



Multipoint characterization of the emission of odour, volatile organic compounds and greenhouse gases from a full-scale membrane-based municipal WWTP

Daniel González^{a,b}, Joan Colón^c, Antoni Sánchez^a, David Gabriel^{b,*}

^a Composting Research Group (GICOM) Dept. of Chemical, Biological and Environmental Engineering, Universitat Autònoma de Barcelona, 08193, Bellaterra, Barcelona, Spain

^b Group of Biological Treatment of Liquid and Gaseous Effluents (GENOCOV) Dept. of Chemical, Biological and Environmental Engineering, Universitat Autònoma de Barcelona, 08193, Bellaterra, Barcelona, Spain

^c BETA Technology Centre: "U Science Tech", University of Vic-Central University of Catalonia, 08500, Vic, Barcelona, Spain

ARTICLE INFO

Keywords:

Wastewater treatment plant (WWTP)
Gaseous emission
Volatile organic compounds (VOC)
Emission factors

ABSTRACT

Different environmental and social concerns can arise due to the generation of gaseous emissions during the treatment of urban wastewater. However, there is not an extensive knowledge about which are the main potential odour and greenhouse gas (GHG) emission sources in a wastewater treatment plant (WWTP) and their variability. In this study, a multipoint characterization of the gaseous emissions generated in a full-scale municipal WWTP located in Barcelona was conducted, aiming at identifying the main odour and GHG emission sources. The WWTP under study treats an average inlet flow of 33,000 m³ d⁻¹ using a Ludzack-Ettinger system with Membrane BioReactor (MBR) technology, and it has installed a gas capture and treatment system consisting of a biotrickling filter followed by a conventional biofilter to treat part of the off-gases produced during the wastewater treatment. For this work, gaseous emissions characterization campaigns were conducted to assess the proper performance of the gas treatment unit and to estimate the emission factors referred to odorants and GHGs for the different emission sources and to assess the proper performance of the gas treatment system. Besides, a chemical characterization of the different volatile organic compounds (VOC) present in the gaseous emissions was performed through TD-GC/MS. The main potential odour sources were the reception tank, the barscreens building and the primary settler, where odour concentrations were in the range of 1300 and 2600 ou·m⁻³. Moreover, GHG emissions were found during the primary treatment and in the MBR units, ranging from 2.21 to 68,217.13 mg CO_{2eq}·m⁻³. Different VOCs such as aromatic hydrocarbons, alkanes and ketones were found in the gaseous emissions with a high variability among all the emission sources. The results obtained are valuable indicators that can be used to develop odour and GHG mitigation strategies in WWTPs and to estimate the environmental impact of these facilities.

1. Introduction

The treatment of urban wastewater is well known and extended around European countries. Different technologies or strategies can be used to treat urban wastewater, all with the inherent drawback of generating solid and gaseous wastes in the course of the applied treatments (Gostelow et al., 2001). Gaseous streams are the main responsible for air pollution, mainly in the form of odour, which can have great impact over the population in the vicinity of wastewater treatment

plants (WWTPs) (Frechen, 1988). These gaseous emissions are characterised by the presence of a large number of volatile organic compounds (VOCs) at trace level concentrations, together with volatile sulphur compounds (VSCs), hydrogen sulphide and ammonia, which are the main responsible for odour nuisance (Gostelow et al., 2001; Lebrero et al., 2011).

Odour emissions are one of the major concerns for local authorities due to the nuisance generated to the WWTP's surrounding neighbourhoods. Responses to them are highly variable and although they are not

* Corresponding author. Group of biological treatment of liquid and gaseous effluents (GENOCOV) Dept. of Chemical, Biological and Environmental Engineering, Universitat Autònoma de Barcelona Bellaterra, 08193, Spain.

E-mail address: david.gabriel@uab.cat (D. Gabriel).

<https://doi.org/10.1016/j.jenvman.2022.115002>

Received 26 November 2021; Received in revised form 2 March 2022; Accepted 29 March 2022

Available online 4 April 2022

0301-4797/© 2022 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY license (<http://creativecommons.org/licenses/by/4.0/>).

a direct cause of human disease, long exposure to these odorants can have adverse effects on people's life quality, causing nausea, headaches, insomnia and/or irrational behaviour (Lebrero et al., 2011; Zarra et al., 2008). Main odour and odorants generation stages along the wastewater process have been identified as the wastewater collection, its transfer and its treatment (Carrera-Chapela et al., 2014). During this stages, many different compounds can be formed and emitted due to diverse reasons such as: i) the development of anoxic conditions in sewers leading to hydrogen sulphide and sulphur-based organic compounds formation and emission (Dincer and Muezzinoglu, 2007), ii) the turbulence generated at the reception tank of WWTP leading to the strip and volatilization of compounds formed during the wastewater transportation, iii) sludge treatment where anaerobic conditions can form new odorants or iv) sedimentation tanks where the calm flows and large surfaces may promote the emission of compounds previously formed during the wastewater treatment. Different techniques have been applied in order to characterize and to assess odour impact from WWTP: high performance analytical techniques as gas chromatography coupled to mass spectrometry (GC/MS) for the identification and quantification of odorants or sensorial techniques such as dynamic olfactometry (Comité Européen de Normalisation, 2003) or the use of portable devices such as the Scentroid SM-100 olfactometer or the Nasal Ranger® (Kulig and Szyłak-Szydłowski, 2019), which are capable of quantifying odours in terms of intensity and/or concentration. This is better related to the sensation perceived by a human receptor (Capelli et al., 2013a; González et al., 2019a). Moreover, new approaches have been developed in the direction of using multisensory arrays (often called eNoses) based on combination of specific and non-specific sensors to relate different odorants concentrations with odour concentration obtained from sensorial analysis such as dynamic olfactometry, with the final aim of obtaining an analytical device capable of substituting human noses and enhancing continuous field monitoring (Brattoli et al., 2011; Zarra et al., 2014).

However, not only odorants can be found in the gaseous emissions generated during the wastewater treatment. Greenhouse gases (GHGs) such as carbon dioxide, nitrous oxide or methane can be formed and emitted during the biological processes that take place during organic matter and nutrient removal (Massara et al., 2017). Normally, CO₂ is produced during the wastewater treatment by the respiration of the microorganisms that degrade organic matter, which concerns short-cycle CO₂. As the CO₂ generated is predominantly biogenic and therefore climate neutral, it is not usually included in the CO₂-balance (Parravicini et al., 2016). On the other hand, N₂O and CH₄ are expected to be produced and emitted during the biological organic matter and nutrient removal along the wastewater treatment, either through nitrification and subsequent denitrification or in those parts of the WWTP where anoxic/anaerobic conditions prevail, such as sewers or process units related to sewage sludge treatment (Daelman et al., 2012, 2013; Rodriguez-Caballero et al., 2014). Moreover, in terms of global warming potential (GWP), both nitrous oxide and methane represent much higher environmental impact than carbon dioxide. In the case of N₂O, the last IPCC report fixed its GWP in 265 times the one of CO₂ in a 100-year time horizon, whereas in the case of CH₄, its GWP was fixed as 28 times the one of CO₂ in the same 100-year time horizon (IPCC, 2014).

In the direction of assessing the environmental impact of WWTPs, the estimation of the emission factors for specific pollutants as well as for odour is important, as it gives the first information about the quantity of each of them that is being emitted during a treatment process. The emission factors were defined by the US Environmental Protection Agency (USEPA) as the factors that relate the quantity of a pollutant released to the atmosphere to a specific activity related to the release of that pollutant, such as the plant's average wastewater inflow or the emitting surface amongst others (USEPA, 1995). Analogously, in the past years a similar methodology has been developed to assess the odour impact of different facilities by the use of the so-called odour emission factors (OEF) (Capelli et al., 2009; Sironi et al., 2005, 2006). Moreover,

the determination of emission rates and emissions factors of specific pollutants and odour are valuable information that can be further used to determine the environmental impact of a specific facility by applying Life Cycle Analysis and dispersion modelling (Carrera-Chapela et al., 2014). This information can be helpful in different scenarios such as to understand the potential nuisance on the surroundings of an actual WWTP, to predict the effect on the surroundings of an operating WWTP by any process modification or even to estimate the potential impact on the surroundings of a new WWTP before its construction (Capelli et al., 2009).

