

FOAMING CONTROL IN ACTIVATED SLUDGE TREATMENT PLANTS BY COAGULANTS ADDITION

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ABSTRACT

This paper presents the results of an investigation that aimed to evaluate the efficiency of various inorganic coagulants and organic polymers to combat filamentous foaming and bulking problems, caused by the proliferation of *M. parvicella* and/or *Gordona amarae*.

The duration of the investigation covered 14 months. During this period foam samples were taken from the aeration basins of two full-scale wastewater treatment plants that contained high concentrations of *M. parvicella* and/or *Gordona amarae*. Bench scale batch experiments were conducted to evaluate the efficiency of the following coagulants: ferric chloride, ferrous chloride, polyaluminium chloride, hydrated aluminium sulphate, cationic polymer. In addition bench scale batch experiments (ammonia uptake rate (AUR) and oxygen uptake rate (OUR) measurements) were conducted to evaluate the toxicity effects of the most promising coagulants on nitrification and organic matter removal.

Polyaluminium chloride (PAX) and cationic polymer proved to be the most efficient among all the coagulants investigated. By adding PAX (aluminium application of 6.6 – 11.5 g Al³⁺ kg⁻¹ MLSS) a general improvement of the settling properties of the activated sludge was achieved. High foaming control was also achieved with cationic polymer addition at doses in the 3.5 to 4.5 g kg⁻¹ MLSS. According to microscopic analysis of the sludge samples following PAX or polymer addition, the floc strength was improved and flocs appeared more compact and dense. In addition both *M. parvicella* and *Gordona amarae* filamentous organisms were embedded inside the floc material, making access to particulate and colloidal substrates more difficult due to increased diffusional resistance.

PAX or polymer addition, at the above specified doses, resulted in a 75 – 100 % reduction of the sludge foaming potential. PAX potential toxicity was investigated in the context of this study. PAX addition caused no inhibition on autotrophic and heterotrophic bacteria that perform nitrification and organic carbon removal, respectively. The estimated operational costs of PAX and polymer addition for foaming control, are approximately 0.0057 euros m⁻³ and 0.0026 euros m⁻³ of wastewater treated, respectively.

KEYWORDS: Foaming, bulking, coagulants, filamentous bacteria, *Microthrix parvicella*, *Gordona amarae*, control strategies, scum.

INTRODUCTION

Foaming and bulking problems in activated sludge wastewater treatment plants are associated with the presence of a variety of filamentous bacteria. The viscous brown foam resulting from the growth of these organisms, can create safety hazards, deteriorate effluent quality and be a source of odours. The most frequent filamentous microorganisms causing sludge foaming are *Microthrix parvicella* and *Gordona amarae*. Wastewater composition is one of the significant factors affecting

foam formation, as it has been found that slowly degradable organic material and especially lipids favour the growth of both *M. parvicella* and *G. amarae* (Mamais *et al.*, 1998; Jenkins *et al.*, 1993).

Filamentous bulking and foaming can be controlled by specific strategies. These strategies are selectively targeted at achieving a proper composition of the sludge biocenoses that address the causes of the filamentous overabundance. Other means of achieving bulking and foaming control are non-specific methods that tend to alleviate the symptoms associated with the filamentous proliferation without though addressing the actual cause of the filamentous growth. Therefore specific control strategies are preferable as they are selective and they offer a permanent solution of the problem whereas non-specific methods tend to provide only temporary solutions.

Existing specific foaming control methods may be successful in some cases in alleviating severe foaming problems. However, especially for *Microthrix parvicella*, there are no reliable specific control methods that can be applied in all activated sludge systems that are experiencing foaming problems. For example reduction of sludge age may prove to be an efficient method to suppress *M. parvicella* growth (Noutsopoulos *et al.*, 2006). However this method cannot be applied in activated sludge systems that must nitrify throughout the year and especially in winter, because the sludge age required to washout *M. parvicella*, may also eliminate nitrifying bacteria. Therefore non-specific methods are currently the only available strategies for effective foaming control that can be applied in all cases.

