RESEARCH ARTICLE

Evaluation of foaming potential for water treatment: limits and developments

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Abstract

The critical issue generated by foaming in wastewater treatment plants (WWTPs) is a problem that is currently very common and shared, but which to date is treated mainly only at the management level. In this work, an experimental study with foam tests on real and synthetic waters was conducted using a laboratory scale plant and foaming power indices were calculated. To date, the estimation of foaming potential is mainly based on these indices which give information only on height/volume of foams but not on the type of foams, in terms of consistency and therefore stability. Tests showed that foaming power indices were highly variable with the same water: it was not possible to identify a single foaming potential value for each water. Two models were proposed to estimate the percentage increase in height of chemical foams produced following the introduction of air below the surface of a liquid. In terms of determination coefficient, the results obtained from the complex model were better: R^2 was 0.82 for the simple linear model and 0.90 for the complex one. This approach has allowed to underline some critical aspects of foaming potential as it is determined today and the possible improvements applicable for a more objective evaluation.

Keywords Foaming · Chemical foams · Foaming potential · Foam test · Sodium dodecyl sulfate · Water

Abbreviations

CAS	Conventional activated sludge
COD	Chemical oxygen demand
EPS	Extracellular polymeric substances
FP1	Foaming power index calculated as consumed sample per liter of supplied air
FP2	Foaming power index calculated as foam volume produced per liter of supplied air
R^2	Determination coefficient
RW	Real water
SDS	Sodium dodecyl sulfate
SW	Synthetic water
WW	Wastewater
WWTP	Wastewater treatment plant
ΔH_R	Real percentage increase of the height of foams
ΔH_E	Estimated percentage increase of the height of foams

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Introduction

Studies on the formation of chemical and biological foaming in conventional activated sludge (CAS) plants are carried out towards the end of the 1960s (Jenkins et al. 2004; Fryer and Gray 2012; Capodici et al. 2014). Excessive foam formation in biological wastewater treatment plants (WWTPs) is a common and shared problem but it can lead to serious management difficulties and above all to the lowering of purification yields (Capodici et al. 2014). As already expressed for drinking water (Sorlini et al. 2015a, 2015b, 2019), the same

approach should also be applied for WWTPs in order to optimize the currently existing processes. This would allow to cope with the increasingly presence of industrial contaminants in wastewater (WW) (Roy et al. 2018; Collivignarelli et al. 2019a) but also have a good quality sludge suitable for reuse in agriculture (Collivignarelli et al. 2015, 2019b; Ashekuzzaman et al. 2019). In order to optimize WWTP management, foam formation, quantification, and removal must be investigated. Foam is a set of stable bubbles, produced when air or other gases are introduced below the surface of the liquid which expands to enclose the gas with a liquid film called "lamellae" of the foam (Heard et al. 2008). As already widely discussed in the scientific literature (Davenport et al. 2000, 2008; De Los Reyes and Raskin 2002; Schilling and Zessner 2011; Capodici et al. 2014), foams can be chemical (white foams) or biological (brown foams). The formation of chemical foams is mainly due to the presence of synthetic surfactants and other surface-active compounds, i.e., synthetic detergents, fats, oils, greases but also biosurfactants (Blackall et al. 1991). For instance, in biological treatment, high concentration of methylene blue active substances produces foams and has a toxic effect on microorganisms, depolarizes the bacterial cell wall and reacts with the enzymes and other proteins essential to the proper functioning of bacterial cells (Aloui et al. 2009; Collivignarelli et al. 2019c).

Instead, the biological foams are generated following the growth of filamentous bacteria in the activated sludge and/or the presence of extracellular polymeric substances (EPS) (Nakajima and Mishima 2005; Di Bella et al. 2011; Petrovski et al. 2011; Di Bella and Torregrossa 2013; Capodici et al. 2014). Studies carried out in CAS processes have shown that the formation of biological foams is associated mainly with filamentous bacterial populations of *Nocardioforms* and *Microthrix parvicella* (Iwahori et al. 1997; Di Bella et al. 2011). Their proliferation is induced by WW properties, such as fats or oil content, and operational aspects such as high retention times of both sludge and sewage to be treated, low dissolved oxygen concentrations, high temperatures, low food/biomass ratio, high mixed-liquor suspended solid concentrations (Oerther et al. 2001; Jenkins et al. 2004; Xie et al. 2007; Di Bella et al. 2011). The EPSs are hydrophobic substances which have properties of surface-active agents, of both protein and polysaccharide nature, excreted by microorganisms, produced from cell lysis, and adsorbed organic matter from WW (Nakajima and Mishima 2005; Sheng et al. 2010; Capodici et al. 2014).

