

Review

Full-Scale Odor Abatement Technologies in Wastewater Treatment Plants (WWTPs): A Review

Vincenzo Senatore ¹, Tiziano Zarra ¹, Mark Gino Galang ¹, Giuseppina Oliva ^{1,*}, Antonio Buonerba ², Chi-Wang Li ³, Vincenzo Belgiorno ¹ and Vincenzo Naddeo ¹

- ¹ Sanitary Environmental Engineering Division (SEED), Department of Civil Engineering, University of Salerno, Via Giovanni Paolo II 132, 84084 Fisciano, SA, Italy; vsenatore@unisa.it (V.S.); tzarra@unisa.it (T.Z.); mgalang@unisa.it (M.G.G.); v.belgiorno@unisa.it (V.B.); vnaddeo@unisa.it (V.N.)
- ² SPONGE Srl, Academic Spin Off of the University of Salerno, Laboratory SEED, Via Giovanni Paolo II, 132, 84084 Fisciano, SA, Italy; abuonerba@unisa.it
- ³ Department of Water Resources and Environmental Engineering, Tamkang University, 151 Yingzhuang Road Tamsui District, New Taipei City 25137, Taiwan; chiwang@mail.tku.edu.tw
- * Correspondence: goliva@unisa.it; Tel.: +39-089-967911

Abstract: The release of air pollutants from the operation of wastewater treatment plants (WWTPs) is often a cause of odor annoyance for the people living in the surrounding area. Odors have been indeed recently classified as atmospheric pollutants and are the main cause of complaints to local authorities. In this context, the implementation of effective treatment solutions is of key importance for urban water cycle management. This work presents a critical review of the state of the art of odor treatment technologies (OTTs) applied in full-scale WWTPs to address this issue. An overview of these technologies is given by discussing their strengths and weaknesses. A sensitivity analysis is presented, by considering land requirements, operational parameters and efficiencies, based on data of full-scale applications. The investment and operating costs have been reviewed with reference to the different OTTs. Biofilters and biotrickling filters represent the two most applied technologies for odor abatement at full-scale plants, due to lower costs and high removal efficiencies. An analysis of the odors emitted by the different wastewater treatment units is reported, with the aim of identifying the principal odor sources. Innovative and sustainable technologies are also presented and discussed, evaluating their potential for full-scale applicability.

Keywords: odor impact; VOCs; biofilter; ammonia; biological treatment; chemical-physical treatment



Citation: Senatore, V.; Zarra, T.; Galang, M.G.; Oliva, G.; Buonerba, A.; Li, C.-W.; Belgiorno, V.; Naddeo, V. Full-Scale Odor Abatement Technologies in Wastewater Treatment Plants (WWTPs): A Review. *Water* **2021**, *13*, 3503. <https://doi.org/10.3390/w13243503>

Academic Editor: Liu Ye

Received: 19 October 2021
Accepted: 26 November 2021
Published: 8 December 2021

Publisher's Note: MDPI stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.



Copyright: © 2021 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

Odorants arise from many anthropogenic sources, such as refineries, petrochemical industries, livestock production, food processing, chemical factories, and sanitary environmental facilities [1]. This phenomenon is mostly encountered in developing countries due to the proliferation of industries and lack of environmental protection policies [2,3]. Meanwhile, the advent of EU environment and climate change policies demonstrates a growing concern for the quality of the environment in terms of focusing on an improvement of air quality and reduction of greenhouse gas (GHG) emission [4]. In the case of air quality management, odor emission is considered an air pollutant that required immediate attention [5]. Unwanted odors are mostly generated from environmental treatment facilities such as wastewater treatment plants (WWTPs), sanitary landfills, composting, etc. In the past, WWTPs were engineered and designed primarily for the removal of inorganic and organic pollutants in the influent. However, there is no comprehensive program in odor management in WWTPs implemented by the operators [6]. The identification of effective solutions to reduce odor emissions and related complainants are thus of fundamental importance to increase the acceptability and sustainability of the facilities needed in the urban water cycle and to limit the negative impacts on the surrounding area to ensure correct process management [7,8].

