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A feasibility study of the installation of a modular bioreactor inside a chemical scrubber at a wastewater treatment plant

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ABSTRACT

Chemical scrubbing and biofiltration are well-established technologies for treating contaminated pollutants generated at wastewater treatment plants (WWTPs). Nevertheless, the growing need to reduce the ecological footprint of abatement technologies without affecting process efficiency is prioritizing biological alternatives. This study deals with the challenge of designing a structure for converting a chemical scrubber currently operating at a WWTP with a capacity of 6400 population equivalent (PE) into a modular bioreactor without any actual modification of the scrubberś structure. The inside of the reactor was divided into three levels or platforms for holding the biomaterial, and the corresponding parts were manufactured in PVC, with the exceptions of the screws and cross bracing. The study of the parts' stress and strain limits revealed that the slats and half-rings should be reinforced with ribs, and the optimal rib height was studied on a case-by-case basis. It was also concluded that the base legs could hold the weight of 80 cm height biomaterial bed onto each of the three platforms. Based on previous studies, the converted biofilter with an inlet flow rate of 1150 m^3/h could render simultaneous removal efficiencies greater than 90 % for H_2S and NH_3. Regarding the viability study, the annual savings from the elimination of chemical consumption were around 9.7 % of the total investment cost. One of the main strengths of replacing the scrubber with a biofilter was the improvement in sustainable performance and health and safety, reducing both risk and the budget for prevention.

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1. Introduction

Over the past decade, the number of complaints from the local community about the unpleasant odours around large industrial and municipal plants has increased considerably (de Blas et al., 2017). This odour issue affects approximately 20 % of the population in Europe, with malodours from wastewater treatment plants WWTPs being amongst the most offensive ones (Muñoz, 2013). In many cases, WWTPs were designed and constructed in the early 1980s on landfill sites or highly industrialised environments at a safe distance from residential areas. Nevertheless, the spread of new housing is unavoidable, while hindering the adoption of strategies for odour control and abatement due to the lack of available land for new constructions (Estrada et al., 2015). As a result, odour management has become a priority in the design and operation of WWTPs, forcing managers to search for innovative and sustainable solutions for odour prevention (Lasaridi et al., 2010; López-Etxebarria, 2015).

Different odour abatement technologies have been installed in WWTPs, and they can be classified into physicochemical techniques (e.g., chemical scrubbers or activated carbon filtration), and biological techniques (e.g., biofilters, biotrickling filters and bioscrubbers). Chemical scrubbing can be used to treat virtually any water-soluble compound as long as the contaminants solubilise from the gas phase into an aqueous chemical solution. Depending on the nature of the contaminant to be treated, alkaline and acid scrubbers are usually combined. The latter works at low pH levels, whereby alkaline components (particularly amines, ammonium, esters and other alkali reacting compounds) are collected. Corrosive sulfuric acid (H_2SO_4) is commonly used to keep a low pH

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of around 2.5−3.5. The alkaline scrubber works at high pH levels (9.5–13.0), and sodium hydroxide (NaOH) and sodium hypochlorite (NaOCl) are used in a recirculating chemical solution. Sodium hydroxide is needed to solubilise hydrogen sulphide (H_2S), whereas other odour-causing compounds are best treated by the strong oxidiser hypochlorite, which also reacts with the sulphide that is solubilised by the sodium hydroxide. The main advantage of chemical scrubbers is the protracted experience gained over the years in their design and operation, their low empty bed residence times (EBRTs), and their rapid start-up (Sanchez et al., 2006). This means scrubbing is a robust technology from an operational point of view, in addition to being reliable and flexible (Kraakman et al., 2014). Among its disadvantages are the fact that hazardous chemicals need to be handled with care, pH control is recommended, and wastewater is generated. In economic terms, chemical scrubbing is highly impacted by the concentration of H_2S and the consumption of chemicals, being considered poorly sustainable and expensive (Estrada et al., 2013).

The gaseous contaminants generated at WWTPs can also be biologically degraded in the biofilters used to treat a variety of biodegradable and water-soluble odorous contaminants, with lower operating costs and waste generation (Estrada et al., 2012). The compounds are degraded by the biomass developed inside the bioreactor and attached to the solid support or packing material (Fig. 1) (Lebrero et al., 2013). Biofiltration is highly impacted in economic terms by the packing material's lifespan, the EBRT, and the operating cost (Estrada et al., 2013). The packing materialś cost can be drastically reduced when using more durable media (e.g., mixtures of organic and inorganic materials) (Dorado et al., 2010). Thus, lifespans ranging from 1 to 15 years have been reported for nutrient enriched inorganic media, and from 1 to 3 years for conventional organic media (Prado et al., 2009a, 2009b). Other major challenges facing these types of bioreactors are their slow start-up, the difficult control of the biodegradation process, and the instability of the medium (Manczarski et al., 2019). Unlike chemical scrubbers, biofilters maintain high and stable removal efficiencies for the odorants emitted from WWTPs despite seasonally fluctuating odorant concentrations (Sówka et al., 2017) and avoiding the corresponding overdosage of chemical reactants (Einarsen et al., 2000; Karageorgos et al., 2010). Biofilters also have lower operating costs because the contaminants' oxidation mechanisms occur at ambient temperature and pressure without an external supply of chemicals (only water and nutrients). The absence of extreme operating conditions and hazardous chemicals constitute an additional advantage from both a safety and an eco-friendly viewpoint (Alfonsín et al., 2015; Cano et al., 2018). In addition, the use of biofilters may pose a significant advantage for bioaerosols control (Singh et al., 2020). Liu et al. (2020) concluded that 55 % of heterotrophic bacteria and 47 % of total fungi were removed in a two-stage full-scale biofilter composed of polyurethane and volcanic rock, each of them with an effective volume of 24 m^3 and an inlet airflow rate of 5760 m^3/h (EBRT of 36 s).