The phenomenon of biological and chemical foam formation in WWTPs is a problem that negatively affects the management of the processes and the quality of the treated effluent (Capodici et al. 2014; Collivignarelli et al. 2020). This operative problem occurs simultaneously in both aerobic and CAS processes (aeration basins and clarifier) (Davenport et al. 2008; Di Bella et al. 2011; Guo et al. 2015), in thermophilic

aerobic digesters (Collivignarelli et al. 2017) and in the anaerobic processes of biogas production (Jiang et al. 2018), such as mesophilic anaerobic sludge digesters (Subramanian and Pagilla 2015). In the CAS treatment plants, the foams appear on the surface of the aeration basins in the form of stable air bubbles enclosed in a liquid film (Capodici et al. 2014). On the surface of the aeration basin, at the mixed liquor-air interface where the foam is concentrated, there is a high concentration of suspended solids inside the foams. The biomass is retained by the foam bubbles and this causes a decrease in the concentration of biomass inside the mixed liquor. Therefore, the biological reactor decreases its ability of remove pollutants (Pujol et al. 1991; Fryer and Gray 2012). The primary consequence is a worsening of the quality of the effluent and a formation of bad smells due to the excessive formation of foams (Di Bella et al. 2011). The discomfort generated by foaming in WWTPs is a problem that is currently very common and shared, but which to date is treated mainly only at a management level and still too little studied through a shared scientific method. The determination of volume/height of foams is not enough to assess the problematic organically and systematically. It is also necessary to dwell on the type of foams that has formed since foams of different consistency and stability cause different problems. Foam stability, defined by Blackall et al. (1991), as the foam collapse time after the stopping of aeration. A more labile foam (which is destroyed faster) is objectively less alarming from a management point of view.

The purpose of this study is to examine and investigate the problem of chemical foams through the methodological approach of research. Starting from the calculation of foaming potential, real and synthetic waters were compared and subsequently, an applicative model for the quantification of foams was proposed and validated. Through the model, it was possible to confirm the different weights of the variables present in the foaming potential formula. This finding is very significant considering that in literature, the information on this aspect is almost absent. This approach has allowed to underline (i) some critical aspects of foaming potential, as it is determined today, (ii) the possible improvements applicable for a more objective evaluation and (iii) the need to provide an evaluation method that can be used as a management tool for WWTPs.

Materials and methods

Description of the pilot plant

Usually, to evaluate the formation of foams simulating the conditions of aeration in CAS treatment plants, a series of foamability tests are carried out (Di Bella and Torregrossa 2013). The experimentation was performed with the plant

represented in Fig. 1, applying the aeration method already used in literature by Patist et al. (1998); Fryer et al. (2011); Jiang et al. (2018). The sample was inserted into a graduated plexiglass cylinder (35 mm of internal diameter and 1000 mm height) positioned vertically and fitted with a porous bottom stone. To generate foams, a predetermined air flow rate as introduced from the bottom of the cylinder for a specific interval of aeration time using an air pump (25 W) coupled with a flowmeter.