Several works have reported emissions from different WWTP configurations, focusing mainly on specific pollutants. For example, Daelman et al. (2013) and Masuda et al. (2015a) performed long-term studies to assess emissions of methane and nitrous oxide from two different full-scale WWTP with an activated sludge process, pointing out the seasonal variability present on these emissions. On the other hand, the emission of volatile organic compounds has been studied by different authors such as Li et al. (2021b, 2021a), who showed the evolution of the emission of different volatile sulphur compounds along the wastewater treatment in an A²/O process. However, there is a lack of studies that integrates global characterization of gaseous emissions from entire WWTPs. In this sense, the present work provides a comprehensive analysis of gaseous emissions (GHG, VOCs, odorants and odour) in a WWTP with a particular configuration including membrane-based biological reactor. The aim of this work was to identify and characterize the critical emission sources present in the studied WWTP before the installation of a gas capture and treatment system and to verify the proper performance of this gas treatment system once installed. Subsequently, a characterization in terms of odour and odorants (mainly NH₃, H₂S and total VOCs), specific VOCs and GHGs emission was conducted to reveal the actual gaseous emissions generated during the wastewater treatment in this specific full-scale plant, which can be helpful information for future environmental impact assessment studies.

2. Materials and methods

2.1. Description of the wastewater treatment plant

The experimental site was an opened full-scale urban wastewater treatment plant located in Barcelona. The WWTP treats an average wastewater inflow of 33,000 m³ d⁻¹ with an average COD, TKN and P inlet concentrations of 600 mg O₂-L⁻¹, 92 mg TKN-L⁻¹ and 11 mg P-L⁻¹, respectively. By using the Ludzack-Ettinger configuration with a membrane bioreactor Technology (MBR), the WWTP accomplishes the specific discharge legislation, reducing COD, TKN and P concentrations at the effluent in a percentage of 88%, 87.5% and 82%, respectively. The study of the gaseous emissions was held between the years 2014 and 2018. Initially (2014), the WWTP did not count with an off-gases capture and treatment system, which was installed and started up in 2016. Before its installation, an identification and characterization of the most relevant emission sources of the WWTP was performed. Afterwards, the proper performance of the gas capture and treatment system was verified by checking the removal efficiency of the treatment train and by characterizing the current gaseous emissions of the WWTP in terms of odours, total and specific VOCs, NH₃, H₂S and GHGs.

A scheme of the current WWTP is presented in Fig. 1, and all the treatment units under study are listed in Table 1. Briefly, the WWTP consists of a wastewater primary treatment with a reception tank, barscreens, a grit chamber and a primary settler, followed by a second step of biological removal of organic matter and nutrients using a Ludzack-Ettinger process with an MBR. Finally, the sludge generated is treated using two sludge thickeners before entering an anaerobic digester (AD). The digestate produced in the AD is further centrifuged in a dehydration building. On the other hand, in 2016, the gas treatment system was designed and installed to treat 13,000 m³ h⁻¹ of the off-gases collected from the reception tank, the water screw, the barscreens

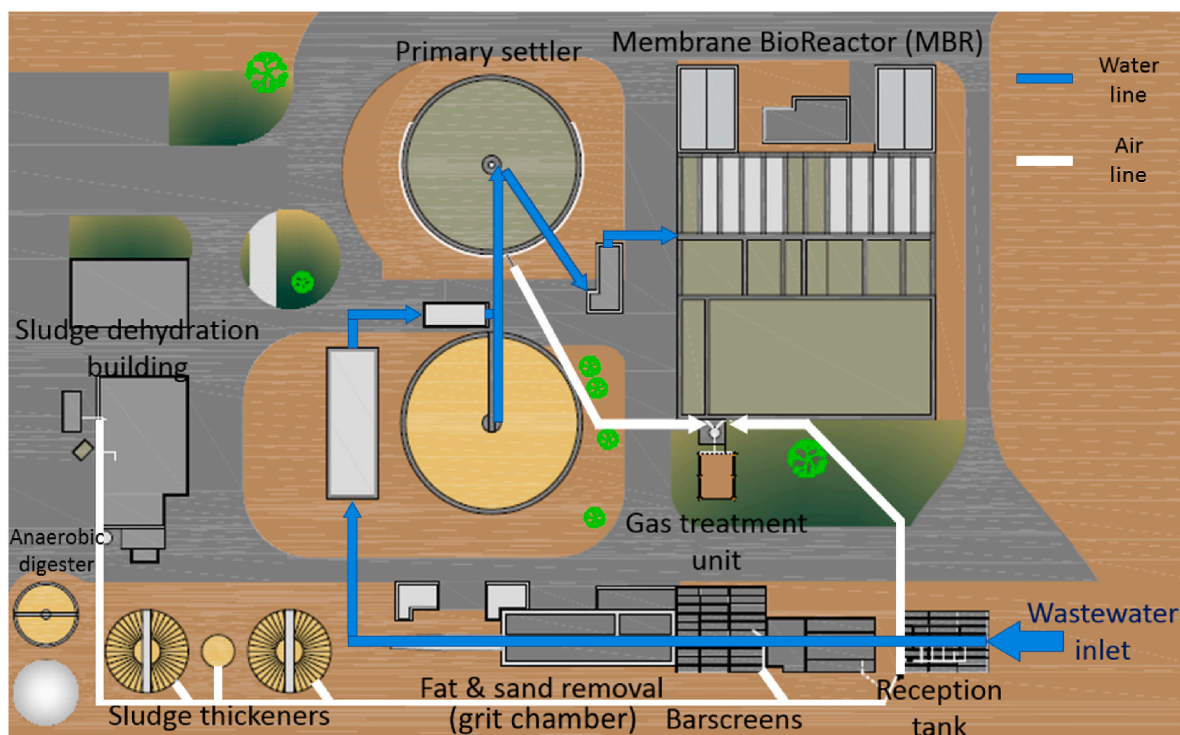


Fig. 1. Scheme of the wastewater treatment plant and the different sampling points defined (in blue lines: the wastewater line; in white lines: the gas line to the gas treatment system). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 1

Treatment units monitored during the study (Y: monitored; N: not monitored).

Treatment unit	Monitored 2013–2014	Monitored 2018
Reception tank – Inlet	Y	Y
Barscreens – Inlet	Y	N*
Barscreens – Outlet	Y	Y
Fat & sand removal (grit chamber)	Y	Y
Primary settler	Y	Y
MBR aerated	N	Y
MBR non-aerated	N	Y
Sludge thickener A	Y	N*
Sludge thickener B	Y	N*
Sludge dehydration building A	Y	Y
Biotrickling filter – Inlet A	N	Y
Biotrickling filter – Inlet B	N	Y
Biotrickling filter - Outlet	N	Y
Biofilter - Outlet	N	Y

*Covered with GRFP at that moment

building, the sludge thickeners, the primary settler overflow and the dehydration building. These treatment units were covered with fiberglass reinforced plastic (FRP) and different gas caption blowers were installed to drive the off-gases to the biological gas treatment system. The gas treatment system consists of a biotrickling filter (BTF) followed by a biofilter (BF). The BTF has a total volume of 33 m³, using RVT Bioflow 401 rings as packing material, targeting the biological removal of H₂S of the gas stream (designed for a total load of 79 g H₂S·m⁻³·h⁻¹ with an empty bed retention time of 4.5 s). A conventional biofilter (BF) of 90 m³ with an empty bed retention time of 24.4 s and shredded poplar wood as packing material targets the removal of any remaining H₂S and basically the VOCs carried out in the gas stream.

2.2. Gas sampling procedure

Six sampling campaigns were distributed between October 2013 and September 2014 for the determination of the most relevant emissions

sources present in the WWTP before the installation of the gas treatment system, whereas four sampling campaigns were carried between April and August 2018 to verify the proper performance of this gas treatment system once installed. During the sampling campaigns performed during 2013–2014, a gas sample was obtained from each of the units listed in Table 1 for total volatile organic compounds (tVOCs), NH₃ and H₂S emission determination as described in the following sections. On the other hand, during the sampling campaigns carried out during 2018 a gas sample was obtained from each of the units under study (Table 1) for the determination of tVOCs, NH₃ and H₂S emission, GHGs emission, odour emission and VOCs distribution as detailed in the subsequent sections.

All the emission sources registered in this study were defined as area emission sources. As reported by different authors (Capelli et al., 2009; Laor et al., 2014), the determination of odour flow from area sources requires the use of sampling hoods such as flux chambers or wind tunnels in order to simulate environmental conditions to which the emission sources are normally subjected. In this case, the flux chamber (FC) methodology, which is recommended by the USEPA (USEPA, 1986), was used to obtain the different samples for further odour, methane and nitrous oxide concentration measure and VOCs characterization. The FC used (Scentroid, IDES Canada Inc., Whitchurch-Stouffville, ON, Canada), was a semi-spherical stainless-steel FC (0.443 m, 0.154 m², 0.045 m³ of base diameter, base area and volume, respectively) equipped with stainless steel fittings and Teflon™ tubing. Pure nitrogen was introduced inside the FC at a flow rate of 4.5 L min⁻¹ during 25 min, which represented about 3 FC residence times, to reach constant concentrations inside the FC before sampling. Eight litter Nalophan® bags, a hermetic sampling drum and a vacuum pump were used to obtain the gaseous samples avoiding cross-contamination (Capelli et al., 2013a), as shown in Fig. 2.