Bearing in mind that biological-based technologies are especially suitable for treating gas streams such as those originating in WWTPs (Barbusinski et al., 2017), the conversion of chemical scrubbers into biofilters is an attractive solution for reducing the maintenance costs associated with energy and water use, as well as removing the need to use and handle toxic and dangerous chemicals, considerably improving health and safety and process sustainability (Cano et al., 2018; Gabriel and Deshusses, 2004).

Surprisingly, chemical scrubbers and biofilters share many common structural features, with the main differences being the humidification step required solely in the bioreactor and the irrigation solution (nutrients in the bioreactor and acid or alkaline chemicals in the chemical reactor) (Fig. 1). Although there are successful examples in the literature of full scale conversion of chemical scrubbers into biotrickling filters for the treatment of gases in municipal solid waste treatment facilities and wastewater treatment plants (Gabriel and Deshusses, 2004; Prado et al., 2009a, 2009b; Santos et al., 2015), the conversion into conventional biofilters has not been reported yet.

Taking into account the Best Available Techniques (BAT) Reference Document (BREF) for Common Waste Water and Waste Gas Treatment/Management Systems in the Chemical Sector under the 2010/75/EU Directive, the implementation of biological-based technologies as end-of-pipe treatment for minimizing emissions (BAT 21) is recommended (Brinkmann et al., 2016). Thus, the aim here is the design of a mechanical structure to be installed inside a chemical scrubber (chemical system) to convert it into a modular bioreactor (biological system) to be used at a WWTP. A mandatory requirement for this conversion is that the scrubber cannot undergo any structural modifications, and the mechanical conversion is not to involve new spaces in the facility. Thus, all the parts for this assembly should fulfil three conditions: they must be inserted into the reactor through the three inspection hatches (or manholes) available in the scrubberś casing, they should be corrosion resistant, and they should pass stress and strain tests. A new inner structure has been designed to hold the support material for the biomass, and the stress and strain limits have been calculated. The conversion's economic and safety feasibility have also been studied. This modification helps to prevent pollution by promoting sustainable biotechnologies.

2. Materials and methods

2.1. Characteristics of the chemical scrubber and biofilter

The two-stage scrubber system, located at the Orduña WWTP (Bizkaia - Spain), is property of the waterboard Consorcio de Aguas de Bilbao Bizkaia and is operated by DRACE Infraestructures. It comprises one alkaline scrubber and one acid scrubber. The facility treats the sewage generated by a population equivalent of around 6400 inhabitants. The two chemical polypropylene scrubbers are six metres high and two metres in diameter. Each scrubber has one inlet tube at the bottom, one outlet tube at the top, and three circular inspection hatches or manholes of 50 cm in diameter at 80, 432 and 577 cm from the base. Each scrubber receives an industrial water supply, with a second inlet provided for feeding chemicals. Only one of the two aforementioned reactors was selected for this study, with the conclusions also being applicable to the other one.

According to the information kindly provided by the WWTP's managers, chemical odour control setup is designed to treat up to 23000 m^3 of contaminated gas per hour and average inlet concentrations over a 12-month period for mercaptans, ammonia (NH_3) and hydrogen sulfide (H_2S) have been below 0.25 ppm, 0.2 ppm and 0.5 ppm, respectively. Slightly higher values have occasionally been recorded during the summer.

As far as the biofilter is concerned, the packing material used as a model for this study consists of a pelletized compost obtained by mixing pig manure and sawdust. It has been characterised according to standard methods, and records a pH of 8.5, natural moisture content of 25 % and a BET (N_2) surface area of 12.06 m^2/g (Barona et al., 2005). The low pressure drop and the absence of bed compaction after long-term operation, allows the electrical consumption of the fans to be up to 40 or 50 % lower compared to pure organic packing materials (EMASESA, 2018). Besides, its indigenous microbial population's ability to degrade typical malodorous compounds in WWTPs (H_2S and simple aromatic VOCs) has confirmed its suitability for this study (Elías et al., 2000; Gallastegui et al., 2011). The medium should be replaced at regular intervals (2–5 years), while the estimated lifespan for any pure organic would be

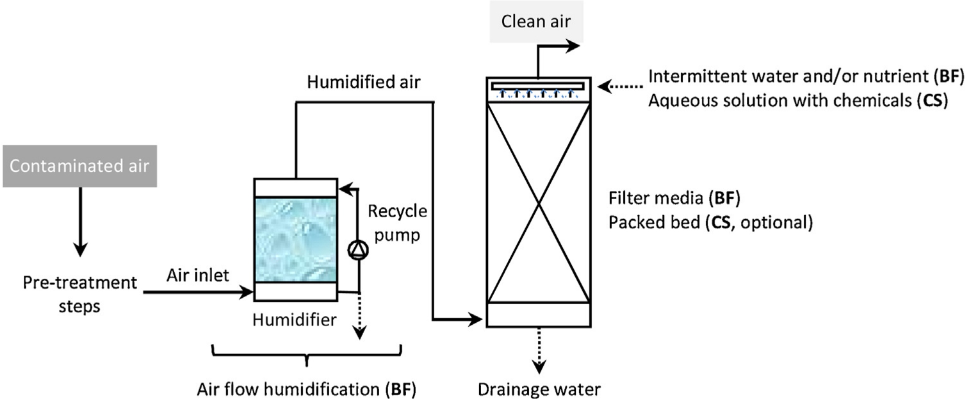

Fig. 1. Diagram of the chemical scrubber/biofilter, showing both the common and the distinguishing parts of the two configurations (BF, biofilter; CS, chemical scrubber).

two years (Dorado et al., 2010; Gao et al., 2001). The controlled humidification and the reduced contaminant concentration in the inlet flow suggest that there will probably not be any preferential paths or clogging episodes associated with biomass accumulation.

2.2. Simulation and design methods

Two commercial software packages were used: Solid Edge ST8 and ANSYS R16.2 academic software. Solid Edge ST8 software is an exceptional tool for creating and managing 3D digital prototypes. It was used here to design the main parts for the assembly, namely, three horizontal platforms for holding the biomaterial, three ring sets for holding the three platforms, and legs for supporting the entire structure. ANSYS R16.2 academic software was used to calculate the stress and strain limits on the new structure, and force equilibrium and stress were also calculated for the buckling and compression study.