Characteristics of waters and operative conditions

The behavior of two real waters (RWs) and three synthetic waters (SWs) with different concentrations of sodium dodecyl sulfate (SDS) (80 mg L^{-1}, 120 mg L^{-1}, and 160 mg L^{-1}) were tested. It is an anionic surfactant and is a known foaming agent (Folmer and Kronberg 2000). In the following experiments, it was used as a "reference white" due to its marked foaming effect and because it consists of known molecular composition. The operative parameters of the experimental tests and the characteristics of tested waters, including the chemical oxygen demand (COD), are reported in Table 1.
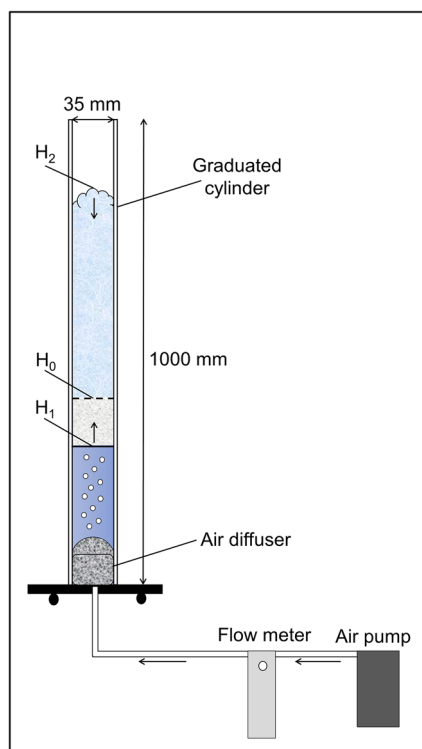

Fig. 1 Pilot plant for aeration tests (the arrows inside the cylinder indicate the movement over time of H_1 and H_2 when the aeration was stopped)

Table 1 Foaming power tests: operative conditions and characteristics of waters

Parameter	Tested values		
	SW	RW1	RW2
Volume [mL]	100, 150	100	
Aeration time [s]	20, 30, 40	20, 40	
Air flow rate [NL min^{-1}]	3, 3.5, 4	1, 2	
SDS concentration [mg L^{-1}]	80, 120, 160	-	
COD [mg L^{-1}]	160, 240, 320	3000 ÷ 6000	

Experimental tests and data processing methods

The initial height reached by the liquid in the cylinder (H_0) was measured and the air flow has been kept constant for the chosen aeration time. After turning off the air diffuser, the level of the foam-liquid interface (H_1) and the maximum level reached by the foams (H_2) were measured. The last measure of H_1 corresponded to H_0. The different heights are represented in Fig. 1.

Foam power

The foaming power test proposed by Nakajima and Mishima (2005) allowed to establish the foaming power index (FP1) as the consumed sample volume (mL) from foaming by 1 L of aeration through the Eq. (1):

$$FP1 \left[mL\, L_{air}^{-1}\right] = (H_0 - H_1) \times S / (Q \times \Delta T) \qquad (1)$$

where:

H_0 the level of the interface between air and water before aeration (cm)

H_1 the level of the interface between water and foams after an aeration interval ΔT (cm)

S   the area of the cylinder (cm^2)

Q   the aeration flow rate (L_{air} min^{-1})

ΔT the aeration period (min)

This approach has also been used by Capodici et al. (2014), Di Bella et al. (2011), and Di Bella and Torregrossa (2013) to assess the foaming potential of membrane bioreactor activated sludge.

Fryer and Gray (2012), and later Jiang et al. (2018), proposed an alternative approach to the quantification of foaming potential. Instead of evaluating the lowering of the foaming liquid interface, the height reached by foams in the column following aeration (H_2) was measured in (cm). In this case, the foaming power index, called FP2, can be quantified using Eq. (2):

$$FP2 \left[mL \ L_{air} \ ^{-1} \right] = (H_2 - H_1) \times S / (Q \times \Delta T) \qquad (2)$$

Applicative model

The study has been developed based on a two-level factorial experiment to evaluate the influence of some operative parameters on foam formation, especially those that appear in the equations of foaming potential. In order to quantify the foams with a value of management interest, the percentage difference between the level of the interface reached by foams at the end of the aeration (H_2) and the initial level of the interface between air and water (H_0) has been calculated as follows (Eq. 3):

$$\Delta H \ [\%] = \frac{H_2 - H_0}{H_0} \times 100 \qquad (3)$$

In order to bypass the interferences caused by different molecules, the model was developed referring to a SW with SDS. The foamability of a sample (as the volume of foams generated during the test) depends on the composition of the liquid to be tested, on temperature, and foam generation method (Fryer et al. 2011). Therefore, for the development of the factorial, the experimentation focused on four operative parameters: the interface level between the air and the water before aeration (H_0), the aeration time (t), the aeration flow normalized to the base surface of the cylinder (Q/A), and the SDS concentration of the solution (SDS). The correlation between the increasing of the real percentage increase of the height of foams (ΔH_R) and the estimated values (ΔH_E) has been investigated by two linear models.