Adsorption stainless steel tubes packed with two different hydrophobic sorbents (Tenax® TA and Carbograph™ 1TD, Markes International, Inc., Gold River, CA, USA) were used to obtain gaseous samples for VOCs characterization as detailed by the USEPA TO-17 method and

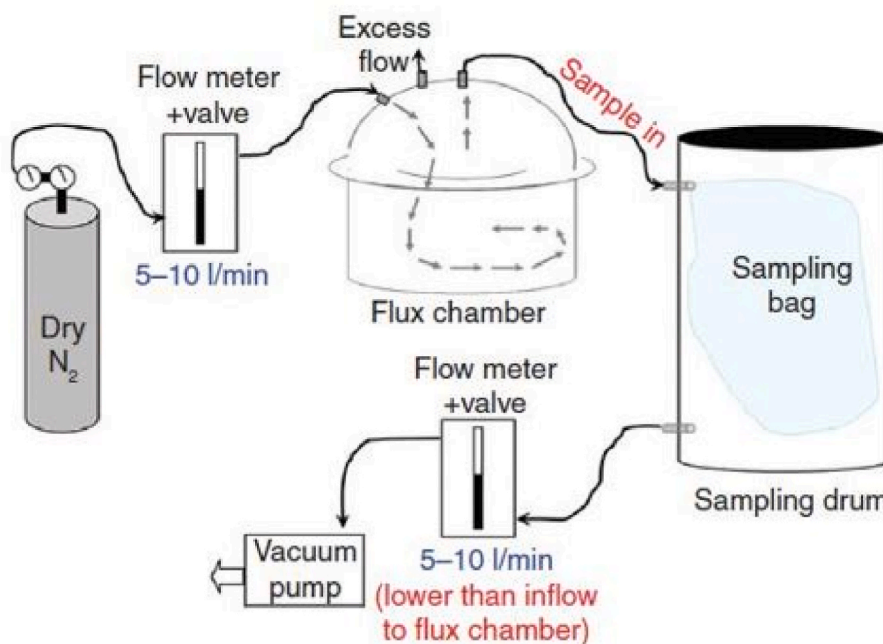


Fig. 2. Gas sampling from an area source using the USEPA flux chamber methodology.

elsewhere (González et al., 2019b; Ramírez et al., 2011; USEPA, 1999). A volume of 1 L of each specific gaseous sample retained in the Nalphan® bags was pumped through an adsorption tube by means of an Easy-VOC manual sampling pump (Markes International, Inc., Gold River, CA, USA) to retain the different VOCs. According to the tubes' maker, the sorbents packed in the adsorption tubes are able to retain a high range of VOCs, from polar to non-polar compounds such as aromatics compounds, ketones, aldehydes or alcohols. All the adsorption tubes used for retaining the different gaseous samples were sealed with Swagelock end caps fitted with PTFE ferrules and stored at 4 °C until the moment of analysis in the lab.

2.3. Analytical methodology

2.3.1. Odorant compounds

The determination of ammonia, tVOCs and hydrogen sulphide concentration was obtained using different portable analysers. NH₃ and H₂S concentration were measured by means of an iBrid™ MX6 multi-gas monitor (Industrial Scientific Corporation, Pittsburgh, PA, USA), which had installed an electrochemical sensor for NH₃ measurement with a detection range from 0 to 500 ppm_v of NH₃ and a resolution of 1 ppm_v, and an electrochemical sensor for H₂S measurement with a detection range from 0 to 500 ppm_v of H₂S and a resolution of 0.1 ppm_v. For the calibration of each sensor, specific NH₃ and H₂S standard calibration gases of 25 ppm concentration were used (Calgaz™, TX, USA). tVOCs concentration was determined using a portable MiniRAE 3000 photoionization detector (PID) (RAE Systems, San José, CA, USA) with a detection range from 0 to 15,000 ppm_{veq} isobutylene and a resolution of 0.1 ppm_{veq} isobutylene. For its calibration, a standard calibration gas of 100 ppm of isobutylene was used (Calgaz™, TX, USA).

2.3.2. Odour analysis

Odour concentration analysis of the gaseous samples was performed using a Scentroid SM-100 portable field olfactometer (IDES Canada, Inc.) (González et al., 2019a). Briefly, the olfactometer, which is factory-calibrated, works by diluting a fixed flow of clean non-odorous air with the odorous sample. This dilution is presented to the panelist/s until a change in odour is detected. The calibration range of the

SM-100 ranges from 3.5 to 11,355 ou·m⁻³ and each sample was analysed the same sampling day two times by the same panellist in a separated, closed and well-ventilated laboratory, taking 10 min between analyses.

2.3.3. Greenhouse gases

Methane and nitrous oxide analysis were performed by means of an Agilent 6890N Gas Chromatograph (GC) (Agilent Technologies, Inc., Santa Clara, CA, USA). On one side, for methane analysis a flame ionization detector was used. A HP-PLOT Q semi-capillary column (30 m × 0.53 mm × 40.0 μm, Agilent Technologies, Inc.), with nitrogen as carrier gas at 2 psi pressure and a post-column particle trap (2 m, n° 5181-3352, Agilent Technologies, Inc.) were used. The injector temperature was 240 °C, the detector temperature was 250 °C and the oven, which worked isothermally, was at 60 °C. The injection volume used for each sample was 500 μL and the total time of analysis was 4 min. On the other hand, an electron capture detector was used for nitrous oxide analysis. A HP-PLOT Q semi-capillary column (30 m × 0.53 mm × 40.0 μm, Agilent Technologies, Inc.), with nitrogen as carrier gas at 2 psi pressure and a post-column particle trap (2 m, n° 5181-3352, Agilent Technologies, Inc.) were used. The injector temperature was 120 °C, the detector temperature was 345 °C and the oven, which worked isothermally, was at 60 °C. The injection volume used for each sample was 500 μL and the total time of analysis was 6 min.

2.3.4. VOCs characterization

To perform the VOCs characterization and evaluate the presence of different VOC families in the gaseous samples obtained, the methodology proposed by (González et al., 2018, 2019a) was used. Briefly, a liquid VOCs custom mix solution was prepared with 35 standard compounds in methanol, all obtained from Sigma-Aldrich Química SL (Madrid, Spain), considered as representative VOCs emitted through wastewater treatment processes (Godayol et al., 2013). From the VOCs custom mix solution, seven different dilutions were prepared for calibration, which was done by using a Calibration Solution Loading Rig (Markes International, Inc.). A UNITY-2 thermal desorber (Markes International, Inc.) was used to desorb the VOCs retained in the adsorption tubes. Then, an Agilent 7820 GC coupled to an Agilent 5975 Mass

spectrometer (MS) (Agilent Technologies, Inc.) was used to analyse and characterize the different VOC present in each gaseous sample. Compounds were identified by matching its mass spectra with the Wiley275 mass spectra library. All gaseous samples for VOC characterization were analysed before 7 days to preserve the stability of VOCs in the adsorption tubes (Ribes et al., 2007). A standard deviation of 5% was calculated for all VOCs analysed.

2.4. Determination of the emission rates and the emission factors

The methodology used for the determination of the emission factors was based on the measured pollutant, odour or GHGs concentration, the N_2 flow introduced in the FC and normalized by a representative variable of the treatment process (Capelli et al., 2009). In this case, the daily averaged wastewater inlet flow was used as the representative variable of the wastewater treatment process ($m^3 \cdot d^{-1}$). Since all the monitored emission sources were area sources without outward flow (passive area sources), where the liquid surface is exposed to atmospheric perturbations, it is required the previous calculation of the so-called specific emission rate (SER), which relates the pollutant concentration, the N_2 flow rate introduced into the FC and its surface area (Eq. (1)). The first step was to obtain the emission rate of each specific pollutant at each emission source (Eqs. (1) and (2)).

$$SER_i = \frac{C_i \cdot F}{A_{FC}} \quad (1)$$

where SER_i is the specific emission rate of the pollutant i ($mg \cdot d^{-1} \cdot m^{-2}_{FC}$ or $ou \cdot d^{-1} \cdot m^{-2}_{FC}$); C_i is the measured concentration of the pollutant i ($mg \cdot m^{-3}$ or $ou \cdot m^{-3}$); F is the N_2 flow introduced in the FC ($m^3 \cdot d^{-1}$); A_{FC} is the surface covered by the FC (m^2).