Pollutants generated during the treatment of wastewater can bring physical and psychological discomfort to the people living in the surrounding area of the plants [5,9]. Some odorous compounds such as hydrogen sulfide (H₂S), ammonia (NH₃) and volatile organic compounds (VOCs) might lead psychological impacts to humans such as anger, mood disturbance, depression, etc., as well as health effects such as headaches, eye sores and mucous membrane irritation, dizziness and other respiratory-related problems [10,11]. These compounds are considered dominant among the several substances identified by some studies in odor emissions produced in wastewater treatment processes [12,13]. As a result, there has been a boost in the number of complaints caused by malodorous emissions associated with wastewater treatment plants over recent years [14]. The unpleasant odor may economically affect the value of the surrounding properties [13,15]. This mandates the authorities to legislate new laws such as adjusting and setting emission limits [16].

Countries, individual states and provinces adopt odor policies with different strategies, which have been summarized in [17]:

- No specific mention of odor issues in environmental legislation;
- Setting of emissions limits of the single pollutants which can be related to odor impact;
- Assessment of odor in terms of perceived nuisance;
- Extensive odor assessments, with odor sources characterization, dispersion modelling, ambient odor monitoring, setback distances, process operations, and odor control technologies and procedures.

There is no comprehensive approach used in odor regulatory systems, and methods and tools for management and control can derive from the characterization of the odor concentration or of individual chemicals. Jurisdictions have not yet promulgated regulations with standardized odor methodologies and objective criteria commonly use the principles of nuisance law to fundament the management of odor annoyance [17]. Some European countries generally determine odor exposure limits set as emission limit values (ELV) in $\text{ouE}\cdot\text{s}^{-1}$ or $\text{ouE}\cdot\text{h}^{-1}$. On the other hand, in several U.S. states, the dilution-to-threshold (D/T) field olfactometry approach is used to set the limits [18].

Nowadays, wastewater treatment industries have to adapt to a stricter law on odor management by providing more efficient, cost-effective and environmental-friendly odor-control technologies to make WWTPs management more sustainable. There are two main strategies for controlling malodorous emissions released from WWTPs, which consist in (1) the prevention of odor production as a result of good management of the plant [19,20], and (2) the applications of abatement and control technologies for the identified odorous compounds [21–23]. Barriers to contain odor emissions within certain areas using trees as buffer zones is a passive strategy used for reducing annoyance among the residents. However, the efficiency of this solution relies on weather conditions (i.e., wind speed, direction, etc.) [24]. On the other hand, chemical agents are used to control malodorous molecules released from WWTPs by masking and/or destroying them [25] but this method is only ideal at low concentration levels [11]. Although some chemicals can stabilize odors, they may potentially determine even more odor if they are not properly dosed [26,27]. An odor emission characterized by high odor concentration may indeed still be present, with a different degree of pleasantness or unpleasantness (i.e., hedonic tone) due to the numerous byproducts which may be produced during the reaction.

In areas where there is a high density of people, the primary strategy is to convey the odor source and treat the emissions. This strategy can be implemented by isolating the source with confinement structures and then collecting the conveyed flue gases to an Odor treatment technology (OTT) system. OTTs can treat odorous compounds chemically and/or biologically, removing or turning odorants into odorless compounds [28]. The utilization of structures for covering the different treatment units in WWTPs minimizes odor emissions, disperses them in the atmosphere and reduces evaporation. In this way, less water and chemicals are required in the wastewater treatment process.