One of the most common non-specific methods for bulking control is the use of oxidizing chemicals such as chlorine. However chlorine addition for foaming control is not always successful. In many cases the high chlorine doses required cause floc break-up and may inhibit both nitrification and organic matter removal. Therefore alternative non-specific methods need to be developed to control filamentous foaming. For example a dose of 0.5 mg l^{-1} of a polyacrylamide cationic polymer has been proven to effectively eliminate *Gordona amarae* foaming problems in the aeration tank of an activated sludge plant (Shao *et al.*, 1997). Recent attempts using polyaluminium chloride (PAX) have provided some promising results and PAX addition may prove to be an effective method of controlling filamentous foaming in activated sludge wastewater treatment plants in the future (Rossetti *et al.*, 2005; Paris *et al.*, 2005; Nielsen *et al.*, 2005). Roels *et al.*, (2002) reported a loss of surface scum following PAX addition at dosages ranging from 1.5 to $4.5 \text{ g Al}^{+3} \text{ kg}^{-1} \text{ MLSS-day}$. Depending on the sludge age; the lower the sludge age the higher the dosage required. The exact mechanism of PAX foaming controlling mechanism is still largely unknown. Some hypotheses relate PAX addition to possible partial inhibition of the ability of *M. parvicella* to metabolize hydrophobic substrates, to a decrease in the hydrophobicity of activated sludge and to a better flocculation of activated sludge.

This paper presents the results of an investigation that aimed to evaluate the efficiency of various inorganic coagulants and organic polymers to combat filamentous foaming and bulking problems, caused by the proliferation of *M. parvicella* and/or *Gordona amarae*. Bench scale batch experiments were conducted to evaluate the efficiency of the following coagulants: ferric chloride, ferrous chloride, PAX, hydrated aluminium sulphate, cationic polymer. In addition bench scale batch experiments (ammonia uptake rate (AUR) and oxygen uptake rate (OUR) measurements) were conducted to evaluate any potential toxicity effects of the most promising inorganic coagulants on nitrification and organic matter removal. No toxicity experiments were performed with polymers because addition of cationic organic polymers is not expected to cause toxic effects on activated sludge cultures.

EXPERIMENTAL MATERIALS AND METHODS

Bench scale batch experiments were conducted in order to evaluate the efficiency of each coagulant to control foaming and bulking problems. The duration of the experiments was 14 months, from June 2005 to August 2006. During this period foam samples were taken from the aeration basins of two full-scale wastewater treatment plants that contained high concentrations of *M. parvicella* and/or *Gordona amarae* with a frequency ranging from 4 – 5 (scale 0 – 5). Both treatment plants are nutrient removal activated sludge systems operating at a sludge age of approximately 7 – 8 days. The batch experiments were conducted with 1 l foam samples diluted at a concentration of $7000 \pm 1000 \text{ mg l}^{-1}$. Coagulants were dosed at various concentrations and then the sample was intensively mixed for 5 minutes. Following mixing, the efficiency of each coagulant at a specific dose, was determined by microscopic evaluation of the activated sludge prior and following coagulant addition,

by measuring the foaming propensity of the activated sludge and by diluted sludge volume index (DSVI) measurements.

All analyses were in accordance with the Standard Methods (1994); DSVI values were measured in unstirred 1 l cylinders. Microscopic examination of the sludge samples was performed according to Eikelboom and van Buijsen (1981). Foaming capacity of the samples was assessed using a modification of the foaming test developed by Pitt and Jenkins (1990). According to the original foaming test, a mixed liquor sample was taken from the aeration basin, diluted with distilled water at a mixed liquor suspended solids (MLSS) concentration of 2000 mg l⁻¹. A 250 ml volume of the diluted sample was then transferred to an ethanol washed and dried 1 l graduated cylinder fitted with an airstone at the bottom. The sample was spurge with N₂ gas for 2 minutes at a flow rate of 1600 cm³ min⁻¹. Foaming potential is equal to the height of the foam layer reached during the test. In order to increase the sensitivity of the foaming test the following changes were made: the duration of the test was 7 min instead of 2 min, the target suspended solids concentration was 7000 mg l⁻¹ instead of 2000 mg l⁻¹ and the volume of the sludge sample was 500 ml instead of 250 ml. In addition to the foaming potential, the amount of solids that tend to foam was also determined as the difference between the suspended solids concentration in the mixed liquor at the start and at the end of the aeration period.

