year <sup>-1</sup>	€	€ year <sup>-1</sup>
<b>CAPEX</b>	Reactor basin (160 m <sup>3</sup> )	91,177		81,177	
	Sludge thickener (60 m <sup>3</sup> )	39,755		39,755	
	Heating system (75 kW)	36,200		36,200	
	Carbon dosage system	28,547		0	
	Base dosage system	12,000		12,000	
	Electric installation	70,480		70,480	
	Control and automation (pH, DO, level, TS)	58,550		58,550	
	Detailed engineering	67,342		59,632	
	<b>Sum</b>	<b>404,051</b>	<b>48,584</b>	<b>357,795</b>	<b>43,022</b>
<b>OPEX</b>	Heating		1,775		1,775
	Pumping and mixing		2,010		2,010
	Aeration		2,215		567
	Base usage (NaHCO <sub>3</sub> )		2,906		2,906
	Carbon usage (Acetic acid 80%)		7,061		0
	Sludge thickening		10,756		1,208
		<b>Sum</b>		<b>26,723</b>	
<b>CAPEX + OPEX</b>			<b>75,307</b>		<b>51,487</b>

account a biomass concentration of 4 g VSS L<sup>-1</sup> and a nitrogen load of 16 kg N d<sup>-1</sup>, a reactor volume of 160 m<sup>3</sup> is required. Assuming ambient temperature for the wastewater, heating to 15 °C was included for both technologies, particularly relevant from September through May. Since the alkalinity requirements for OLAND or nitrification/denitrification are about 71 meq g<sup>-1</sup> NH<sub>4</sub><sup>+</sup> while only 4.4 meq g<sup>-1</sup> NH<sub>4</sub><sup>+</sup> was present in the real FFWW (7/12, Table 2), base addition is needed in both cases, using NaHCO<sub>3</sub> in the cost calculation. The detailed cost comparison of both nitrogen removal technologies is given in Table 3.

The cost calculation showed that 11% of the capital and 68% of the operational costs could be saved by the OLAND process compared to nitrification/denitrification, resulting in total cost savings of 32%. It has to be noted that labor costs for start-up, operation and maintenance were not included, which could in practice turn out to be slightly higher for the OLAND process. The potential cost savings for OLAND are lower than the 52% previously reported for sludge reject water treatment by Fux & Siegrist (2004), when considering the same cost factors. This difference derives from the case-specific characteristic needed for the FFWW application, including heating requirements and base addition for both treatment options. Furthermore, the

particular conditions at a fire training center call for a rather conservative design of the bioreactor basin in order to cope with fluctuations in influent flow rate and nutrient concentrations. In case of very large fluctuations, a storage tank should be incorporated in the design to store and buffer the FFWW prior to treatment. The capital costs dominated 65 and 84% of the total costs for nitrification/denitrification and OLAND, respectively. As the reactor basin has a major share of 23% in the total nitrogen removal cost with OLAND, it would be recommended to perform an OLAND reactor test at laboratory-/pilot-scale to investigate whether a more compact reactor would be able to render long-term process stability under the varying influent characteristics of the FFWW.

## CONCLUSIONS

This study characterized and successfully simulated the composition of FFWW, demonstrating nitrogen pollution as the main issue for further treatment. It was shown that sensitive biological treatment processes are unhindered by the presence of the investigated FFCs. After chemical removal of phosphorus, a dedicated biological treatment

process with nitrogen removal by OLAND is the most recommendable process for treating FFWW, saving 32% of the total costs compared to nitrification/denitrification.

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