The odor treatment technologies are classified mainly into hybrid (e.g., physical and chemical) and biological techniques. Physical and chemical techniques have a high

abatement efficiency and robustness when operated and maintained properly, low empty bed retention time (EBRT), rapid start-up. However, some drawbacks are still present [6], mainly consisting in the fact that regular use of consumables (i.e., adsorption material and chemical agents) can be a contributing factor to a high operating cost and the disposal of waste materials is a challenge in a circular economy perspective [27]. On the other hand, biological techniques constitute a more cost-effective and environmental-friendly alternative [29,30], but can present significant investment costs (e.g., bioscrubbers) or land requirements (e.g., biofilter) [31]. Among the biological techniques, the biotrickling filter has been identified as one of the promising solutions due to its efficiency, cost-effectiveness and sustainability [32].

The present review aims to categorize and critically analyze different abatement and control technologies applied to WWTPs for odor management. A proof and updated analysis of the state-of-the-art about full-scale OTTs installation in WWTPs is needed due to the scarcity of comparative analyses in terms of cost-benefits balance. It is essential to compare technologies at the industrial scale to show the robustness of the process under working flows fluctuation and wide range of pollutant concentrations.

2. Odor Emissions in WWTPs

During the wastewater collection and treatment operations, a mixture of several chemical compounds that can produce an unpleasant odor are generated through anaerobic decomposition of organic matter [1,23,33]. The odor is generated from the mixture of different volatile chemical species which can trigger the sensation of odor [33]. It is thus due to the interaction of different volatile chemical species, in particular sulfur compounds (e.g., sulfides, mercaptans), nitrogen compounds (e.g., ammonia, amines) and volatile organic compounds (e.g., esters, acids, aldehydes, ketones, alcohols) [34]. Volatile organic compounds (VOCs) are a large group of compounds, with different functional groups such as volatile fatty acids, alcohols, aldehydes, amines, carbonates, esters, sulfides, disulfides, mercaptans, and heterocyclic nitrogen compounds, characterized by a certain volatility. Conversely, inorganic compounds (H_2S , NH_3 , Cl_2) due to their low molecular weights can bind olfactory receptors and affect odor level [35]. Table 1 summarized the threshold levels of principal malodorous compounds detected in WWTPs.

Table 1. Odor threshold level of the main WWTP odor compounds.

Compounds	Odor Threshold Level (ppb)	Description	References
Hydrogen sulfide (H_2S)	0.47	Rotten eggs	
Sulfur dioxide (SO_2)	10	Pungent garlic	
Methyl mercaptan (CH_3SH)	0.07	Rotten cabbage	
Dimethyl sulfide ($(CH_3)_2S$)	0.2	Rotten vegetables, garlic	
Ammonia (NH_3)	10	Pungent, irritating	
Methylamine (CH_3NH_2)	4700	Fish	
Dimethylamine ($(CH_2)_2NH$)	340	Fish	[11,12,29,36,37]
Trimethylamine ($(CH_3)_3N$)	4	Fish	
Acetic acid (CH_3COOH)	1000	Vinegar	
Indole (C_8H_7N)	0.0014	Fecal, repulsive	
Skatole (C_9H_9N)	0.006	Fecal	
Benzene (C_6H_6)	270	Paint thinner	
Toluene ($C_6H_5CH_3$)	46	Fruity, paint, pungent, rubber	
Xylene ($C_6H_4(CH_3)_2$)	38	Plastic	

Over the years, scientists analyzed many WWTPs and odor emission capacity (OEC) measurements were realized in primary sedimentation units ($10,000 \text{ OU m}^{-2} \text{ h}^{-1}$), in sludge-digestion tanks ($8200 \text{ OU m}^{-2} \text{ h}^{-1}$), and sludge thickening and dewatering facilities ($2500 \text{ OU m}^{-2} \text{ h}^{-1}$). Lower values have been identified in the denitrification (anoxic) ($730 \text{ OU m}^{-2} \text{ h}^{-1}$) and nitrification (aerobic) tanks ($510 \text{ OU m}^{-2} \text{ h}^{-1}$). Primary sedimentation units, sludge thickeners and dewatered sludge are considered the main responsible for odor nuisance. To further justify this finding, Giuliani et al., (2015) [36] and Zarra et al., (2014) [37] demonstrated that raw wastewater and sludge thickening account for roughly 52% of the total emissions and for 40% of disposal activities. The major odor sources are indeed associated with pretreatment units (pumping station, grid), primary sedimentation and sludge thickening (Figure 1) [13,15,38,39].