The specific emission rate is defined as a function of the velocity of the N_2 stream introduced into the FC. Thus, in order to extrapolate the data obtained during sampling to real environmental conditions, the specific emission rate is normalized by the real wind velocity using Eq. (2), which is derived from the liquid-gas phase mass transfer phenomena described by the Prandtl boundary layer theory (Capelli et al., 2013b).

$$SER_{v2,i} = SER_{v1,i} \cdot \left(\frac{v2}{v1} \right)^{1/2} \quad (2)$$

where SER_{v2} is the normalized specific emission rate of the pollutant i for real environmental conditions ($mg \cdot d^{-1} \cdot m^{-2}_{FC}$ or $ou \cdot d^{-1} \cdot m^{-2}_{FC}$); SER_{v1} is the specific emission rate of the pollutant i obtained from the FC measurement ($mg \cdot d^{-1} \cdot m^{-2}_{FC}$ or $ou \cdot d^{-1} \cdot m^{-2}_{FC}$); $v2$ is the real wind velocity over the emission surface, measured with a TSI 5725 anemometer (TSI Incorporated, Shoreview, MN, USA) ($m \cdot s^{-1}$); $v1$ is the N_2 velocity inside the FC ($m \cdot s^{-1}$).

Once the specific emission rate is normalized, the emission rate can be calculated by multiplying the $SER_{v2,i}$ with the surface of the emission source (Eq. (3)).

$$ER_i = SER_{v2,i} \cdot A_s \quad (3)$$

where ER_i is the emission rate of the pollutant i ($mg \cdot d^{-1}$ or $ou \cdot d^{-1}$); A_s is the surface of the emitting source (m^2).

Once the emission rates of each specific pollutant are calculated, the emission factor can be estimated by normalizing the emission rate by the average daily wastewater inlet flow, as shown by Eq. (4).

$$EF_i = \frac{ER_i}{I} \quad (4)$$

where EF_i is the emission factor of the pollutant i ($mg \cdot m^{-3}_{influent}$ or $ou \cdot m^{-3}_{influent}$); I is the plant's average daily wastewater influent ($m^3_{influent} \cdot d^{-1}$).

Finally, a global emission factor for each specific pollutant can be estimated by adding each emission factor referred to each treatment unit

(Eq. (5)).

$$EF_{i, global} = \sum EF_i \quad (5)$$

3. Results and discussion

3.1. Current odour and GHG emissions characterization

3.1.1. Odorant and odour emissions

Fig. 3 presents the emission rates for the different odorant pollutants as well as for odour estimated during the sampling campaigns carried out from April to August 2018. As it can be observed, the reception tank, the outlet of the grit chamber and the primary settler were the main emission sources found, being the last one the most significant. During these sampling campaigns, the higher concentrations measured for tVOCs, NH_3 and H_2S were registered in different treatment units. Firstly, maximum tVOCs concentrations were measured in the reception tank (1.9–2.3 ppm_{veq} isobutylene). On the other hand, maximum NH_3 concentrations were registered in the barscreens outlet and the grit chamber (4.5–7 ppm_v NH_3). Finally, the higher H_2S concentrations were obtained in the primary settler surface (0.6–1.0 ppm_v H_2S), similar as it has been reported before by other researchers (Dincer and Muezzinoglu, 2008; Jeon et al., 2009). Besides, the greatest odour concentrations measured were registered in the grit chamber and in the surface of the primary settler, which were 2025 and 2578 $ou \cdot m^{-3}$, respectively. Many studies have reported that the main odorant emission sources found during the wastewater treatment correspond generally to the first steps of the wastewater treatment such as the plant headworks or the primary settlers, and that these emissions decrease as the process goes forward (Carrera-Chapela et al., 2014). In fact, Capelli et al. (2009) studied the odour emissions from 17 Italian WWTP and reported that the major odour emission sources were the pre-treatments and the primary settlers, registering average odour concentrations from 1490 to 3840 $ou \cdot m^{-3}$. This can be explained by the fact that primary settlers represent a large emission source with a large surface area where wastewater remains calmed, and due to the high wastewater retention times and the settling of the organic/inorganic matter, anoxic/anaerobic conditions can develop to promote formation of odorant compounds (Carrera-Chapela et al., 2014).

Table 2 shows the average emission factors for tVOCs, NH_3 and H_2S , as well as the odour emission factor (OEF) obtained during the sampling campaigns conducted in 2018. These are expressed in representative units to allow the comparison with the emission factors obtained from other WWTPs. The emission factors obtained were compared with the scarce literature found reporting full-scale WWTP emission factors. For example, Bell et al. (1988) performed a study on four different WWTP in Ontario, obtaining tVOC emission factors of 3.60E-02 to 5.00E-02 $g \cdot C \cdot m^{-3}_{inf}$. Zhang et al. (2017) reported ammonia emission factors of 0.15–0.29 $g \cdot NH_3 \cdot m^{-3}_{inf}$ from a full-scale WWTP with a maximum treatment capacity of 1.2E+06 $m^3 \cdot d^{-1}$. Furthermore, Colomer et al. (2012) reported average hydrogen sulphide emission factors of 2.50 and 1.90 $g \cdot H_2S \cdot m^{-3}_{inf}$, for two different WWTP treating 61,821 and 38,962 $m^3 \cdot d^{-1}$ of urban wastewater, respectively, which were obtained by merging experimental data with dispersion modelling. In contrast, Jeon et al. (2009) found much lower emission factors for NH_3 and H_2S (9.48E-04 $g \cdot NH_3 \cdot m^{-3}_{inf}$ and 7.40E-05 $g \cdot H_2S \cdot m^{-3}_{inf}$), what could be influenced by the fact that the estimated emission rates were not normalized by the real environmental conditions. In terms of odour emission, Capelli et al. (2009) studied different Italian WWTP (with treatment capacities from 1000 to 800,000 $m^3 \cdot d^{-1}$) and reported average OEF from 2.20E+04 to 1.82E+05 $ou \cdot m^{-3}_{inf}$, highlighting the contribution to global OEF of the first stages of the WWTP.

3.1.2. GHGs emissions

Fig. 4 shows the estimated emission rates for methane and nitrous oxide in the different treatment units during the sampling campaigns

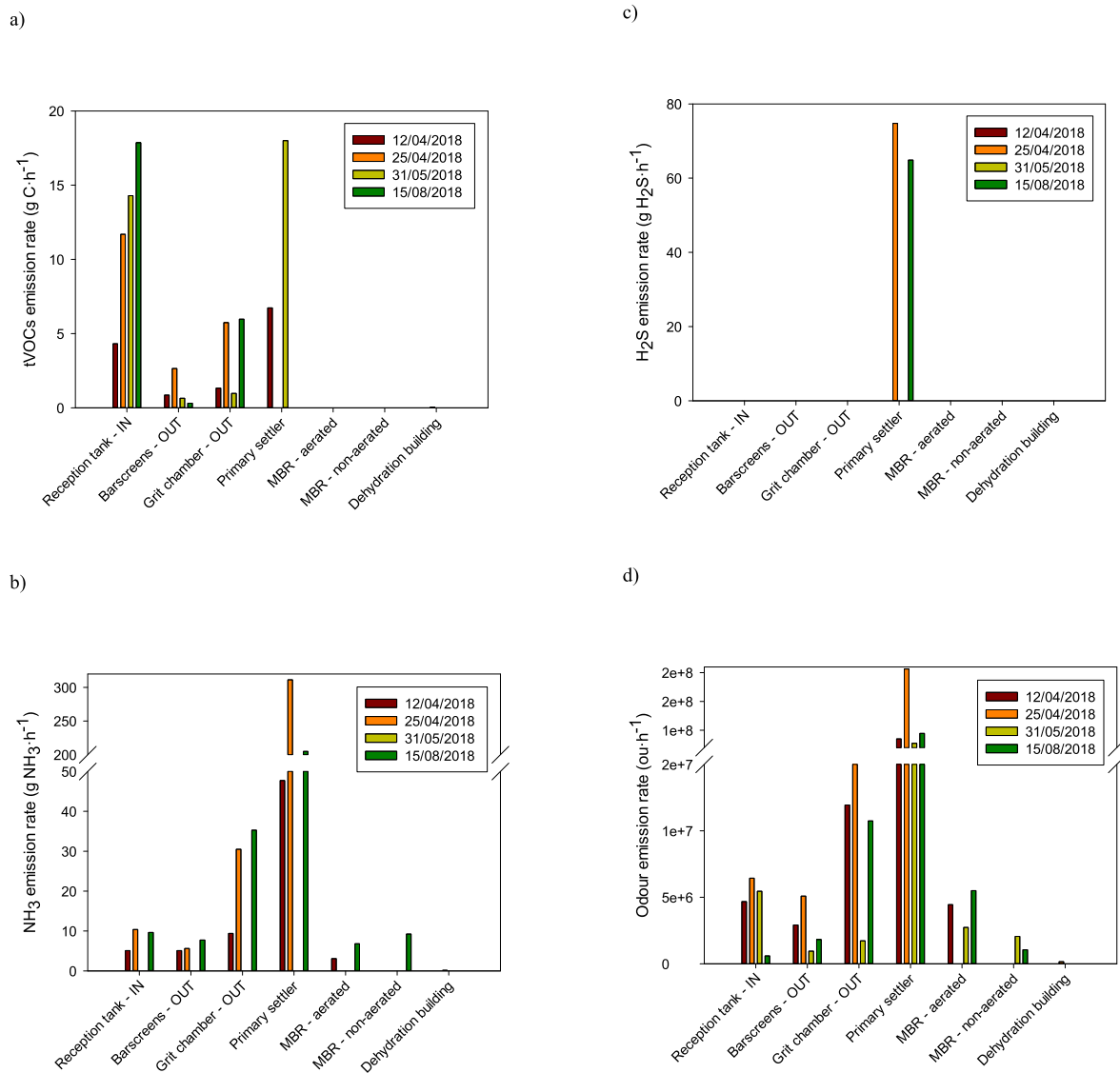


Fig. 3. Emission rates obtained in the different monitoring points during the sampling campaigns for (a) total volatile organic compounds, (b) ammonia, (c) hydrogen sulphide and (d) odour.