In addition bench scale batch experiments, ammonia uptake rate (AUR) and oxygen uptake rate (OUR) measurements, were conducted according to Kristensen *et al.* (1992), to evaluate the toxic effects of the most promising coagulants on nitrification and organic matter removal.

RESULTS

Bench Scale Batch Experiments

Bench scale batch experiments were conducted in order to evaluate the efficiency of each coagulant in controlling foaming and bulking problems. The efficiency of each coagulant was determined by microscopic evaluation of the activated sludge prior and following coagulant addition, by measuring the foaming propensity of the activated sludge and by DSVI measurements. DSVI measurements are not shown in this paper because DSVI values appeared to be approximately constant irrespective of the dose of coagulant added. This response was attributed to the relatively good settling characteristics of the activated sludge used, with DSVI values in the 100 – 180 ml g⁻¹ SS range.

During the bench scale batch experiments the following coagulants were evaluated:

- Ferrous chloride (FeCl₂, Fe²⁺ concentration = 8,85% on a w/w basis, trade name = Ferrosol 9)
- Ferric chloride (FeCl₃, Fe³⁺ concentration = 12,93% on a w/w basis, trade name = Ferrisol Cl 130)
- Hydrated aluminium sulphate (Al₂(SO₄)₃·14H₂O, Al³⁺ concentration = 5,15% on a w/w basis, trade name = Alusol 30)
- Polyaluminium chloride low basicity (Al_n(OH)_{3m}Cl_{3n-m}, Al³⁺ concentration = 5,4 % on a w/w basis, pH = 2.7, trade name = PAC B40)
- Polyaluminium chloride high basicity (Al_n(OH)_{3m}Cl_{3n-m}, Al³⁺ concentration = 5,1% on a w/w basis, pH = 3.0, trade name = PAC B70)
- Cationic polymer (medium molecular weight with a high degree of cationic charge).

Foam samples were taken from two full-scale treatment plants in Greece. As shown in Table 1 all foam samples taken, contained high concentrations of *M. parvicella* and/or *Gordona amarae* with a filament index (FI) ranging from 4 – 5 (scale 0 – 5, 0 = none, 5 = overabundance). Based on the results of the bench scale experiments the dose of each coagulant in g kg⁻¹ of mixed liquor suspended solids (MLSS), required to decrease the foaming propensity of the activated sludge samples by 80%, was determined (Table 2). Polyaluminium chloride and cationic organic polymer proved to be the most efficient among all coagulants investigated, with effective doses ranging from 6 – 11 g Al⁺³ kg⁻¹ MLSS and 3.5 – 4.5 gr kg⁻¹ MLSS, respectively.

Table 1. Dominant filamentous organisms and filament index (FI) in foaming activated sludge samples employed in this study

Sampling period	Sampling place	<i>M. parvicella</i> and <i>G. Amarae</i> content	Filament Index (0 = none, 5= overabundance)
Phase 1: May – June 2005	WWTP 1	<i>G. amarae</i> <i>M. parvicella</i>	4,5 1,0
Phase 2: March – April 2006	WWTP 1	<i>G. amarae</i> <i>M. parvicella</i>	4,0 2,0
Phase 3: May – June 2005	WWTP 2	<i>M. parvicella</i> <i>G. amarae</i>	5,0 3,5
Phase 4: May – June 2005	WWTP 1	<i>G. amarae</i> <i>M. parvicella</i>	4,0 3,5
Phase 5: June – July 2006	WWTP 2	<i>M. parvicella</i> <i>G. amarae</i>	4,5 3,5