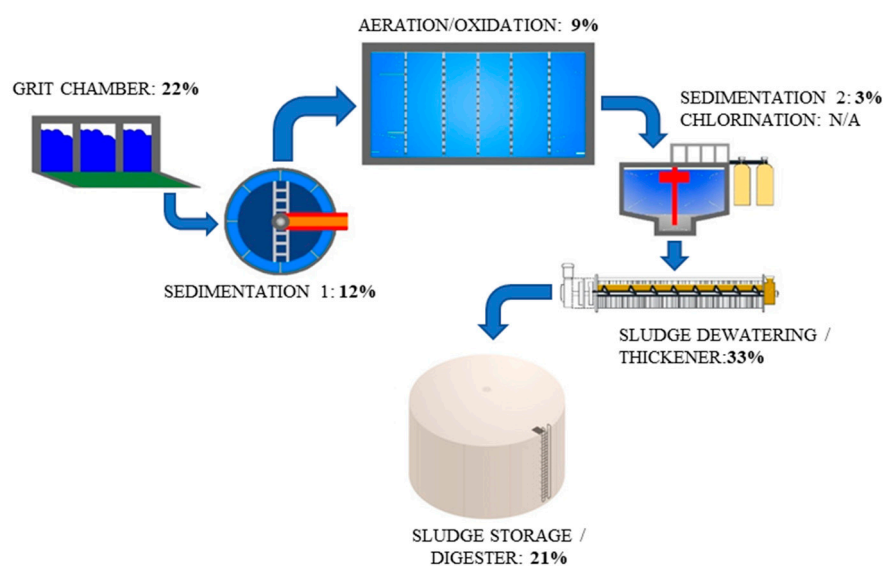


Figure 1. Average percentage distribution of odor emission sources from the principal treatment units in WWTPs.

2.1. Volatile Organic Compounds (VOCs)

Volatile organic compounds (VOCs) are toxic organic chemicals that evaporate under normal atmospheric conditions due to their high vapor pressures, low boiling points and low water solubility [31,40]. The main alarming VOCs emissions are related to the presence of “BTEX” (benzene, toluene, ethylbenzene and xylenes) that are considered harmful gases and detrimental to the environment. In particular, petrochemical WWTPs have been characterized among the main VOCs emissions sources, with consistent emissions of BTEX [38,39,41].

The World Health Organization (WHO) identified many VOCs as the most dangerous for human health [42]. In fact, benzene is known as one of the strongest carcinogenic agents [43]. Others are suspected to be carcinogens but also can have toxic effects on human health and destroy the stratospheric ozone, produce tropospheric ozone and form photochemical smog [10].

2.2. Hydrogen Sulfide (H_2S)

Hydrogen sulfide (H_2S) is an extremely toxic gas, and it is responsible for the typical odor of rotten eggs in WWTPs. When the concentration of H_2S is around 1000–2000 ppm with an exposure time of minutes, it can be rapidly absorbed through the lungs causing instant death [44]. Table 2 reported the hazardous concentration at different exposure times. Crude petroleum and natural gas contain H_2S . However, in WWTPs H_2S is also a byproduct of bacteria digestion of organic materials. In WWTPs, sulfur exist as either organic sulfur from feces or inorganic sulfur from the sulfate ion (SO_4^{2-}). Typically, microbial reduction of SO_4^{2-} is the dominant mechanism of H_2S formation. Besides, H_2S can be formed whenever

sulfur-containing compounds are exposed to organic materials at high temperatures [45]. Hydrogen sulfide has low solubility in wastewater. The TLV–STEL (threshold limit values at short term exposure limit) is the maximum concentration that workers can be exposed to for 15 min during a workday. TLV–STEL for H₂S in the air is 24 mg m^{−3} 35 ppmv), and the concentrations of H₂S founds nearby WWTPS without odorous compounds control systems generally exceeds the following limit. If the workers' exposure is below the preset daily limit, they may avoid the adverse health effects.