All the calculations were carried out assuming that the parts would be made of polyvinyl chloride (PVC) (with the exception of the cross bracing and screw). This material's mechanical properties are as follows: elastic modulus 3 GPa, Poisson's ratio 0.4, density 1385 kg/cm^3, and yield stress 57 MPa.

2.3. Sets of parts for the assembly

Bearing in mind the assembly conditions fixed in the introduction section, an initial decision was made to divide the inside of the scrubber into three levels (platforms), giving the bioreactor a modular arrangement. The selection of the three levels was conditional on the scrubber structure because there were three circular inspection hatches in the scrubber's casing. Thus, an operator accessing the corresponding level through each hatch could perform the maintenance work on each level. Therefore, this arrangement entailed an easier extraction and partial replacement of the bed in comparison to traditional one-level biofilters with one single bed of 1–2 m depth (Gao et al., 2001; Prado et al., 2009a, 2009b). It also contributed to increasing the exposed surface area of the support material facilitating adsorption and, it offered the opportunity to alleviate interspecific competition for substrate (i.e., NH_3 and H_2S) within different active microorganisms developed in the individual levels of the same bioreactor. Chung et al. (2007) proposed the implementation of a two-stage biofilter to improve NH_3 removal from waste gases containing high H_2S concentrations. Specific pure bacterial strains (*Thiobacillus thioparus* and *Nitrosomonas europaea*) were inoculated in this study for the H_2S and NH_3 abatement in the first and second stage, respectively. Finally, the modular assembly avoids the accumulation of sulphate (SO_4^{2-}) that would take place in the bottom part of a hypothetical unimodular biofilter (Li et al., 2013), which would have an inhibitory effect both in the sulphur and in the ammonia converting microorganisms (Rabbani et al., 2016a, 2016b).

Thus, the biomaterial's bed height on each level was initially calculated to be around 10 cm. Nevertheless, bearing in mind the dimensions of the manholes and the need to easily replace the spent material, the design took into account that the biomaterial could be loaded in 25 kg air permeable sacks.

Three sets of parts with different functions were designed, as shown in Fig. 2. Set A is the platform or circular surface for holding the biomaterial. It was divided into four 4 cm thick slats (two outer slats and two inner slats) that are joined to form the round platform (174 cm diameter). Made of PVC, each slat was designed to be introduced into the scrubber through the three 50 cm diameter manholes available (numbers 1–3 in Fig. 2), and drilled (1 cm diameter holes) to let the waste airflow pass through the sacks of biomaterial.

Set B is the ring set for supporting the modular platform and holding the structure's legs. Each ring set had upper and lower rings, with an internal space to fasten the slats, and each one was divided into two parts (lower half-ring and upper half-ring) to be introduced into the scrubber. The outer diameter was 200 cm. They were also made of PVC.

Finally, set C is the system for holding the assembly that was arranged into three levels (at 210, 400 and 500 cm, respectively, from the base and conditioned by the manholes). The PVC legs at the intermediate and base levels were fitted with steel cross bracing to avoid rotation, and the latter had two additional stop rods for preventing leg flexion. Steel screws were used to attach the legs to the rings.

3. Results and discussion

3.1. Stress and strain on the slats

Each slat on the platform should bear both its own weight and the weight of the biomaterial placed on it. The maximum stress and strain on these parts were calculated by ANSYS R16.2 for two cases: when the packing material is loaded and operating, and when an 80-kg person stands in the centre of the slat, with the latter being the most unfavourable situation. Only the inner slats were studied, as they represent the most unfavourable case. The two inner slats are longer than the two outer ones, as shown in Fig. 2 (parts assembly A) and their ring-holding area is shorter. The ANSYS analysis was conducted by assuming the slats without holes (although holes are necessary for letting the waste airflow pass through the biomaterial). Thus, the total mass of the drilled slat was used to recalculate the equivalent slat dimensions without holes (Table 1).

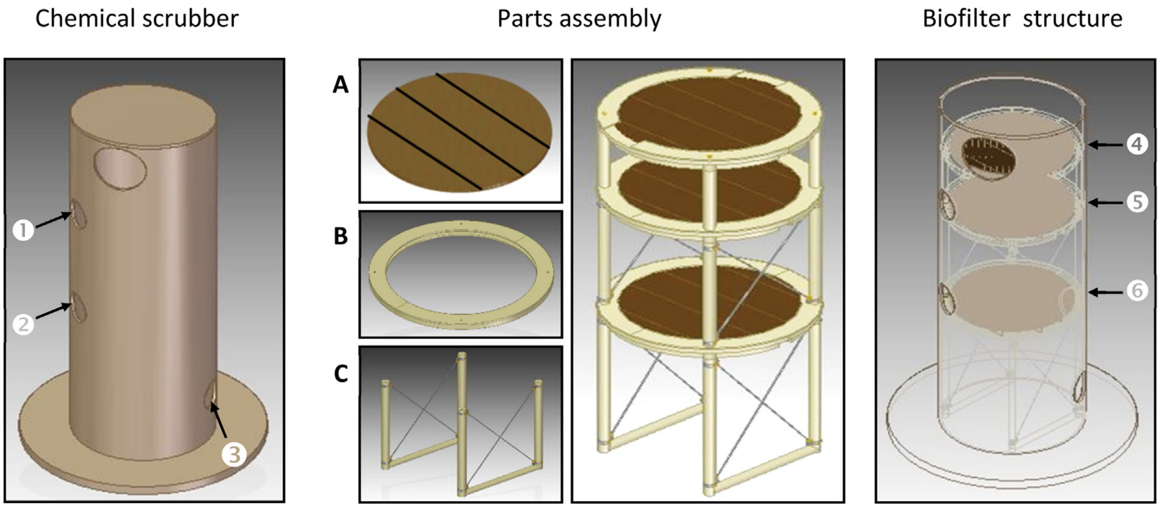

Fig. 2. Layout of the assembly for converting the chemical scrubber into a biological reactor. Numbers stand for the position of the scrubberś manholes (1–3) and filter media level (4–6), and capital letters represent the three sets of parts used in the assembly.