Table 2. Coagulant dose required to achieve an 80% reduction of foam propensity

Type of coagulant	Dose required to achieve an 80% reduction of the total volume of foam produced during the foam test (g kg ⁻¹ MLSS)	Dose required to achieve an 80% reduction of the suspended solids that tend to accumulate in the foam (g kg ⁻¹ MLSS)
FeCl ₂	30	35
FeCl ₃	25.6	34.2
Al ₂ (SO ₄) ₃ .14H ₂ O	30	26
PAC B40	11.0	10.5
PAC B70	6.6	11.5
Cationic polymer	4.4	3.5

Ferrous chloride addition at doses as high as 20 g Fe²⁺ kg⁻¹ MLSS, caused no more than 50% reduction in foaming potential. Similarly ferric chloride addition at doses that exceeded 20 g Fe³⁺ kg⁻¹ MLSS resulted in a 50% reduction of the sludge foaming potential. Significant foaming control was achieved only at high doses of ferrous and ferric chloride addition, equal to approximately 32.5 Fe²⁺ kg⁻¹ MLSS and 29.9 Fe³⁺ kg⁻¹ MLSS, respectively. Similarly, low foaming control efficiency was also obtained with aluminium sulphate addition.

Polyaluminium chloride and cationic polymer proved to be the most efficient among all the coagulants investigated. By adding polyaluminium chloride (aluminium application of 6.6 – 11.5 g Al³⁺ kg⁻¹ MLSS) a general improvement of the settling properties of the activated sludge was achieved. High foaming control was also achieved with cationic polymer addition at doses in the 3.5 to 4.5 g kg⁻¹ MLSS range. According to the microscopic analysis of the sludge samples following PAX or polymer addition, the floc strength was improved and flocs appeared more compact and dense. As illustrated in Figures 1 and 2 filament index decreased from 4.5 – 5 to approximately 3 – 3.5. Addition of any of these coagulants resulted in larger flocs, most of them having a diameter greater than 150 µm. In addition both *M. parvicella* and *G. amarae* filamentous organisms were embedded inside the floc material.

Figures 3 and 4 illustrate the effect of PAX addition on the sludge foaming propensity determined as the maximum volume reached by the expanding foam and as the amount of solids that tend to foam. PAX doses in the range between 6.6 – 11.5 g Al³⁺ kg⁻¹ MLSS resulted in a 75 – 100 % reduction of the sludge foaming potential. As shown in Figures 5 and 6, high foaming control was also observed with cationic polymer addition at doses that range from 3.5 to 4.5 gr kg⁻¹ MLSS.

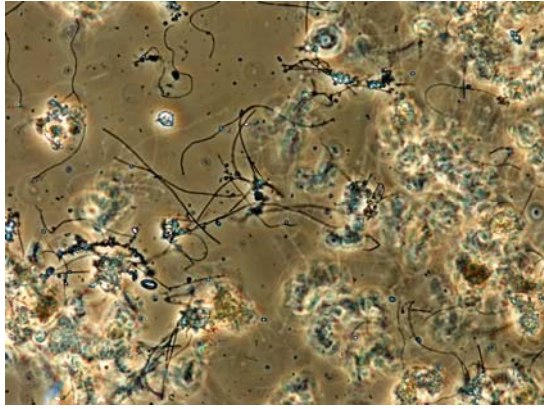


Figure 1. Activated sludge before addition of PAX (magnification X 100) FI = 4.5

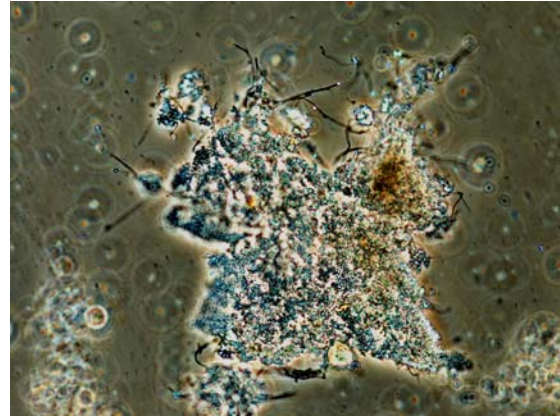


Figure 2. Activated sludge following PAX addition (magnification X 100) FI = 3 - 3.5