Table 2. Hazardous concentration levels for H₂S.

Concentration (ppm)	Duration of Exposure	Effect on Human Health	References
0	-	Normal concentration in air	
5	-	Moderate odor, easily detectable	
10–20	10 min	Eye irritation	
30–100	4–10 min	Serious eyes damage	[38,46–48]
100–250	2–16 min	Coughing, loss of smell	
300–700	30–60 min	Pulmonary oedema and risk of death	
1000–more	Few seconds	Immediate collapse with paralysis of respiration	

2.3. Ammonia (NH₃)

Ammonia (NH₃) is another malodorous compound in WWTPs caused by bacterial decomposition of urea generated from human activities. Its pungent character makes it easy to identify, among other gases. Furthermore, it can cause nose and throat irritation, bronchiolar and alveolar edema, and airway destruction. Due to the low evaporation temperature, ammonia can easily evaporate and release odors in the atmosphere. The TLV–STEL for NH₃ in the air is 69 mg m^{−3} (50 ppm). Usually, the concentrations of NH₃ that arise in wastewater is lower than the threshold value. However, an air pollution control system is still mandatory to avoid NH₃ reacting with other compounds, thus, reducing the overall emissions. Table 3 reported the hazardous concentration at different exposure times.

Table 3. Hazardous concentration levels for NH₃.

Concentration (ppm)	Duration of Exposure	Effect on Human Health	References
15–30	-	Mild discomfort, depending on whether an individual is accustomed to smelling ammonia	
40–90	2 h	Perceptible eye and throat irritation	
100–140	5 min	Tearing of the eyes, eye irritation, nasal irritation, throat irritation, chest irritation	[49,50]
100–140	2 h	Serious irritation, need to leave exposure area	
300–500	30 min	Respiratory tract irritation, tearing of the eyes	
700–2000	-	Incapacitation from tearing of the eyes and coughing	
5000–more	Few seconds	Rapidly fatal/lethal	

3. Odor Emissions Management in WWTPs

During the last decade, national and international authorities have increased their interest in resolving odor problems. In Europe, according to the Directive 2008/98/CE, “Member States shall take the necessary measures to ensure that waste management is carried out without endangering human health, without harming the environment and, in particular: (b) without causing a nuisance through noise or odors”.

There are two main approaches to odor emission control, the first one is to apply a different strategy without any treatment unit, and the second one is to apply an OTT for the specific treatment of emissions.

The main strategies for reducing or masking the odorous emissions from WWTPs are good process design, good operational practices [46], implementation of buffer zones [51] and spraying masking agents [25].

Different technologies are applied for the odor emission treatment, they can be divided into three main groups: physical, chemical, and biological technologies. For the treatment of the emissions from the different units of the WWTP, it is necessary to cover the odorous sources. OTTs are based on the collection and treatment of the odorous emissions generated in WWTPs, reducing or removing the concentration of odorants before being released to the atmosphere [31].

Chemical scrubbers and activated carbon filters are the most widespread pilot plant scale physical/chemical technologies used in WWTPs for odor treatment [47]. These odor abatement techniques are based on chemical oxidation [48] and solid-phase adsorption [52]. Biological OTTs such as biofilters, biotrickling filters, bioscrubbers and activated sludge diffusion, are based on the biological oxidation of chemical agents by microorganisms once they have been transferred from the gaseous emission to an aqueous phase [23,30]. Different methods can be used for odor measurement such as sensorial, analytical and senso-analytical techniques [53,54]. Sensorial approaches such as dynamic olfactometry, field inspection and recording from residents are based on how humans respond to emissions, while analytical methods, such as gas chromatography-mass spectrometry (GC/MS), identification of specific compounds, infrared and electrochemical sensors, etc., are based on a laboratory. Senso-analytical methods are the most promising. They overcome the main drawbacks of using analytical instruments (e.g., expense and inability to quantify the odor of a gas mixture), in the field for the prediction of the odor released on-site [53]. Among senso-instrumental methods, instrumental odor monitoring systems (IOMSs), also known as “electronic noses” (e.Noses), represent the tool with the greatest potential for future development for the continuous monitoring of environmental odors, with a view to obtaining real-time information [5].