Table 1
Data for each inner PVC slat.

Parameter	
Weight (kg)	32.76
Original thickness (cm)	4.00
Modified thickness (cm)	3.26
Projected area (cm^2)	7241
Original volume with holes (cm^3)	28962
Modified volume without holes (cm^3)	23651

Table 2
Weight and stress and strain limits for the inner ribbed slat with an operator standing in the centre.

Rib height (mm)	Weight (kg)	Stress limit (MPa)	Strain limit (mm)
50	34.94	4.14	6.6
100	37.12	2.33	3.6
150	39.30	1.56	2.3
200	41.49	1.49	1.7

The simulated reduction in slat thickness did not affect safety, as the consequent inertia was also reduced.

The biomaterial to be used for this study had a bulk density of 1.15 kg/dm^3 (standard value in bioreactors) (Elías et al., 2000), rendering a weight over the inner slat of 83.27 kg. The total weight of the biomaterial on each platform was actually 242.93 kg, but bearing in mind the whole area of the inner and outer slats (without the space lost by the holding system), the total weight was overestimated as 273.46 kg. The inner slat would record its maximum stress with the biomaterial placed on its surface, and the maximum strain (total deformation) would be with an operator standing in the centre of the slat. The stress and strain (total deformation) limits for both situations are shown in Fig. 3a–d.

The stress limit for the inner PVC slat was calculated by assuming a safety coefficient of 1.25. The result was 45.6 MPa, which is considerably higher than the stress limit of 6.04 MPa and 5.99 MPa calculated for the cases of the loaded biomaterial and with the operator standing in the centre, respectively. Bearing in mind that the calculated stress limit is seven times lower than the PVC stress limit, it was estimated that a bed (biomaterial) height of 80 cm (1943 kg) could be loaded onto each platform within the safety limit.

As far as the strain limit is concerned, the highest value of 8 mm was obtained for the operator standing in the centre. Although this value was acceptable, minimal strain was sought for safety reasons. Consequently, the inner slat was redesigned by adding a 30-mm width rib beneath the surface. Thus, four rib heights of 50 mm, 100 mm, 150 mm and 200 mm were tested, bearing in mind the limitation of the manholesd́imensions and weight. The stress and strain limits were calculated again, and the results are shown in Table 2. The strain limit for the 50-mm option was still too high, even if the stress limit was considerably lower than the value calculated in the previous section. The lowest strain limit was obviously obtained for the 200-mm ribbed slat, but the 8.76 kg increase in the part's weight meant a 1.2 kg increase per 1-mm reduction. The other two options (100 and 150 mm) were compared on the basis of the increase in the weight ratio and the reduction in the strain limit. The ratio was 0.81 kg mm^{-1} and 0.98 kg mm^{-1}, respectively, which showed that the 150-mm rib was the best option, with an acceptable strain limit of 2.3 mm (considerably lower than the original value of 8 mm).

Fig. 4 shows the simulation of the strain and stress distribution in the 150-mm inner ribbed slat for the load situation and with the operator in the centre. As expected, the troublesome area is in the centre of the slat (Fig. 3b & d), but the strain limit is 1.2 mm for the load situation and 2.3 mm for the operator, accounting for a reduction of 85 % and 71 % respectively. The stress limit is 1.33 MPa for the load situation, being similar to the 1.56 MPa value for the operator.

As far as the outer slat is concerned, when the 150-mm rib was included into the part's original design, the stress limit with the operator decreased from 4.72 MPa (original value) to 1.91 MPa, and the strain limit from 5.2 mm (original value) to 1.8 mm, recording a 65 % reduction in strain (figures not included).

3.2. Stress and strain on the lower ring

Each one of the three ring sets consisted of two whole rings (upper and lower rings) and the screw for attaching the legs. Each ring was divided into two pieces (four half-rings) (Fig. 5). The three slat platforms on the scrubber/bioreactor were supported by introducing the edge of the slats into the space between the upper and lower rings.

Two ring set types were distinguished. The ring set on the top level was supported only by the legs below, but the other two were held by the legs above and below (Fig. 5). The holding systems made a difference in the calculation of the stress and strain limit on the lower half-ring, as shown in Table 3. The most unfavourable values obtained for the holding system below (supported by legs