Table 2
Average emission factors for tVOCs, NH₃, H₂S and odour (OEF).

	g C·kg ⁻¹ TOC _{inf}	g C·m ⁻³ inf
tVOCs	1.84E-01	1.66E-02
	g NH ₃ ·kg ⁻¹ TN _{inf}	g NH ₃ ·m ⁻³ inf
NH ₃	1.84	1.70E-01
	g H ₂ S·m ⁻³ inf	
H ₂ S	5.08E-02	
	ou·m ⁻³ inf	
Odour	9.90E+04	

conducted from April to August 2018. As it can be observed, different potential GHG emission sources were found for methane and nitrous oxide. CH₄ emissions were mainly observed at the inlet of the reception tank, the outlet of the grit chamber and in the primary settler, registering maximum CH₄ concentrations from 12.8 to 171.0 ppm_v. During wastewater transportation, it is known that anaerobic environment can be formed in sewers and some methane as well as VOCs and other odorants and GHG can be formed and emitted (Guisasola et al., 2008). Part of this CH₄ can be dissolved in the wastewater and reach the WWTP. Thus, the emission of methane in the reception tank can be explained by the

volatilization of the dissolved CH₄ present in the influent. However, it has been reported that the main CH₄ emission sources are related to sewage sludge line units (Campos et al., 2016) such as sewage sludge anaerobic digestion, which was present in the actual WWTP. During anaerobic digestion, some of the CH₄ formed by methanogens remains dissolved in the anaerobically digested sludge and pumped back to the water line as reject water after the dehydration step. In the specific WWTP under study, the reject water is recirculated to the barscreens entrance. This fact, together with the high turbulence created by the blowers used in the grit chamber, can explain the significant emission of CH₄ observed at this point of the WWTP. Moreover, the CH₄ emission observed in the primary settler can be explained by the fact that anaerobic conditions were created there, as reported elsewhere (Daelman et al., 2012). These findings contrast with what is reported by the IPCC (2014), which does not take into account ordinary units such as sedimentation tanks as methane emission sources. On the other hand, the MBR was the main emission source of N₂O, measuring maximum concentrations up to 140.8 ppm_v. As it has been reported by different researchers, most of the N₂O emitted from the wastewater treatment processes comes from aeration tanks during nitrification at low dissolved oxygen concentrations and subsequent denitrification (Daelman

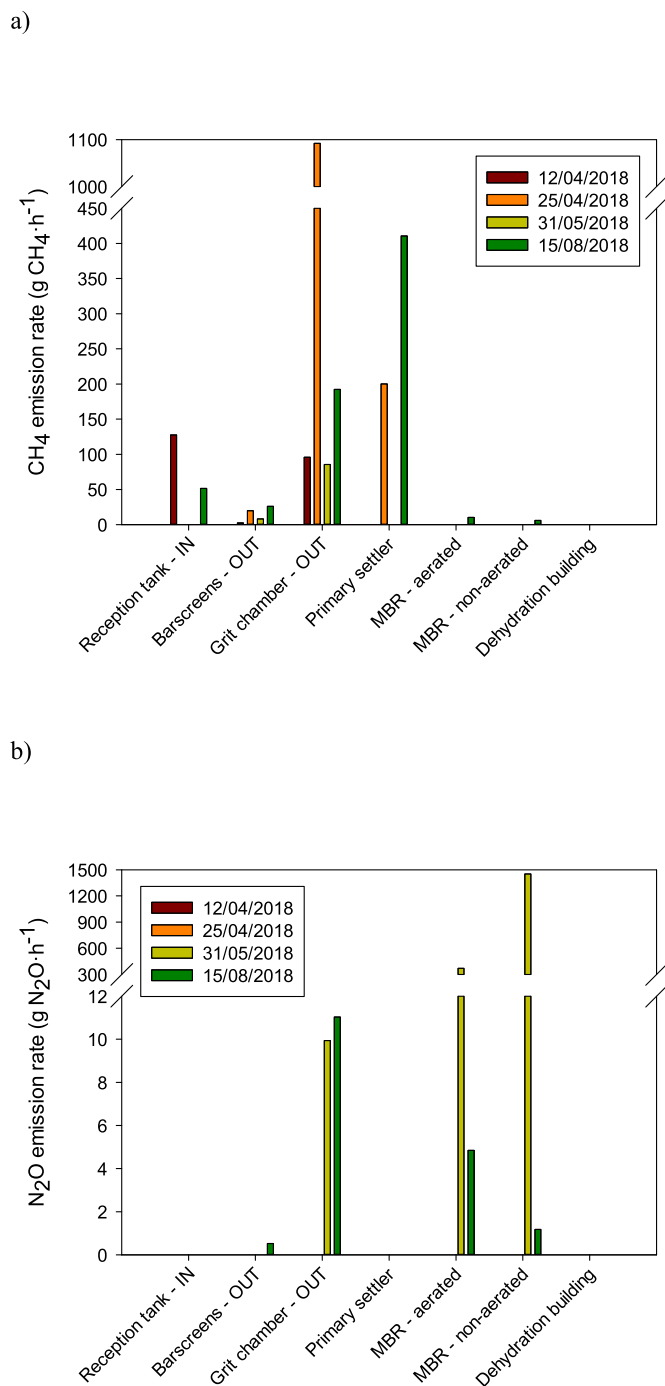


Fig. 4. Emission rates obtained in the different monitoring points during the sampling campaigns for (a) methane and (b) nitrous oxide.

et al., 2013; Rodriguez-Caballero et al., 2015), although other emission sources and processes inside the wastewater treatment can be associated (Kampschreur et al., 2009). For example, in the work reported herein, some N_2O emissions were also found at the outlet of the grit chamber in low concentrations (0.6–1.1 ppm_v).

Table 3 presents the average CH_4 and N_2O emission factors obtained during the sampling campaigns conducted in 2018, expressed in different representative units to allow comparison with the emissions of other WWTP. The emission factors for CH_4 ($0.42 \text{ g } CH_4 \cdot m^{-3} \text{ inf}$), N_2O ($0.34 \text{ g } N_2O \text{ m}^{-3} \text{ inf}$) and global GHG ($101 \text{ g } CO_{2eq} \cdot m^{-3} \text{ inf}$) have been compared with other studies conducted in full-scale WWTPs. Even though the high variability observed in the estimation of the GHG

Table 3

Average CH_4 and N_2O emission factors.

CH_4	$\text{g } CH_4 \cdot \text{kg}^{-1} \text{ TOC}_{\text{inf}}$	$\text{g } CH_4 \cdot \text{m}^{-3} \text{ inf}$	$\text{g } CO_{2eq} \cdot \text{m}^{-3} \text{ inf}$
	4.63	4.24E-01	11.86
N_2O	$\text{g } N_2O \cdot \text{kg}^{-1} \text{ TN}_{\text{inf}}$	$\text{g } N_2O \cdot \text{m}^{-3} \text{ inf}$	$\text{g } CO_{2eq} \cdot \text{m}^{-3} \text{ inf}$
	3.12	3.36E-01	89.10
GHG	$\text{g } CO_{2eq} \cdot \text{m}^{-3} \text{ inf}$		
	100.96		

emissions generated in different WWTP due to the existing influence of operational conditions such as loading rate or temperature, some similarities have been found. For example, the results obtained in this work were significantly lower in terms of CH_4 and CO_2 equivalent compared to previous studies. Masuda et al. (2015b), reported total average emission factors of $1.15 \text{ g } CH_4 \cdot m^{-3} \text{ inf}$, $0.39 \text{ g } N_2O \cdot m^{-3} \text{ inf}$ and $146.10 \text{ g } CO_{2eq} \cdot m^{-3} \text{ inf}$ from a WWTP with conventional activated sludge process as biological reactor that treats and average inlet flow of $327,178 \text{ m}^3 \text{ d}^{-1}$. On the other hand, Daelman et al. (2013) reported higher average emission factors for both pollutants from a WWTP based on a conventional Ludzack-Ettinger that treats the domestic wastewater of 360,000 population equivalents, being $3.32 \text{ g } CH_4 \cdot m^{-3} \text{ inf}$, $1.62 \text{ g } N_2O \cdot m^{-3} \text{ inf}$ and $521.04 \text{ g } CO_{2eq} \cdot m^{-3} \text{ inf}$. Thus, an MBR-based configuration for the removal of nitrogen and organic matter may result in lower emissions of GHG.