The simple linear model was evaluated with no constant: the hypothesis was $\Delta H_E = \Delta H_R$ for $\Delta H_R = 0$. The following linear model was applied (Eq. 4):

$$\Delta H_E [\%] = aQ/A + bt + cH_0 + dSDS \qquad (4)$$

where Q/A is the aeration flow divided by the cylinder base surface [NL min^{-1} cm^{-2}], t is the aeration time [min], H_0 is the level of the interface between air and water before the aeration [cm], SDS is the concentration of SDS surfactant in the solution [mg L^{-1}], and a [min cm^2 NL^{-1}], b [min^{-1}], c [cm^{-1}], and d [L mg^{-1}] are the weights of the above operative parameters. Furthermore, a more complex linear model was proposed (Eq. 5). In this case, the correlation between the two- and three-level operative parameters is taken into consideration.

$$\begin{aligned} \Delta H_E [\%] = {} & aQ/A + bt + cH_O + dSDS + eQ/At \\ & + fQ/aH_O + gQ/ASDS + htH_O + itSDS \\ & + 1H_0SDS + mQ/AtH_0 + nQ/AtSDS \\ & + otH_0SDS + pQ/AH_0SDS \end{aligned} \qquad (5)$$

where a [min cm^2 NL^{-1}], b [min^{-1}], c [cm^{-1}], d [L mg^{-1}], e [cm^2 NL^{-1}], f [min cm NL^{-1}], g [min cm^2 mg^{-1}], h [min^{-1} cm^{-1}], i [L mg^{-1} min^{-1}], l [L mg^{-1} cm^{-1}], m [cm NL^{-1}], n [cm^2 mg^{-1}], o [L min^{-1} cm^{-1} mg^{-1}], and p [cm min mg^{-1}] represent the weights of the operative parameters.

The parameters of both linear and non-linear models were optimized minimizing the squared error sum $(\Delta H_E - \Delta H_R)^2$. Each variable of the model was also normalized to assume a value between 0 and 1. The normalization was made by dividing each variable by the greater value assumed by the variable itself. In this way, at the end of the model development, the normalized parameters were obtained.

In order to (i) evaluate the variability of the FP indices around the mean value obtained from the tests and (ii) make a comparison in absolute terms between the parameters of the simple linear model, a continuous probability distribution has been calculated. The normal distribution is characterized by the probability density function reported by Eq. (6). The probabilities of a normal distribution depend only on the values assumed by the two parameters μ (average value of the sample of data) and σ (standard deviation of the sample of data). The distribution is symmetric with respect to μ and is asymptotic to the axis on both sides. The average value is the center of the distribution and characterizes the position of the curve with respect to the ordinate axis. As the average changes, the curve translates along the abscissa axis, but its shape remains unchanged. The σ parameter characterizes the shape of the curve as it represents the dispersion of the values around the maximum of the curve, as σ changes, the curve changes its shape by flattening or rising.

$$f(X) = \frac{1}{\sigma \sqrt{2\Pi}} e^{-\frac{(X-\mu)^2}{2\sigma^2}} \qquad (6)$$

Results and discussion

Foam potential

Real waters

The two RWs have completely different chemical characteristics and consequently, they produce qualitatively different foams:

- RW1: considerable formation of very stable foams that can easily reach the maximum height of the pilot plant and which slowly collapse.
- RW2: formation of less thick and much fewer stable foams. The suspension of ventilation leads to a rapid collapse of foams.
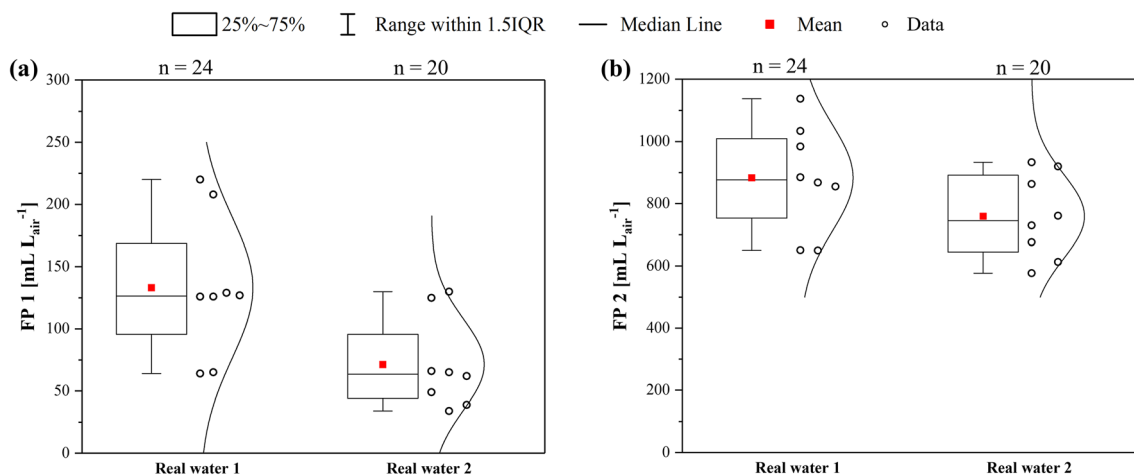
Fig. 2 Foaming power of RWs: FP1 (**a**) and FP2 (**b**) indices. Boxplots represent the distance between the first and third quartiles, while whiskers are set as the most extreme (lower and upper) data point not exceeding 1.5 times the quartile range from the median. Black curves represent the normal distributions of the data. (n number of tests)

The results of the foaming power tests, which were conducted on both RWs samples, are shown in Fig. 2. The foaming potential should be an intrinsic quantity to the water; therefore, for each tested water, a single value associated with it should be found. Considering the same water, it was possible to observe a significant variability of values of the calculated foaming power indices, both for FP1 (Fig. 2a) and FP2 (Fig. 2b). For both RWs tested, in order to evaluate the dispersion of data samples, the normal probability distribution is shown in Fig. 2, also reporting the number of tests carried out for each type of water. For RW1, the confidence interval was 133 ± 39 mL L_{air}^{-1} and 883 ± 199 mL L_{air}^{-1}, respectively for FP1 and FP2. For RW2, the results for FP1 and FP2 were the following: 71 ± 25 mL L_{air}^{-1} and 759 ± 94 mL L_{air}^{-1}. In both cases, FP2 showed a more marked variability than FP1. The RW1 had a mean value of FP1 about twice that of RW2. For FP2, the average values of the two RWs were comparable. Based on these results, it is not immediate and intuitive to define and distinguish the real behaviors of RW1 and RW2. Changing the operative conditions (such as the aeration time or the airflow), with the same water, identifying a single foaming potential value for each water was not possible. This aspect was related to the weight of the parameters of the equations used to calculate the indices and it is better explained below with reference to SWs.

Synthetic waters

In Fig. 3, foaming power trends (FP1 and FP2 indices) of solutions with different SDS concentrations are reported. Changing the concentration of surfactant during the experimental tests, SW produced foams of different consistency and stability. As in the case of tests carried out on RWs, the experimental results showed how the foaming potential calculated with the indices FP1 (Fig. 3a) and FP2 (Fig. 3b) was very

variable keeping constant the concentration of surfactant. For each SDS solution tested, the normal probability distribution is shown in Fig. 3 with the aim of assessing the dispersion of the data sample. The number of tests carried out is also indicated. For each SW, confidence intervals were determined. The results by increasing SDS concentration were the following: 30 ± 4 mL L_{air}^{-1}, 27 ± 4 mL L_{air}^{-1}, 37 ± 4 mL L_{air}^{-1} and 406 ± 22 mL L_{air}^{-1}, 417 ± 37 mL L_{air}^{-1}, 502 ± 30 mL L_{air}^{-1}, for FP1 and FP2 respectively. Comparing the solutions with different concentrations of SDS, there was no significant variation in the mean value, for both the indices used. As with real waters RWs described above, it was not possible to diversify the different solutions of surfactant (80 mg L^{-1}, 120 mg L^{-1} e 160 mg L^{-1}) based on the results obtained on the FP indices. This result was related with the aspect that the foaming potential could depend differently on the air flow rate, and the aeration time was not considered. Instead, in the proposed equations of FP1 and FP2, all variables had the same weight equal to 1. Therefore, an applicative model has been proposed (i) to define the real weight of these variables and (ii) to provide a tool that can be used as a management instrument for WWTPs.