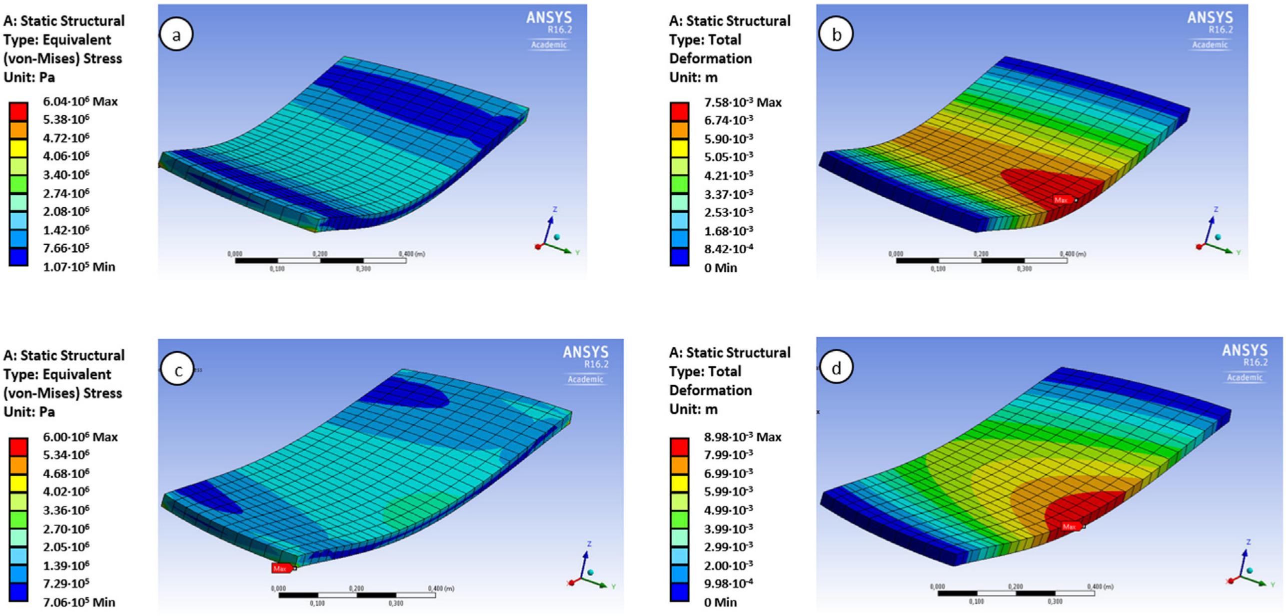

Fig. 3. Stress and strain on the inner slat: a & b, respectively, when the sacks of biomaterial are loaded; and c & d, respectively, when the operator stands in the centre.

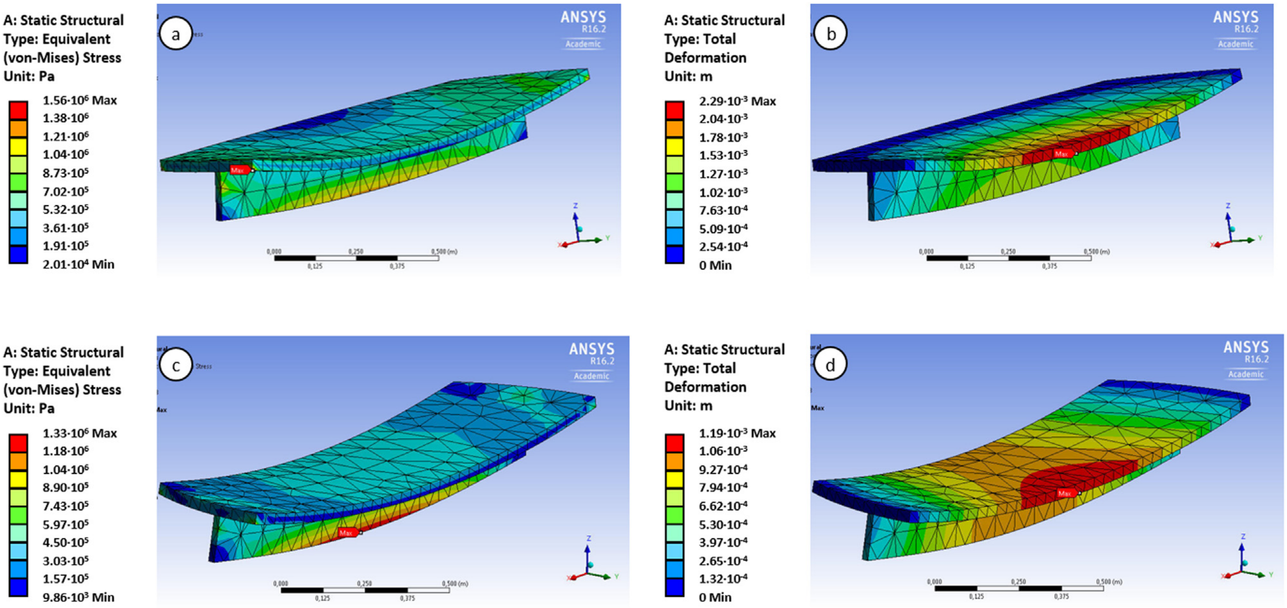

Fig. 4. Stress and strain on the 150-mm inner ribbed slat: a & b respectively, when the biomaterial is loaded; and c & d respectively, when the operator stands in the centre.

Table 3
Weight and stress and strain limits for the lower half-ring.

Case	Weight (kg)	Stress limit (MPa)	Strain limit (mm)
Holding system above and below	35.35	11.61	3.8
Holding system below	35.35	69.15	19.6
Holding system below and 50 mm rib height	40.44	94.85	20.9
Holding system below and 100 mm rib height	45.52	94.35	20.8

below) (69.15 MPa and 19.6 mm for the stress and strain, respectively) required its redesign (Fig. 5). Thus, the lower half-ring was fitted with a rib to improve its rigidity. The rib was divided into three pieces to keep two free spaces (holes) for the legs (Fig. 6a). The rib section was attached at 30 mm, being the same section as in the slat ribs. Two lengths were studied for the rib: 50 and 100 mm. The weight increase for the rib addition was only 5.09 kg, but the stress limit increased considerably, reaching a value of around 94 MPa, and the strain limit was also high (about 21 mm) (Table 3).

According to the ANSYS calculations, the highest stress appeared in the area around the holes for the legs. Consequently, the next step involved modifying the lower half-ring by reinforcing the hole area. Thus, a PVC cylinder was fitted to the leg holes, as shown in Fig. 6b. The two lengths (50 and 100 mm) were studied again, and the results revealed that in both cases the strain limit was very similar (16.2 and 16.4 mm, respectively). Nevertheless, the stress limit was 52.84 MPa for the 50-mm modification (with a weight of 42.14 kg), and 47.49 MPa for the 100-mm modification (with a