In addition, Mannina et al. (2019) reported direct GHG emission factors of $140\text{--}940 \text{ g } CO_{2eq} \cdot m^{-3} \text{ inf}$ from different simulation scenarios of a real WWTP treating $60,000 \text{ m}^3 \text{ d}^{-1}$ of real wastewater, what highlights the great influence of different operational parameters on the emission of both methane and nitrous oxide.

3.1.3. VOCs characterization

Fig. 5 shows the distribution of the VOC families that were found in the gaseous samples obtained from the different emission sources of the WWTP during the sampling campaign in August 2018. The VOCs characterization was made by comparing the VOCs identified in the seven different gaseous samples. More than 150 compounds were identified among the different samples, which presented at least 90% mass spectra matching with the Wiley275 mass spectra library consulted, and then classified into the following VOC categories: acetals, alcohols, aldehydes, alkanes, alkenes, aromatic hydrocarbons, carboxylic acids, esters, ethers, halogenated hydrocarbons, ketones, nitrogenated compounds, phenols, siloxanes, sulphur compounds and terpenes. The compounds that did not reach this matching level were categorized as “others”.

As it can be observed in Fig. 5, a high variability was observed in the distribution of the VOC families found in the different emission sources. From all of them, many different alkanes (mainly hexane, pentamethylheptane, nonane or dodecane), aromatic hydrocarbons (mainly BTEX) and esters were the most abundant (Wu et al., 2006), representing from 25% to 70% of the VOC families found. Moreover, typical VOCs families found in the gaseous emissions generated in WWTPs were present in lower abundance (between 4% and 20%), such as ketones (2-propanone and cyclopentanone) and organosulphur compounds (DMS and DMDS). However, even though appearing in lower abundance, these last families are more likely to produce odour nuisance due to their low odour detection thresholds (Dincer and Muezzinoglu, 2008; Wu et al., 2006).

3.2. Efficiency of the gas treatment system

From October 2013 to September 2014, different monitoring campaigns were conducted to assess the critical emission sources of the WWTP, to propose and implement the current gas treatment system. Fig. 6 shows the estimated emission rates of each specific pollutant for the different points of the WWTP under study during the previous sampling campaigns. As it can be observed, the most important emission sources were found to be the inlet of the barscreens room, the surface of

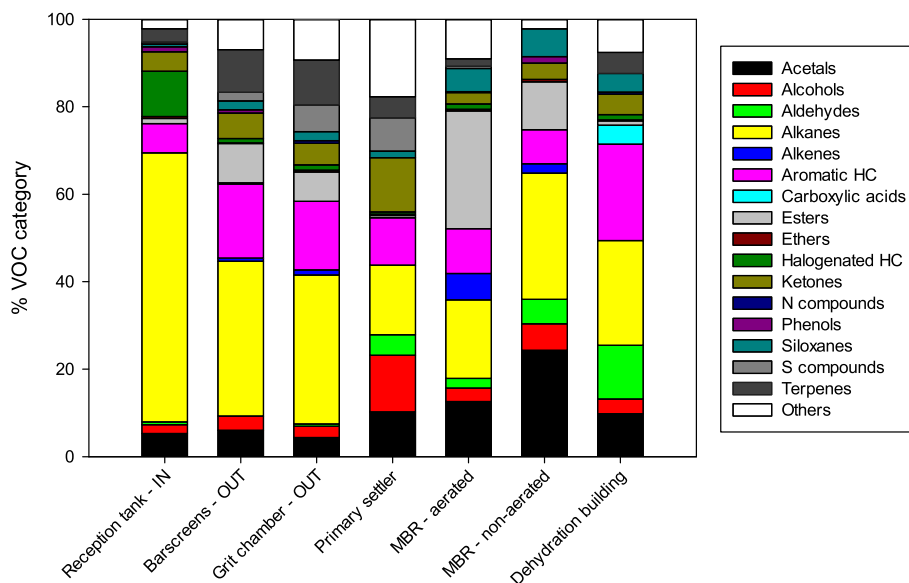


Fig. 5. VOCs characterization from different emission sources performed during the sampling campaign of August 2018.

the primary settler, the sludge thickeners and the dehydration building. However, a clear variability was observed during the different sampling campaigns, depending on the operation of the WWTP and the season when the campaigns were performed. Fig. 6a shows the emission rates estimated for tVOCs on the different sampling points of the WWTP. Clearly, the inlet section of the barscreens building, the primary settler overflow, the sludge thickeners and the sludge dehydration building were the main tVOCs emission sources from the WWTP, where maximum concentrations from 0.4 to 5.8 ppm_{veq} isobutylene were registered. For NH₃ and H₂S (Fig. 6b and c) similar patterns were observed, where the main emission sources corresponded to the inlet section of the barscreens building and the primary settler overflow, with the difference that H₂S was also found in the sludge dehydration building (Dincer and Muezzinoglu, 2008). Maximum NH₃ and H₂S concentrations measured varied from 1.0 to 7.0 ppm_v NH₃ and from 0.5 to 9.1 ppm_v H₂S, respectively. It should be commented that there was a high variability in the measurements performed during the different sampling campaigns, where standard deviation of the data obtained for each of the units studied were on the same order of magnitude of the mean values for each specific compound measured (mean value and standard deviation of the emission rates for all the units monitored among all sampling campaigns were 53.76 g C·h⁻¹ ± 116.42 for tVOCs, 69.17 g NH₃·h⁻¹ ± 115.32 for ammonia and 137.10 g H₂S·h⁻¹ ± 295.63 for hydrogen sulphide, respectively).

With the information gathered during the previous sampling campaigns performed during 2014 and knowing which were the critical emission sources of the WWTP, a gas treatment system was designed and implemented to minimize the environmental impact of the wastewater treatment process. The efficiency of this gas treatment system was evaluated by measuring the inlet and outlet flows and concentrations of both H₂S and tVOCs. Table 4 presents the inlet and outlet measured concentration of both H₂S and tVOCs (in ppm_v) together with the respective elimination efficiency for each treatment step and for the global treatment, respectively. It was observed that during the BTF step, hydrogen sulphide was eliminated in more than 95%, whereas at least an 87.5% of the tVOCs were eliminated in the same operation. This difference appeared due to the easy solubilisation of H₂S in water in contrast to tVOCs, which are compounds characterised by their high volatility and low solubility in water (Pennerman et al., 2016). For this reason, a conventional BF was installed after the BTF. It was observed that with the conventional BF, at least an 89% and a 90% of the remaining H₂S and tVOCs, respectively, were eliminated to finally

obtain global elimination percentages of 99.6% and 98.7% for H₂S and tVOCs, respectively.

4. Conclusions

By performing the sampling campaigns during 2014, it was concluded that the potential emission sources of tVOCs, NH₃ and H₂S were the reception tank, the inlet of the barscreens building, the primary settler and the dehydration building. This information led to the installation of a gas capture and treatment system to minimize these gaseous emissions. Subsequently, the elimination efficiency of the gas treatment system was assessed, obtaining H₂S and tVOCs elimination percentages of 99.6% and 98.7%, respectively. In a later stage, the emission factors of tVOCs, NH₃, H₂S, odour, CH₄ and N₂O were estimated, observing that the main odour emission sources corresponded to the first units of the wastewater treatment process, whereas the main GHG emission sources are focused on the biological organic matter and nutrient removal units. However, a high temporal variability of the gaseous emissions was observed.

Besides, a chemical characterization of the VOCs present in the gaseous emissions was conducted, which showed the high variability of VOCs that are found in the gaseous emissions generated during the wastewater depuration cycle.

Finally, it is important to point out that despite the fact that the emission of diverse pollutants has been studied during the last years by different researchers, their representative estimation is still hampered by the wide variability found in the different WWTPs due to the strong influence of different operation conditions (loading rate, dissolved oxygen or temperature) and the different WWTP configurations. In this case an MBR configuration indicated that GHG emissions may be lower than conventional aeration WWTPs. Moreover, extensive sampling campaigns should be specifically designed and conducted to obtain more robust data that could be later used to steadily mitigate these emissions and their related environmental impact.