Applicative model

In this section, the results of a two-level factorial experiment are shown to study the influence of the operative parameters considered (shown in Table 1) on the height reached by foams following aeration. For the determination of a reliable model, a large number of data were used, corresponding to as many laboratory tests ($n = 180$). These data (ΔH_R) referred to different operative conditions of sample volume (level of interface between air and water before aeration), air flow rate, aeration time, and SDS concentration of the solution, with the variation of a single variable in turn. The purpose of this model was to
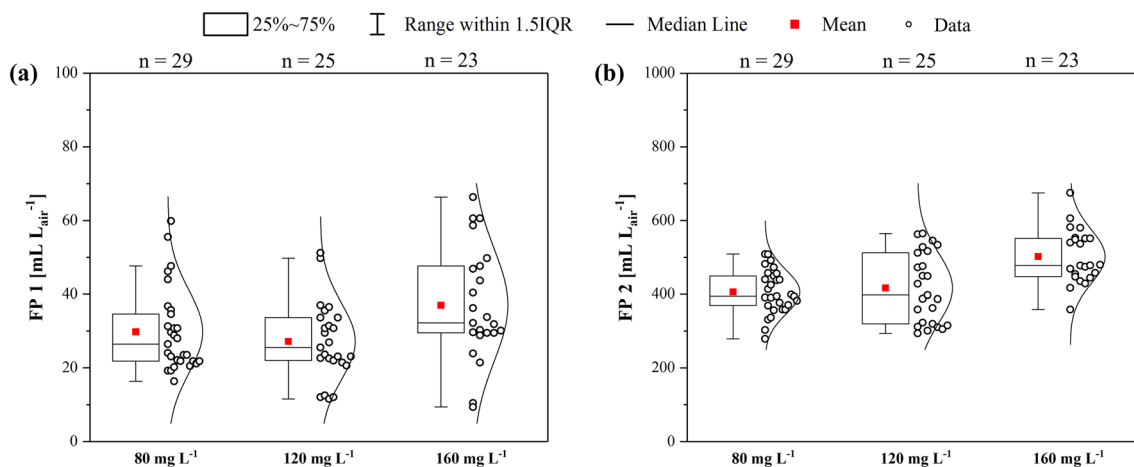
Fig. 3 Foaming power of SWs: FP1 (**a**) and FP2 (**b**) indices. Boxplots represent the distance between the first and third quartiles, while whiskers are set as the most extreme (lower and upper) data point not exceeding 1.5 times the quartile range from the median. Black curves represent the normal distributions of the data. (*n* number of tests

assess the effects of the tested operative parameters (model variables) on ΔH. It was important to analyze the weight of each variable in order to understand which operative parameters most influenced the phenomenon studied. The water used for the development of the model was a solution of surfactant SDS, with different SDS concentration, as shown in Table 1.

The results of the simple linear model (Eq. 4) and of the complex linear model (Eq. 5) are reported in Table 2.

In order to define the real weight of the variables on ΔH after aeration, all data used for the models have been normalized (Table 2).

In Fig. 4, the correlation between ΔH_R and ΔH_E is shown for both models. For the linear model described by Eq. (4), the slope of the interpolation line was about 0.97 (Fig. 4a). This

result suggested that the operative parameters taken into consideration took an important role in the foaming phenomenon. The linear determination coefficient (R^2) to evaluate the goodness of adaptation of the linear model to the observed data has been defined. For construction it varied from zero to one, expressing a good degree of linear adaptation if its value was close to one. R^2 was 0.82 for the simple model (Fig. 4a).

Regarding the more complex model (Eq. 5), the slope of the interpolation line was near 0.98 and R^2 was equal to 0.90 (Fig. 4b). In terms of R^2, the results obtained from the complex model were better than the first model. Considering the interpretation problems related to the second model and the too high number of variables with respect to the experimental data available, it is preferable to use the simple linear model, which

Table 2 Simple linear model and complex linear model parameters (*n* = 180)