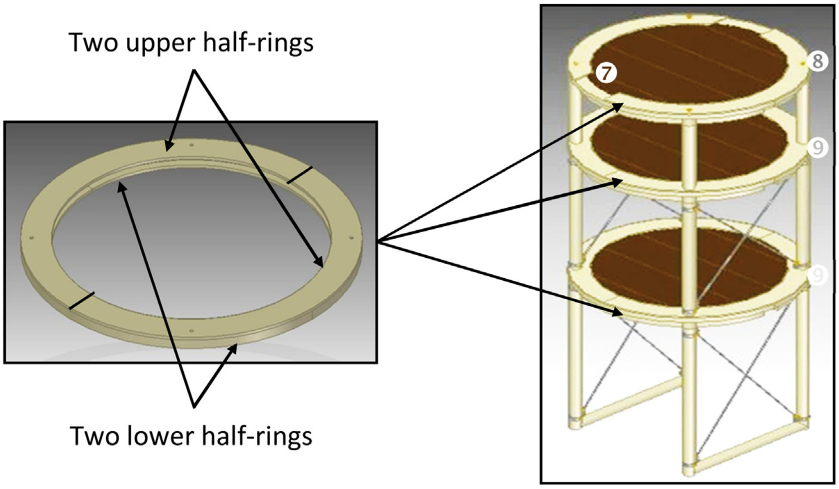

Fig. 5. Layout of the upper and lower rings composed of four half-rings and their position in the structure. The edge of the slat is introduced in the internal space of the ring (7) to fasten it. The upper level ring (8) is supported by legs below, while the intermediate and base levels (9) are supported by legs above and below.

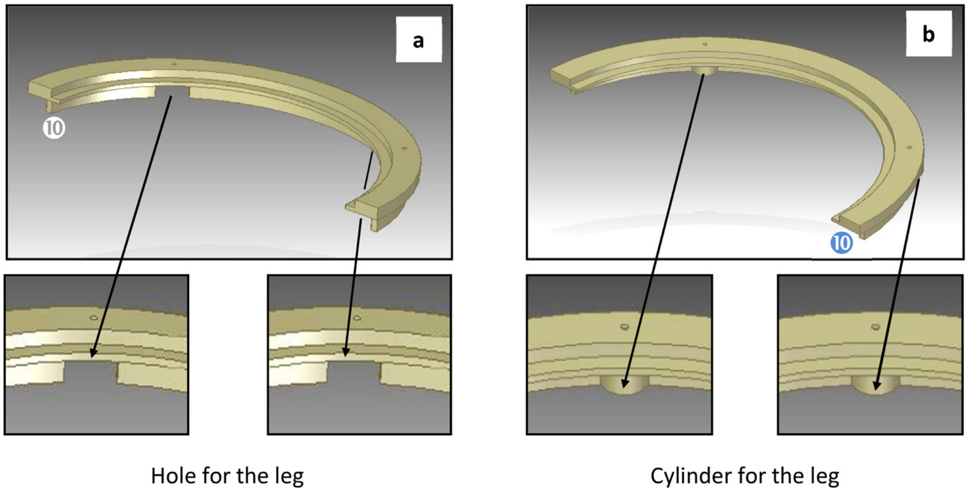

Fig. 6. The consecutive design of the lower half-ring (holding system below) reinforced with ribs (10): (a) the ribbed design with the holes for the legs; (b) the ribbed design with the cylinders for inserting the legs.

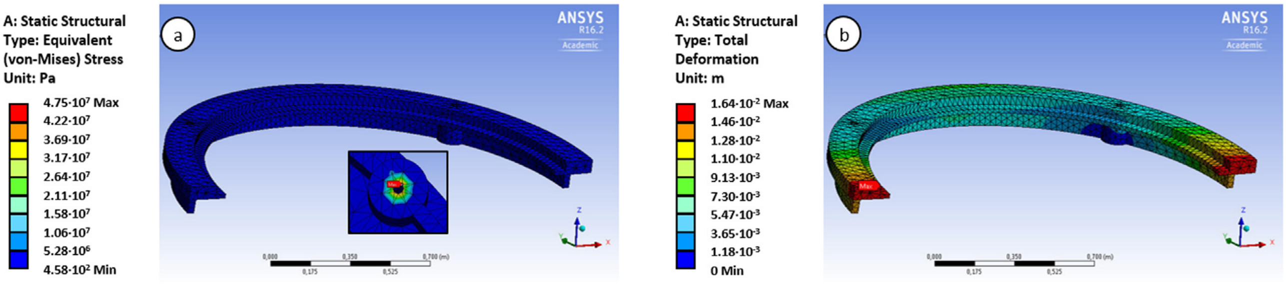

Fig. 7. Stress (a) and strain (b) on the lower half-ring with the modified design (100 mm, and holding system below).

weight of 48.93 kg). The latter result was close to the stress limit for the PVC (45.6 MPa), but if the rib length exceeded 100 mm, the strain limit and the weight would increase accordingly. Thus, the 100-mm rib was selected, and the stress and strain limits for the lower half-ring with the holding system below and with the cylinder are shown in Fig. 7.

After designing the most unfavourable option (lower half-ring with holding system below), the same parameters were checked for the system of holding above and below (Fig. 8). In this case, the stress limit was as low as 5.30 MPa, and the strain limit was 1 mm, with a reduction of 54 % and 73 % in both parameters, respectively, compared to the original results shown in Table 3.

3.3. *Compression stress on the base legs*

The partial and total weight supported by the legs at base level was considered for the compression stress calculation, taking into account the highest loaded stress case. The results are shown in Table 4. The total weight supported by the four 2.1-metre legs at the base was 1613.5 kg (including the biomaterial on the three lev-

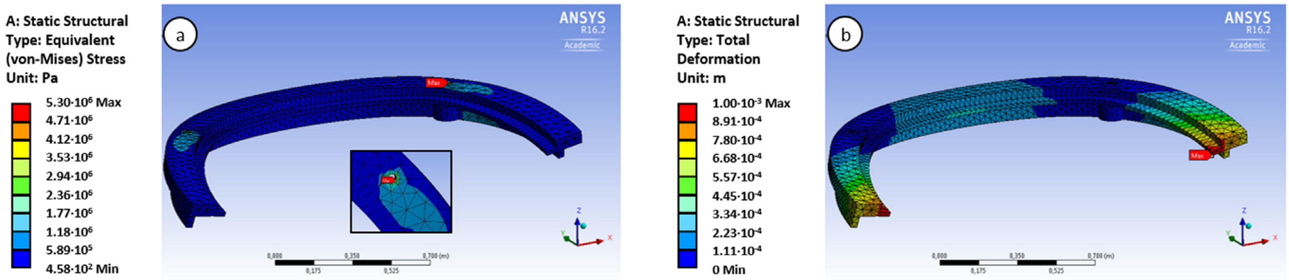

Fig. 8. Stress (a) and strain (b) on the lower half-ring with the modified design (100 mm, and holding system above and below).