According to the results of this study, it appears that PAX and cationic polymer addition changes the morphological characteristics of *M. parvicella* and *Gordona amarae* filamentous organisms, improving flocculation significantly. This is probable due to the neutralization of negative surface charged particles (including *M. parvicella* and *G. amarae*) found in mixed liquor by addition of positively charged coagulants. Minimization of negatively charged particles results in better flocculation and allows activated sludge flocs size to increase. Additionally, negatively charged anionic surfactants and biosurfactants that are produced by foaming forming bacteria (Pagilla *et al.*, 2002) tend to enhance and stabilize foam (Ho and Jenkins, 1991). The addition of positively charged flocculation agents will tend to neutralize these surfactants and minimize their foam stabilizing effect. In the case of cationic polymer bridging mechanism should also enhance flocculation. The overall positive effects of improved flocculation are: 1) most of *M. parvicella* and *Gordona amarae* filamentous organisms are trapped within the flocs, making access to colloidal substrates and lipids more difficult due to increased diffusional resistance and 2) *M. parvicella* and *Gordona amarae* filamentous organisms are embedded within the flocs and removed by excess sludge. Therefore they are not able to form foam and to accumulate in the activated sludge system.

Similar findings can be found in the literature for foaming control. Paris *et al.* (2005) conducted laboratory scale continuous flow activated sludge experiments to investigate means of controlling foam due to excessive *M. parvicella* growth. By dosing PAX ($3.5 \text{ Al}^{3+} \text{ g kg}^{-1} \text{ MLSS day}^{-1}$) a general improvement of the settling and foaming characteristics of the sludge was achieved. PAX addition resulted in a lower *M. parvicella* occurrence and decreased hydrophobicity and floating tendency of activated sludge. Similarly Roels *et al.* (2002) based on operational data from several full-scale activated sludge treatment plants reported a loss of surface scum following PAX addition. In fact Roels *et al.* (2002) developed the following equation to establish the required PAX dose for foaming control as a function of the solids retention time (SRT):

$$60/\text{SRT} = \# \text{ Al}^{3+} \text{ g kg}^{-1} \text{ MLSS} \quad (1)$$

According to eq. (1) the recommended dose for achieving foaming control is approximately $7.5 \text{ g Al}^{3+} \text{ kg}^{-1} \text{ MLSS}$, a value approximately 25% lower than the average dose determined according to the batch experiments presented in this paper. This difference is attributed to the fact that the batch experiments conducted within the context of this study aimed to evaluate one of the effects of PAX addition to activated sludge which is the overall flocculation improvement. According to the literature though, Nielsen *et al.* (2005), apart from the flocculation effect, PAX exerts an inhibiting effect on foaming causing bacteria and especially on *M. parvicella*. PAX addition is reported to attack the ability of this bacterium to use lipids by decreasing the activity of exoenzymes such as lipase. Therefore, PAX addition for foaming control in an activated sludge system should be expected to have a twofold effect on foaming control namely to improve flocculation and to partially inhibit substrate uptake by *M. parvicella*.

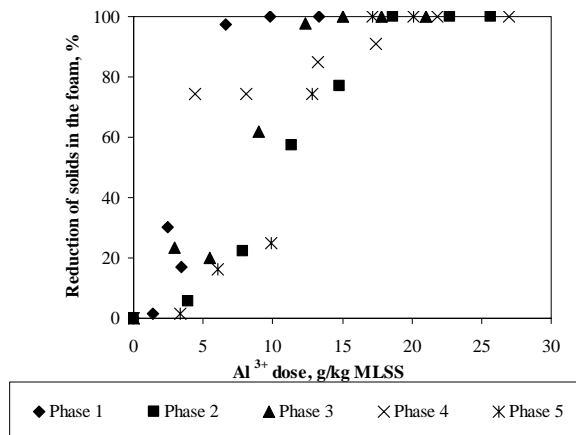


Figure 3. Reduction of the amount of solids that tend to create foam as a function of PAX addition