Parameter	Unit of measure	Simple linear model value		Complex linear model value	
		Not normalized	Normalized	Not normalized	Normalized
a	min cm^2 NL^{-1}	2012.778	0.748	2.836	− 0.036
b	min^{-1}	769.215	0.458	− 9.535	− 0.324
c	cm^{-1}	− 50.916	− 0.646	− 0.312	0.002
d	L mg^{-1}	0.953	0.136	1.392	0.214
e	cm^2 NL^{-1}	-	-	147.504	2.218
f	min cm NL^{-1}	-	-	0.914	0.042
g	min cm^2 mg^{-1}	-	-	3.538	0.239
h	min^{-1} cm^{-1}	-	-	0.355	0.153
i	L mg^{-1} min^{-1}	-	-	0.013	0.035
l	L mg^{-1} cm^{-1}	-	-	− 0.186	− 0.403
m	cm NL^{-1}	-	-	− 7.130	− 1.527
n	cm^2 mg^{-1}	-	-	− 0.252	− 0.609
o	L min^{-1} cm^{-1} mg^{-1}	-	-	0.003	0.341
p	cm min mg^{-1}	-	-	0.316	0.242

(a)   **(b)**
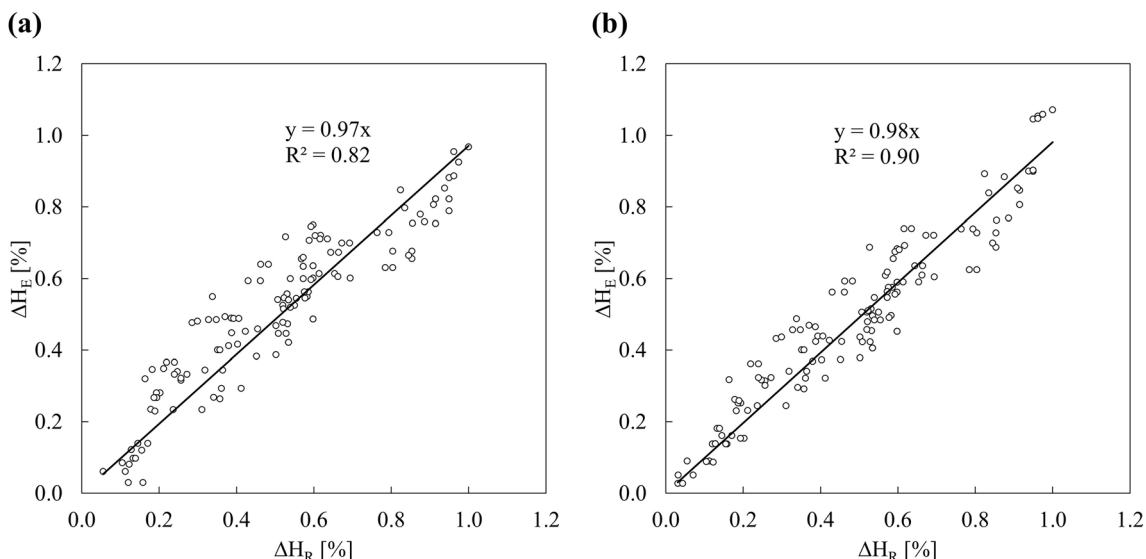

Fig. 4 Correlation between the real height of foams (ΔH_R) and the estimated values (ΔH_E) for the simple linear model (**a**) and the complex linear model (**b**)

can already provide a reliable estimate of ΔH under defined operating conditions.

The calculated values of the weights (a, b, c, and d) in the simple linear model showed the positive effects on the value of ΔH of the aeration flow rate and of the aeration time. As the concentration of SDS surfactant in the solution increased, there was a small increase in ΔH because the corresponding coefficient "d" assumed a value much lower than 1. Therefore, the greater dependence of ΔH was associated with the aeration flow rate. It was also observed that as the level of the interface between air and water before aeration increased, there was a decrease in ΔH.

The normal or Gaussian distribution was used to analytically define how the values assumed by the variables of the simple linear model were distributed. The symbol $f(X)$ was used to denote the mathematical expression of the probability

density function and X was the value assumed by the parameters a, b, c, and d of the simple linear model (Fig. 5). Each normal distribution was obtained by calculating the parameters based on random groups of data. Each point of the curves corresponds to a causal set of tests. From each of these groups of experimental tests, the values of the parameters and the normal distributions were calculated.