Table 4
Weight distribution in the structure and total weight supported by each leg at the base level.

Element	Weight (kg)
Upper level (without biomaterial)	292.5
Intermediate level (without biomaterial)	334.7
Lower level (without biomaterial)	257.4
Packing material at each level	242.9
Total weight	1613.5
Weight supported by each leg at the base	403.4

els), which rendered an average weight of 403.4 kg per leg. The compression stress was calculated at the top of the leg, where the 1-cm radius hole for the screw could have a negative influence. The leg radius was 4 cm. The compression stress on each leg was as low as 0.525 MPa, while the PVC yield stress was 57 MPa. It was concluded that the base legs could support the weight with a very wide safety margin, allowing the addition of more sacks of biomaterial to increase bed height, if required.

3.4. Buckling on the base legs

This calculation was carried out assuming that the base legs had two support points (one at the bottom of the scrubber (stops) and the other one at the ring), so the buckling distance was the leg length (2.1 m). The critical pressure to be withstood was as high as 32904 N, while the calculated pressure on each leg was 3 971 N (15884 N for the four legs). It was concluded that the pressure supported was 48 % of the critical one, reducing the probability of buckling to a minimum.

3.5. Feasibility study

A feasibility study involves different types of analysis, with the main ones being technical, operational, economic, environmental, safety, social, political and financial studies. The technical and operational feasibility of substituting a chemical treatment by a biological one is designed to verify whether the converted biofilter will be an efficient odour abatement technology in the WWTP and whether it will perform even better than the currently installed chemical scrubber.

A comparative study on odour abatement efficiencies between scrubbers and biofilters showed that biofilters achieved a better performance (Schenk et al., 2009). In recent studies, Alinezhad et al. (2019) clearly demonstrated the effectiveness of both chemical scrubbers and biological treatments in abating waste gases containing H_2S and NH_3 at a municipal WWTP. Alfonsín et al. (2015) estimated a reduction of 98 % (biofilter) and 99 % (chemical scrubber) in the potential of malodorous air for the typical emissions from WWTPs (50,000 m^3/h, including 30 different VOCs, methanethiol (1 ppm) and H_2S (15 ppm). Similarly, when a high performance biofilter replaced the previous physicochemical deodorisation system at a WWTP in Galindo (Spain), an increase of up to 95 % in the removal efficiency of the odour present in the treated air has been reported (Consorcio de Aguas Bilbao Bizkaia, 2015). It is noteworthy to mention that biofilters have the advantage of effectively treating low concentrations of contaminants in off-gas streams at WWTP, whereas scrubbersṕerformance is low at those concentrations.

From an occupational safety standpoint, if one of the chemical scrubbers installed at the Orduña WWTP were converted to a biofilter, an EBRT of 24 s could be achieved with the maximum height of packing material (80 cm) onto each of the three platforms. In this case, the minimum allowed flow rate (1150 m^3/h) for the incoming gas would not risk the safety of the workers at the WWTP, since the H_2S and NH_3 concentrations in the air (14 mg/m^3 and 2.8 mg/m^3, respectively) would be below their short-term exposure limit (STEL) (European Commission, 2000, 2009). Studies done on simultaneous removal of H_2S and NH_3 with typical concentrations emanating from WWTPs using biofilters at low EBRTs show efficiencies greater than 90 % for both gases (Table 5).

In terms of economic viability, the fact of not having to construct a new building for the biofilter is a positive point taking into account that investment costs associated to biofiltration are usually highest in comparison with other deodorizing technologies, such as chemical scrubbing or activated carbon absorption, which are traditionally installed even if the operating expense (e.g., maintenance and running costs) is significantly higher (Gao et al., 2001; Nadal et al., 2015).

The investment costs for the conversion of the scrubber have been calculated assuming that the scrubber structure could not be modified, the piping and watering systems have already been installed, and PVC has been used to make the individual redesigned pieces (except for the cross bracing and the screws) to prevent corrosion. Table 6 lists the costs of the parts and the installation, including the packing biomaterial. The parts (€22846) account for 74.4 % of the total investment costs (€30703), and the installation costs account for 16.3 %.

Devinny et al. (1999) and Prado et al. (2009a) (2009b) estimated that the costs of piping, electrical work and equipment installation account for 10 %, 4%, and 4%, respectively, of the total investment of a new compost-based open-bed biofilter with an inlet airflow rate of 20000 m^3/h, a packing material volume of 400 m^3, and EBRT of 60 s. Nevertheless, those costs have not been considered in this study because they have already been accounted for in the facility. Miscellaneous costs in Table 6, estimated as 10 % of the total investment, include insurances, taxes, spare parts, default parts, etc., in contrast to Prado et al. (2009a) (2009b), who estimate a figure of 5 % of the total.

The average annual consumption of commercial chemicals for the operation of the two scrubbers is approximately 3000 kg sodium hypochlorite (NaOCl, 13 % w/w), 500 kg sodium hydroxide (NaOH, 25 % w/w), and 300 kg sulfuric acid (H_2SO_4, 38 % w/w). The average costs of the chemicals (taxes included) are 1.01 €/kg for NaOCl, 1.36 €/kg for NaOH, and 1.01 €/kg for H_2SO_4

Table 5
Comparison of operating conditions and results with previous studies regarding H_2S and NH_3 biofiltration.