CRedit author statement

Daniel González: Conceptualization, Methodology, Formal analysis, Investigation, Data Curation, Writing - Original Draft, Visualization. **Joan Colón:** Validation, Formal analysis, Investigation, Supervision. **Antoni Sánchez:** Validation, Formal analysis, Resources, Writing - Review & Editing, Supervision, Funding acquisition. **David**

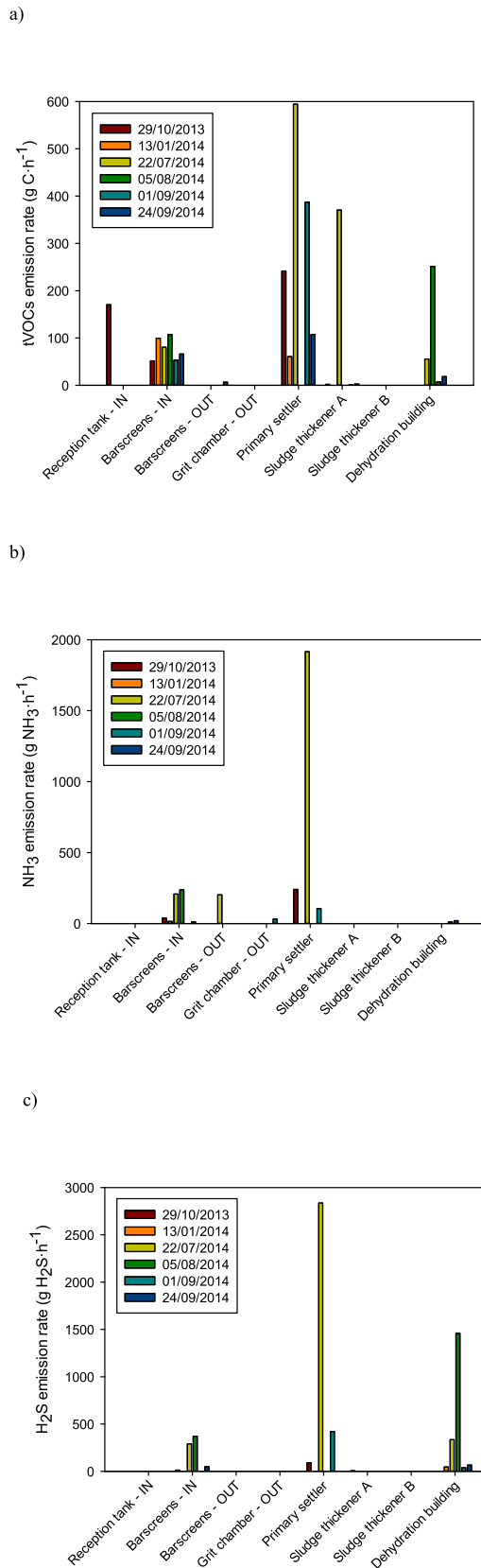


Fig. 6. Emission rates obtained in the different monitoring points during the sampling campaigns of 2014 (before the installation of the gas treatment system) for (a) total volatile organic compounds, (b) ammonia and (c) hydrogen sulphide.

Table 4
Elimination efficiency of the gas treatment system for H₂S and tVOCs.

	Average		Worst scenario	
	H ₂ S (ppm _v)	tVOCs (ppm _v)	H ₂ S (ppm _v)	tVOCs (ppm _v)
BTF inlet	1.80 ± 0.92	0.53 ± 0.42	2.50	0.80
BTF outlet	0.00 ± 0.00	0.03 ± 0.07	0.09	0.10
BF outlet	0.00 ± 0.00	0.00 ± 0.00	0.01	0.01
	Average H ₂ S	tVOCs	Worst scenario H ₂ S	tVOCs
% BTF elimination	100	95.3	96.4	87.5
% BF elimination	–	100	88.9	90.0
% global elimination	100	100	99.6	98.7

Gabriel: Conceptualization, Methodology, Resources, Writing - Review & Editing, Supervision, Project administration, Funding acquisition

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.

Acknowledgements

Joan Colón has received funding from the 2018 call for Ramón y Cajal grants from the Ministry of Science, Innovation and Universities (ref. RYC-2018-026231-I) co-financed by the State Research Agency and the European Social Fund.

The authors would like to thank Grup Cassa, Adolfo Pino, Alex Rodero and all the wastewater treatment plant staff for their kindness and their interest on this work.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jenvman.2022.115002>.

References

Bell, J., Melcer, H., Monteith, H., Osinga, I., Steel, P., 1988. Stripping of volatile organic compounds at full-scale municipal wastewater treatment plants. *Water Environ. Res.* 65, 708–716. <https://doi.org/10.2175/WER.65.6.2>.

Brattoi, M., de Gennaro, G., de Pinto, V., Loiotile, A.D., Lovascio, S., Penza, M., 2011. Odour detection methods: olfactometry and chemical sensors. *Sensors*. <https://doi.org/10.3390/s110505290>.

Campos, J.L., Valenzuela-Heredia, D., Pedrouso, A., Val Del Río, A., Belmonte, M., Mosquera-Corral, A., 2016. Greenhouse gases emissions from wastewater treatment plants: minimization, treatment, and prevention. *J. Chem.* <https://doi.org/10.1155/2016/3796352>, 2016.

Capelli, L., Sironi, S., del Rosso, R., Céntola, P., 2009. Predicting odour emissions from wastewater treatment plants by means of odour emission factors. *Water Res.* 43, 1977–1985. <https://doi.org/10.1016/j.watres.2009.01.022>.

Capelli, L., Sironi, S., del Rosso, R., 2013a. Odor sampling: techniques and strategies for the estimation of odor emission rates from different source types. *Sensors* 13, 938–955. <https://doi.org/10.3390/s130100938>.

Capelli, L., Sironi, S., del Rosso, R., 2013b. Odor sampling: techniques and strategies for the estimation of odor emission rates from different source types. *Sensors* 13, 938–955. <https://doi.org/10.3390/s130100938>.

Carrera-Chapela, F., Donoso-Bravo, A., Souto, J.A., Ruiz-Filippi, G., 2014. Modeling the Odor Generation in WWTP: an Integrated Approach Review. *Water, Air, and Soil Pollution*. <https://doi.org/10.1007/s11270-014-1932-y>.

Colomer, F.L., Morató, H.E., Iglesias, E.M., 2012. Estimation of hydrogen sulfide emission rates at several wastewater treatment plants through experimental concentration measurements and dispersion modeling. *J. Air Waste Manag. Assoc.* 62, 758–766. <https://doi.org/10.1080/10962247.2012.674008>.

Daelman, M.R.J., van Voorthuizen, E.M., van Dongen, U.G.J.M., Volcke, E.I.P., van Loosdrecht, M.C.M., 2012. Methane emission during municipal wastewater