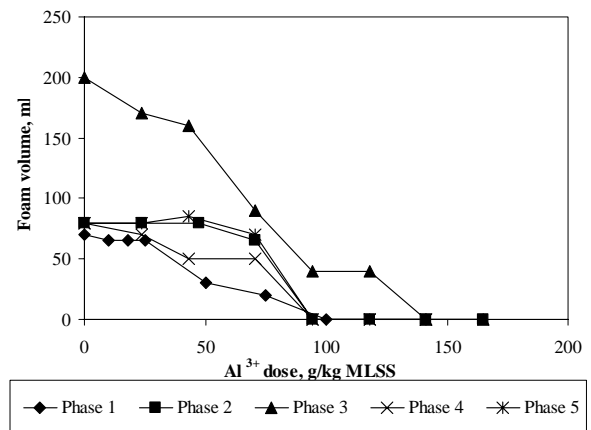


Figure 4. Foam produced during the foaming test as a function of PAX addition

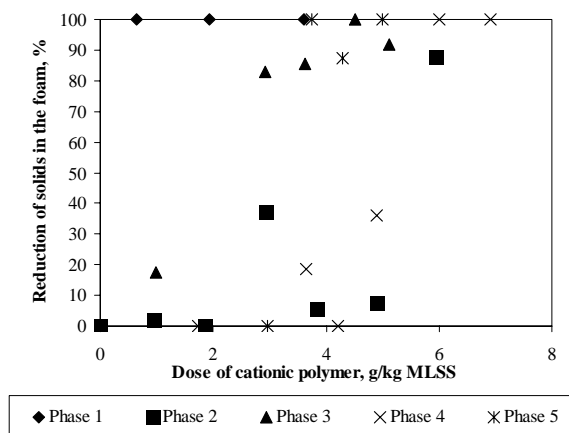


Figure 5. Reduction of the amount of solids that tend to create foam as a function of cationic polymer addition

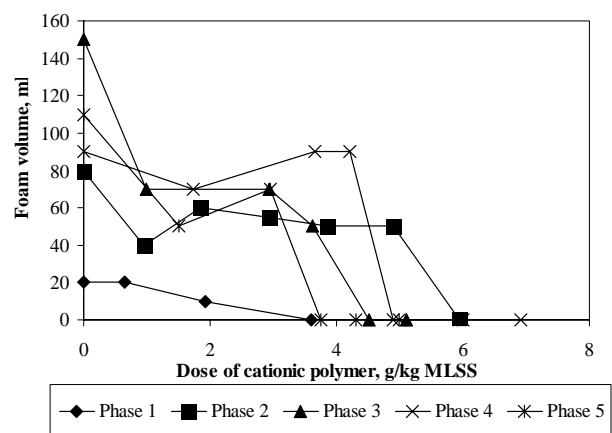


Figure 6. Foam produced during the foaming test as a function of cationic polymer addition

Economic evaluation of coagulant addition for foaming control

A final assessment of the use of coagulants for foaming control should take into account other issues related to the operation of a WWTP such as chemical costs and additional sludge produced. In this paragraph an economic evaluation of the most promising coagulants for foaming control is attempted. The economic evaluation comprised of the following elements: chemicals cost and additional sludge treatment and disposal cost. The coagulants included in this evaluation were ferric chloride, PAX with high basicity and cationic polymer. According to Table 2, target values for foaming control for the three coagulants are $29.9 \text{ g Fe}^{3+} \text{ kg}^{-1} \text{ MLSS}$, $9 \text{ g Al}^{3+} \text{ kg}^{-1} \text{ MLSS}$ and $4 \text{ g polymer kg}^{-1} \text{ MLSS}$, respectively. The economic evaluation was performed for a medium size WWTP with an average treatment capacity of $10,000 \text{ m}^3 \text{ day}^{-1}$, operating at solids residence time of 8 days, a hydraulic residence time of 0.333 days, and an MLSS concentration of 3500 mg l^{-1} .