Packing media	Bed height (m)	Bed volume (m^3)	[a]IC (H_2S; NH_3) (mg/m^3)	Gas flow rate (m^3/h)	[b]EBRT (s)	[c]RE (H_2S; NH_3) (%)	Reference
Biodehydrated compost	1.2	~0.031	200–250; 100–150	10	11.3	>95; ~100	Hou et al., 2016
Organic mixture[d]	0.3	0.06	58–72; 4–6	~119	1.8	89; 80	Karuchit and Rakthaisong, 2018
ABB media[e]	3·(0.47)	~0.025	40; 1.35	3	27.08	~92; 100	Rabbani et al., 2016b

[a] IC = inlet concentration.
[b] EBRT = empty bed residence time.
[c] RE = removal efficiency.
[d] Organic mixture composed of compost:chopped coconut shell:dried cow manure:dried wastewater treatment plant sludge at 60:20:10:10 ratio.
[e] ABB media = AMB Biomedia Bioballs (acid resistant polyethylene).

Table 6
Investment costs for the construction of a biofilter inside a chemical scrubber.

Pieces	Units	Cost per unit (€)	Total cost (€)
Modified half-rings	12	569	6828
Ribbed Slats	12	497	5964
Legs	12	445	5340
Stops	2	390	780
Clamps	16	130	2080
Steel cross bracings	–	–	1334
Standard screw	104	5	520
SUBTOTAL			22846
Sacks of biomaterial (25 kg each)	33	2	66
Installation			5000
SUBTOTAL			27912
Miscellaneous costs (10 % of the subtotal)			2791
TOTAL			30703

(VADEQUIMICA, 2020), amounting to a total annual cost of approximately €2978. In comparison to the scrubber conversion's initial investment cost, the annual saving is 9.7 % of the total, rendering an amortisation period of around 10 years.

The average yearly water consumption in the chemical scrubbers does not account for a significant share of the operating cost, but it increases the environmental impact of the chemical treatment compared to the biofilter, where low water quality requirements permit the use of recycled water for regular irrigation (Estrada et al., 2013). Estrada et al. (2012) have calculated that the average operating costs for a biofilter are 2.0 €$(m^3/h)^{-1}$ for treated air, in contrast to the chemical scrubberś figure of 3.6 €$(m^3/h)^{-1}$. In addition to the economic analysis, Cano et al. (2018) have reported the Life Cycle Assessment of different physicochemical and biological technologies for biogas desulfurisation in WWTPs, concluding that biological technologies are much more expedient in most environmental impact categories than physicochemical ones.

Nevertheless, besides the saving in costs, another significant advantage is the improvement in the health and safety of personnel at the facility, along with the additional savings in chemical risk management (safety feasibility). Chemical risk management includes the policies, training, documentation and funding required to guarantee chemical safety and security programmes throughout the chemicals' life cycle. If the use of chemicals is to be avoided at the WWTP, chemical risk management needs to be greatly simplified, with no application of the European Agreement concerning the International Carriage of Dangerous Goods by Road (ADR - in force since April 1985, and revised in January 2015) (UNECE, 2015). This agreement stipulates that the facility employer has a legal responsibility to protect the health and safety of its staff and the environment. It must therefore assess the risks associated with the chemical storage facility, implement the appropriate preventive measures, control their effectiveness on a regular basis, and ensure their maintenance. Compulsory Personal Protective Equipment (PPE), including impervious gloves, boots, apron and eye goggles for handling highly corrosive sulfuric acid and others, is not needed when operating biofilters, and the risk of an emergency or accidental spillage is considerably reduced. Workers should receive pre-employment and periodical medical examinations, and be trained and prepared to deal with risk situations when handling dangerous chemicals. All these requirements are unnecessary when operating a bioreactor.

In addition to the ADR, Spain's Royal Decree (RD) 393/2007 establishes that any facility that might trigger emergency situations should draft, implement and register a self-protection plan (BOE, 2007), which is a document that analyses the emergencies that could arise from a facilityś activity and the response measures to be adopted in risk situations. This document is to be approved by the authorities and reviewed periodically (every three years). WWTPs using chemical scrubbers are required by law to have their own self-protection plan, which implies deploying the technical and human resources to comply with the aforementioned RD. The substitution of the scrubber by a biofilter thus considerably improves the WWTP's health and safety and sustainable performance, consequently reducing the risk and budget for chemical consumption and prevention.

4. Conclusions

Physicochemical and biological technologies are competitive alternatives for odour abatement in WWTPs, although the latter have only been implemented more recently. The strength of the chemical treatment is the robustness of this mature alternative, while the advantages of the biological option are improved sustainability and lower risk.

Chemical scrubbers and biofilters could be "exchangeable" from a technical and operational point of view, requiring a comprehensive design of the mechanical adjustment on a case-by-case basis, in addition to an assessment of the investment. A mechanical assembly for constructing a modular bioreactor inside a chemical scrubber without altering the original structure has been proposed here. The biofilterś main parts were designed in PVC, and the structure consisted of three round platforms (174 cm diameter), each one divided into four slats, three double half-rings for holding the slats, and legs for supporting the platforms at three levels (in addition to the ancillary material, such as screws and clamps). The analysis of the partsśtress and strain limits was carried out by bearing in mind two cases: when the packing material is loaded and operating, and when an 80-kg person stands in certain parts, with the latter being the most unfavourable situation. The results revealed that the main parts of the three-level structure (inner slats and half-rings) need to be reinforced, with the consequent redesign of the new ribbed pieces. The 150-mm rib was the best option, with an acceptable strain limit of 2.3 mm, being considerably lower than the original value of 8 mm. It was also concluded that the base legs could support the weight with a very wide safety margin, allowing the addition of more sacks of biomaterial to increase bed height if required. The pressure borne by the four base legs was 48 % of the critical value, reducing the probability of buckling to a minimum.

As far as the viability study is concerned, the savings from the elimination of chemical consumption were calculated and compared to the investment cost. The annual saving was low in terms of the assembly's initial investment cost (about 9.7 % of the total cost). Nevertheless, it is important to note that the feasibility of converting a chemical scrubber into a bioreactor should focus on the improvement in sustainable performance and safety (reducing the budget for prevention), rather than exclusively on the savings in chemical consumption.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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