- treatment. *Water Res.* 46, 3657–3670. <https://doi.org/10.1016/j.watres.2012.04.024>.
- Daelman, M.R.J., van Voorhuizen, E.M., van Dongen, L.G.J.M., Volcke, E.I.P., van Loosdrecht, M.C.M., 2013. Methane and nitrous oxide emissions from municipal wastewater treatment - results from a long-term study. *Water Sci. Technol.* 67, 2350–2355. <https://doi.org/10.2166/wst.2013.109>.
- Dincer, F., Muezzinoglu, A., 2007. Odor determination at wastewater collection systems: olfactometry versus H2S analyses. *Clean.* <https://doi.org/10.1002/clean.200700057>.
- Dincer, F., Muezzinoglu, A., 2008. Odor-causing volatile organic compounds in wastewater treatment plant units and sludge management areas. *Journal of Environmental Science and Health - Part A Toxic/Hazardous Substances and Environmental Engineering* 43, 1569–1574. <https://doi.org/10.1080/10934520802293776>.
- Comité Européen de Normalisation, 2003. EN 13725, 2003. *Air Quality – Determination of Odour Concentration by Dynamic Olfactometry*.
- Frecher, F.B., 1988. Odour emissions and odour control at wastewater treatment plants in west Germany. *Water Sci. Technol.* 20, 261–266. <https://doi.org/10.2166/wst.1988.0175>.
- Godayol, A., Marcé, R.M., Borrull, F., Anticó, E., Sanchez, J.M., 2013. Development of a method for the monitoring of odor-causing compounds in atmospheres surrounding wastewater treatment plants. *J. Separ. Sci.* <https://doi.org/10.1002/jssc.201300046>.
- González, D., Colón, J., Sánchez, A., Gabriel, D., 2018. Evaluation of the odorous compounds emitted in a full-scale sewage sludge composting plant and its relationship with the biological stability. *Chemical Engineering Transactions* 68. <https://doi.org/10.3303/CET1868030>.
- González, D., Colón, J., Sánchez, A., Gabriel, D., 2019a. A systematic study on the VOCs characterization and odour emissions in a full-scale sewage sludge composting plant. *J. Hazard Mater.* 373, 733–740. <https://doi.org/10.1016/j.jhazmat.2019.03.131>.
- González, D., Guerra, N., Colón, J., Gabriel, D., Ponsá, S., Sánchez, A., 2019b. Filling in sewage sludge bioreactors: greenhouse gases, volatile organic compounds and odour emissions. *Bioresour. Technol.* 291, 121857. <https://doi.org/10.1016/j.biortech.2019.121857>.
- Gostelow, P., Parsons, S.A., Stuetz, R.M., 2001. Odour measurements for sewage treatment works. *Water Res.* 35, 579–597.
- Guisasola, A., de Haas, D., Keller, J., Yuan, Z., 2008. Methane formation in sewer systems. *Water Res.* 42, 1421–1430. <https://doi.org/10.1016/j.watres.2007.10.014>.
- IPCC, 2014. *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. IPCC, Geneva, Switzerland.
- Jeon, E.C., Son, H.K., Sa, J.H., 2009. Emission characteristics and factors of selected odorous compounds at a wastewater treatment plant. *Sensors* 9, 311–329. <https://doi.org/10.3390/s90100311>.
- Kampschreur, M.J., Temmink, H., Kleerebezem, R., Jetten, M.S.M., van Loosdrecht, M.C.M., 2009. Nitrous oxide emission during wastewater treatment. *Water Res.* 43, 4093–4103. <https://doi.org/10.1016/j.watres.2009.03.001>.
- Kulig, A., Szytak-Szydłowski, M., 2019. Assessment of the Effects of Wastewater Treatment Plant Modernization by Means of the Field Olfactometry Method. *Water (Switzerland)* 11. <https://doi.org/10.3390/w11112367>.
- Laor, Y., Parker, D., Pagé, T., 2014. Measurement, prediction, and monitoring of odors in the environment: a critical review. *Rev. Chem. Eng.* 30, 139–166. <https://doi.org/10.1515/revce-2013-0026>.
- Lebrero, R., Bouchy, L., Stuetz, R., Muñoz, R., 2011. Odor Assessment and Management in Wastewater Treatment Plants: A Review. *Critical Reviews in Environmental Science and Technology*. <https://doi.org/10.1080/10643380903300000>.
- Li, R., Han, Z., Shen, H., Qi, F., Ding, M., Song, C., Sun, D., 2021a. Emission characteristics of odorous volatile sulfur compound from a full-scale sequencing batch reactor wastewater treatment plant. *Sci. Total Environ.* 776 <https://doi.org/10.1016/j.scitotenv.2021.145991>.
- Li, R., Han, Z., Shen, H., Qi, F., Sun, D., 2021b. Volatile sulfur compound emissions and health risk assessment from an A2/O wastewater treatment plant. *Sci. Total Environ.* 794 <https://doi.org/10.1016/j.scitotenv.2021.148741>.
- Mannina, G., Rebouças, T.F., Cosenza, A., Chandran, K., 2019. A plant-wide wastewater treatment plant model for carbon and energy footprint: model application and scenario analysis. *J. Clean. Prod.* 217, 244–256. <https://doi.org/10.1016/j.jclepro.2019.01.255>.
- Massara, T.M., Malamis, S., Guisasola, A., Baeza, J.A., Noutsopoulos, C., Katsou, E., 2017. A review on nitrous oxide (N2O) emissions during biological nutrient removal from municipal wastewater and sludge reject water. *Sci. Total Environ.* 596–597, 106–123. <https://doi.org/10.1016/j.scitotenv.2017.03.191>.
- Masuda, S., Suzuki, S., Sano, I., Li, Y.Y., Nishimura, O., 2015a. The seasonal variation of emission of greenhouse gases from a full-scale sewage treatment plant. *Chemosphere* 140, 167–173. <https://doi.org/10.1016/j.chemosphere.2014.09.042>.
- Masuda, S., Suzuki, S., Sano, I., Li, Y.Y., Nishimura, O., 2015b. The seasonal variation of emission of greenhouse gases from a full-scale sewage treatment plant. *Chemosphere* 140, 167–173. <https://doi.org/10.1016/j.chemosphere.2014.09.042>.
- Parravicini, V., Svardal, K., Krampe, J., 2016. Greenhouse gas emissions from wastewater treatment plants. *Energy Proc.* 97, 246–253. <https://doi.org/10.1016/j.egypro.2016.10.067>.
- Pennerman, K.K., Al-Maliki, H.S., Lee, S., Bennet, J.W., 2016. Chapter 7: fungal volatile organic compounds (VOCs) and the genus *Aspergillus*. In: *New and Future Developments in Microbial Biotechnology and Bioengineering, New and Future Developments in Microbial Biotechnology and Bioengineering*. Elsevier. <https://doi.org/10.1016/C2014-0-00092-5>.
- Ramírez, N., Marcé, R.M., Borrull, F., 2011. Determination of volatile organic compounds in industrial wastewater plant air emissions by multi-sorbent adsorption and thermal desorption-gas chromatography-mass spectrometry. *Int. J. Environ. Anal. Chem.* 91, 911–928. <https://doi.org/10.1080/03067310903584073>.
- Ribes, A., Carrera, G., Gallego, E., Roca, X., Berenguer, M.J., Guardino, X., 2007. Development and validation of a method for air-quality and nuisance odors monitoring of volatile organic compounds using multi-sorbent adsorption and gas chromatography/mass spectrometry thermal desorption system. *J. Chromatogr. A* 1140, 44–55. <https://doi.org/10.1016/j.chroma.2006.11.062>.
- Rodríguez-Caballero, A., Aymerich, I., Poch, M., Pijuan, M., 2014. Evaluation of process conditions triggering emissions of green-house gases from a biological wastewater treatment system. *Sci. Total Environ.* 493, 384–391. <https://doi.org/10.1016/j.scitotenv.2014.06.015>.
- Rodríguez-Caballero, A., Aymerich, I., Marques, R., Poch, M., Pijuan, M., 2015. Minimizing N2O emissions and carbon footprint on a full-scale activated sludge sequencing batch reactor. *Water Res.* 71, 1–10. <https://doi.org/10.1016/j.watres.2014.12.032>.
- Sironi, S., Capelli, L., Céntola, P., Del Rosso, R., Il Grande, M., 2005. Odour emission factors for assessment and prediction of Italian MSW landfills odour impact. *Atmos. Environ.* 39, 5387–5394. <https://doi.org/10.1016/j.atmosenv.2005.05.023>.
- Sironi, S., Capelli, L., Céntola, P., Del Rosso, R., Il Grande, M., 2006. Odour emission factors for the prediction of odour emissions from plants for the mechanical and biological treatment of MSW. *Atmos. Environ.* 40, 7632–7643. <https://doi.org/10.1016/j.atmosenv.2006.06.052>.
- USEPA, 1986. *Measurement of Gaseous Emission Rates from Land Surfaces Using an Emission Isolation Flux Chamber*. Radian Corporation, TX, USA. User's guide.
- USEPA, 1995. *Compilation of Air Pollutant Emission Factors, AP-42 In: Stationary point and area sources, fifth ed., vol. 1*. Research Triangle Park, NC, USA.
- USEPA, 1999. *Compendium Method TO-17 - Determination of Volatile Organic Compounds in Ambient Air Using Active Sampling onto Sorbent Tubes. Compendium of Methods for the Determination of Toxic Organic Compounds in Ambient Air, 2nd Edition*. United States Environmental Protection Agency, OH, USA.
- Wu, B.Z., Feng, T.Z., Sree, U., Chiu, K.H., Lo, J.G., 2006. Sampling and analysis of volatile organics emitted from wastewater treatment plant and drain system of an industrial science park. *Anal. Chim. Acta* 576, 100–111. <https://doi.org/10.1016/j.aca.2006.03.057>.
- Zarra, T., Naddeo, V., Belgiojorno, V., Reiser, M., Kranert, M., 2008. Odour monitoring of small wastewater treatment plant located in sensitive environment. *Water Sci. Technol.* 58, 89–94. <https://doi.org/10.2166/wst.2008.330>.
- Zarra, T., Reiser, M., Naddeo, V., Belgiojorno, V., Kranert, M., 2014. Odour emissions characterization from wastewater treatment plants by different measurement methods. *Chemical Engineering Transactions* 40, 37–42. <https://doi.org/10.3303/CET1440007>.
- Zhang, C., Geng, X., Wang, H., Zhou, L., Wang, B., 2017. Emission factor for atmospheric ammonia from a typical municipal wastewater treatment plant in South China. *Environ. Pollut.* 220, 963–970. <https://doi.org/10.1016/j.envpol.2016.10.082>.