Chemicals cost. The cost of ferric chloride, PAX or polymer addition was estimated by assuming that all the chemicals added are sorbed on activated sludge. This assumption was verified by measuring soluble aluminium concentration, following addition of PAX and mixture with activated sludge. The measurements showed that the effluent soluble Al^{3+} concentration was consistently below $20 \text{ } \mu\text{g l}^{-1}$.

In order to estimate the cost of PAX addition to maintain a target dose of $9 \text{ g Al}^{3+} \text{ kg}^{-1} \text{ MLSS}$ the following equation was applied that was derived by conducting an aluminium mass balance around the activated sludge system:

$$[Al]_{\text{aeration basin}} = (\text{SRT})/\text{HRT} * [Al]_{\text{wastewater}} \quad (2)$$

where:

SRT = solids residence time = 8 days

HRT = hydraulic residence time in the aeration basin = 0.333 days

$[Al]_{\text{aeration basin}}$ = concentration of Al^{3+} in the aeration basin ($mg\ Al^{3+}\ l^{-1}$)

$[Al]_{\text{wastewater}}$ = concentration of Al^{3+} in the wastewater following PAX addition ($mg\ Al^{3+}\ l^{-1}$)

For an MLSS concentration of $3500\ mg\ l^{-1}$ the target Al^{3+} concentration in the aeration basin should be $31.5\ mg\ l^{-1}$. Following eq. (2) we can calculate that the Al^{3+} concentration in the influent wastewater is equal to approximately $1.3\ mg\ l^{-1}\ Al^{3+}$. According to the above for an average flow of $10,000\ m^3\ day^{-1}$ the daily consumption of Al^{3+} is in the order of $13\ kg\ Al^{3+}\ day^{-1}$. Assuming that the cost of commercial PAX solution (5.1% Al^{3+} on a w/w basis) is approximately 270 euros/tonne, the cost of PAX addition is approximately 51 euros/day or $0.0051\ euros\ m^{-3}$ of wastewater treated.

Similar calculations were performed to estimate the cost of ferric chloride and polymer addition. According to eq. (2) Fe^{3+} and polymer concentrations in the influent wastewater were found equal to approximately $4.4\ mg\ l^{-1}$ and $0.6\ mg\ l^{-1}$, respectively. Therefore for an average flow of $10,000\ m^3\ d^{-1}$ the daily consumption of Fe^{3+} or cationic polymer is equal to $44\ kg\ d^{-1}$ and $5.8\ kg\ d^{-1}$, respectively. Assuming that the cost of ferric chloride commercial solution (12.9% Fe^{3+} on a w/w basis) is 200 euros/tonne, the daily cost of ferric chloride addition, is approximately 68 euros/day or $0.0068\ euros\ m^{-3}$ of wastewater treated. Similarly for a polymer cost of 4.5 euros kg^{-1} the daily cost of cationic polymer addition, is approximately 26 euros/day or $0.0026\ euros\ m^{-3}$ of wastewater treated.

Additional Sludge Production: Sludge volume and quantity is expected to increase by the addition of PAX or ferric chloride. The increase in total suspended solids concentration was calculated by measurement of suspended solids concentration before and after inorganic chemicals addition and was found to average approximately $3.3\ grSS\ gr^{-1}\ Al^{3+}$ and $2.0\ grSS\ gr^{-1}\ Fe^{3+}$ added, respectively. No measurable increase in solids concentration was obtained with organic polymer addition. Therefore no significant chemical sludge production is anticipated with polymer addition.

Table 3 presents chemical addition and sludge treatment and disposal costs for each coagulant studied. Based on data for medium size WWTPs provided by Mamais *et al.* (2009), sludge treatment and disposal cost was considered equal to 140 euros/tonne of DS. According to the cost analysis conducted polymer addition appears to be the most cost-effective method for foaming control with total operational cost equal to 26 euros/day or $0.0026\ euros\ m^{-3}$. Application of PAX had the lower operational cost compared to the other inorganic coagulants studied with a total cost of 57 euros/day or $0.0057\ euros\ m^{-3}$.