The skewness and kurtosis of the distributions are shown in Table 3. The skewness was negative for all distributions. The distribution of the parameter "c" had a skewness close to zero; therefore, there was a marked symmetry (a perfectly symmetrical data set has a skewness of 0 as the normal distribution). The dataset relative to the last parameter was lower symmetrical, having a skewness approximately equal to − 2. For the distributions "a" and "b," the kurtosis was close to zero because they had all the

Fig. 5 Normal distribution of the parameters a, b, c, and d (simple linear model)
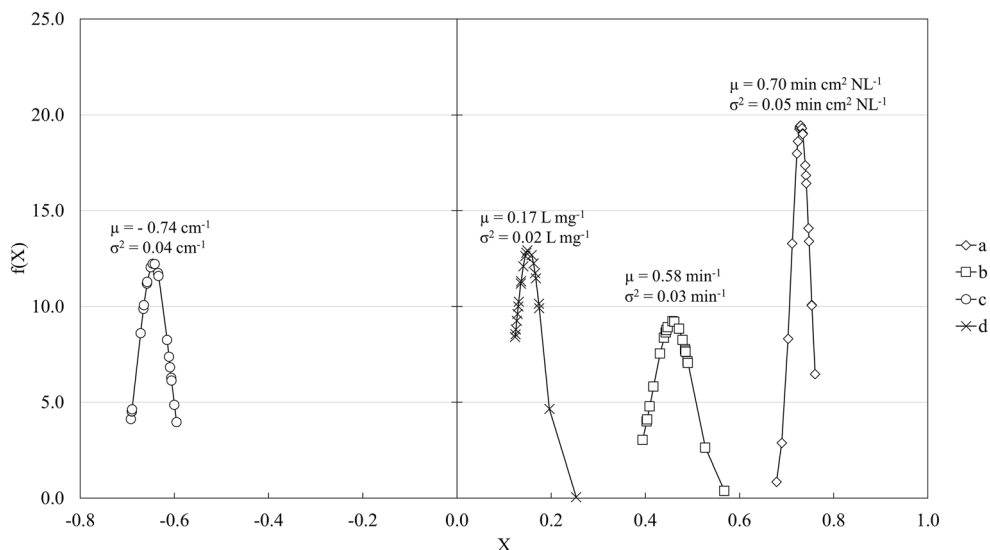
Table 3 Skewness and kurtosis of the normal distributions of the parameters a, b, c, and d

	a	b	c	d
Skewness	− 1.09	− 1.08	− 0.002	− 2.10
Kurtosis	0.16	0.25	− 1.67	5.45

data in each tail as they did in the peak. A kurtosis was less than zero for the "c" distribution and assumed a high positive value for the distribution of the parameter "d".

Conclusions

In this work, an experimental study with quantitative tests on chemical foams produced by RWs and SWs was conducted using a pilot plant on the laboratory scale. The indices of foaming power suggested by literature present several critical aspects.

As demonstrated in this paper, FPs give only information on how many foams are produced in terms of height or volume but not on consistency and stability of foam. Therefore, FPs should not be used individually to define the foaming potential of water. Moreover, considering that FPs of the same water were very variable changing operative conditions, identify a single foaming potential value for each water was not possible. This problem was related with the weight of the parameters of the equations used to calculate the indices.

The proposed alternative linear model showed that keeping constant the concentration of surfactant in the tested solution, the quantity of foams produced (and the FP) was not a constant value that describes the solution but a function mainly related to the aeration flow rate, the aeration time, and the initial height before aeration ($a = 0.748$ min cm^2 NL^{-1}, $b = 0.458$ min^{-1} and c $= − 0.646$ cm^{-1}). In terms of determination coefficient, the results obtained from the complex model were better (0.90) compare with the linear ones (0.82): the use of the simple linear model, which can already provide a reliable estimate of the level reached by foams, is suggested. Starting from the total absence of a model, the simple linear one proposed in this work, represents the first step for the future development of models that take into consideration several variables, such as the viscosity of the fluid, the density of the fluid, and the concentration of others surfactants.

The future goal could be to identify a method for assessing the foaming potential that: (i) best represents the intrinsic nature of the parameter and (ii) it is simple to calculate and quick to apply, especially in view of easy applicability from a management and operative point of view for WWTPs.

Compliance with ethical standards

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