Table 3. Assessment of operational cost for coagulant addition for foaming control

Type of coagulant	Chemical addition Cost, euros d^{-1}	Chemical sludge treatment and disposal cost, euros day^{-1}	Total operational cost, euros day^{-1}
$FeCl_3$	68	12.3	80.3
PAC B70	51	6	57
Cationic polymer	26	0	26

Toxicity Assessment Batch Experiments

Bench scale AUR and OUR batch experiments were conducted, according to Kristensen *et al.* (1992), to evaluate the toxicity of PAX addition to nitrification and organic matter removal. The experiments were conducted employing PAX doses in the range from 0 – $14\ g\ Al^{3+}\ kg^{-1}\ MLSS$, or respectively from 0 – $100\ Al^{3+}\ mg\ l^{-1}$. Activated sludge samples were taken from WWTP 1 that performed nitrification throughout the year. AUR and OUR batch measurements are shown in Tables 4 and 5, respectively. According to the data obtained, PAX addition at the above doses caused no inhibition on nitrification and organic carbon removal. No toxicity experiments were performed with cationic polymers because addition of cationic polymers is expected to cause no toxic effects on activated sludge cultures.

Table 4. Toxicity assessment of PAX addition to nitrifying activated sludge using AUR tests

PAX addition (mg Al ³⁺ l ⁻¹)	PAX low basicity (PAC B40)		PAX high basicity (PAC B70)	
	AUR (mg NO ₃ -N g ⁻¹ VSS hr ⁻¹)	Nitrification inhibition (%)	AUR (mg NO ₃ -N g ⁻¹ VSS hr ⁻¹)	Nitrification inhibition (%)
0	2.2	0	1.7	0
25	2.0	8.2	1.6	6
50	2.2	0	1.7	0
100	2.2	0	1.9	0

Table 5. Toxicity assessment of PAX addition to heterotrophic activated sludge using OUR tests

PAX addition (mg Al ³⁺ l ⁻¹)	PAX low basicity (PAC B40)		PAX high basicity (PAC B70)	
	OUR (mg O ₂ - g ⁻¹ VSS hr ⁻¹)	Organic carbon removal inhibition (%)	OUR (mg O ₂ - g ⁻¹ VSS hr ⁻¹)	Organic carbon removal inhibition (%)
0	18.1	0	14.4	0
25	19.2	0	15.3	6
50	17.8	2	15.6	0
100	18.8	0	14.6	0

CONCLUSIONS

The main conclusions of the present work can be summarised in the following:

- Polyaluminium chloride (PAX) and cationic polymer proved to be the most efficient among all the coagulants investigated. By adding polyaluminium chloride (aluminium application of 6.6 – 11.5 g Al³⁺ kg⁻¹ MLSS) or cationic polymer (polymer doses in the 3.5 to 4.5 gr kg⁻¹ MLSS range) a general improvement of the settling properties of the activated sludge was achieved. According to the microscopic analysis of the sludge samples following coagulants addition, the floc strength was improved and flocs appeared more compact and dense. In addition both *M. parvicella* and *Gordona amarae* filamentous organisms were embedded inside the floc material, making access to particulate and colloidal substrates more difficult due to increased diffusional resistance.
- According to AUR and OUR experiments, PAX addition at the above doses caused no inhibition on autotrophic and heterotrophic bacteria that perform nitrification and organic carbon removal, respectively.
- The increase in sludge production by PAX addition was found to average approximately 3.3 grSS gr⁻¹ Al³⁺ added.
- No measurable increase in sludge production was obtained with cationic polymer addition.
- The cost of PAX addition for foaming control comprising of chemical cost and additional sludge treatment and disposal cost is estimated to be approximately 0.0057 euros m⁻³ of wastewater treated.
- Cationic polymer addition was shown to be the most cost-effective method for foaming control. The cost of cationic polymer addition is estimated to be approximately 0.0026 euros m⁻³ of wastewater treated.

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