One of the main sensorial approaches used to measure odor concentration (OUE m^{-3}) is dynamic olfactometry regulated by EN13725:2003 [14,45]. According to European standardization, 1 OUE m^{-3} is defined as the amount of odorant that, when evaporated into 1 m^3 of gas air at standard conditions, causes a physiological response from a panel (detection threshold) equivalent to that of n-butanol (reference gas) evaporated into 1 m^3 of neutral gas [1,55]. Meanwhile, under analytical methods, GC-MS has been widely used for the measurement of chemical concentration. This tool can only measure the mass concentration (ppm or mg m^{-3}) of a single or multiple gaseous compounds that is/are responsible for odor, but not the odor concentration of the emission [37]. Nonetheless, the quantity of gas determined by GC-MS can correlate to acquire insights on the odor concentration [56].

During the last decades, IOMSs have been improved by hardware components and the selection of the array of the sensors [38,39]. A set of nonspecific sensors are used to characterize an odor by IOMS, where each sensor is responsive to a variety of odorous compounds, but reacts differently to each other [5,57]. It can provide a total response output from a simple or complex odor immediately [37]. In contrast, the measurements in conventional GC-MS required further interpretation of a statistical program to obtain the analysis [56,58]. Moreover, IOMS can be applied on-site while sensorial and analytical analysis of odor can mostly be carried out in the laboratory.

OTTs are installed, principally, where the odor emissions are higher in terms of flow rate and odorant loads. As reported in Figure 2, 52% of the OTTs analyzed were installed at the headworks of the plant (e.g., pumping station, screening systems, grit systems). Twenty-nine percent of the OTT installations investigated were located at the sludge treatment units, while only 19% of OTTs were implemented to treat odorous emissions at primary

treatment. The results obtained from this analysis agree with the data shown in Figure 3, where the principal malodorous units in WWTPs were reported.

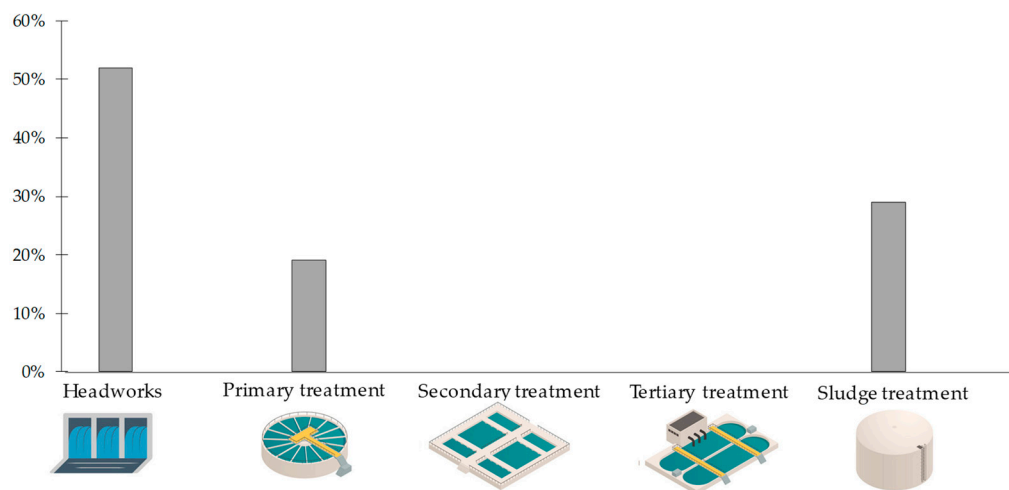


Figure 2. Localization of OTTs in WWTPs.

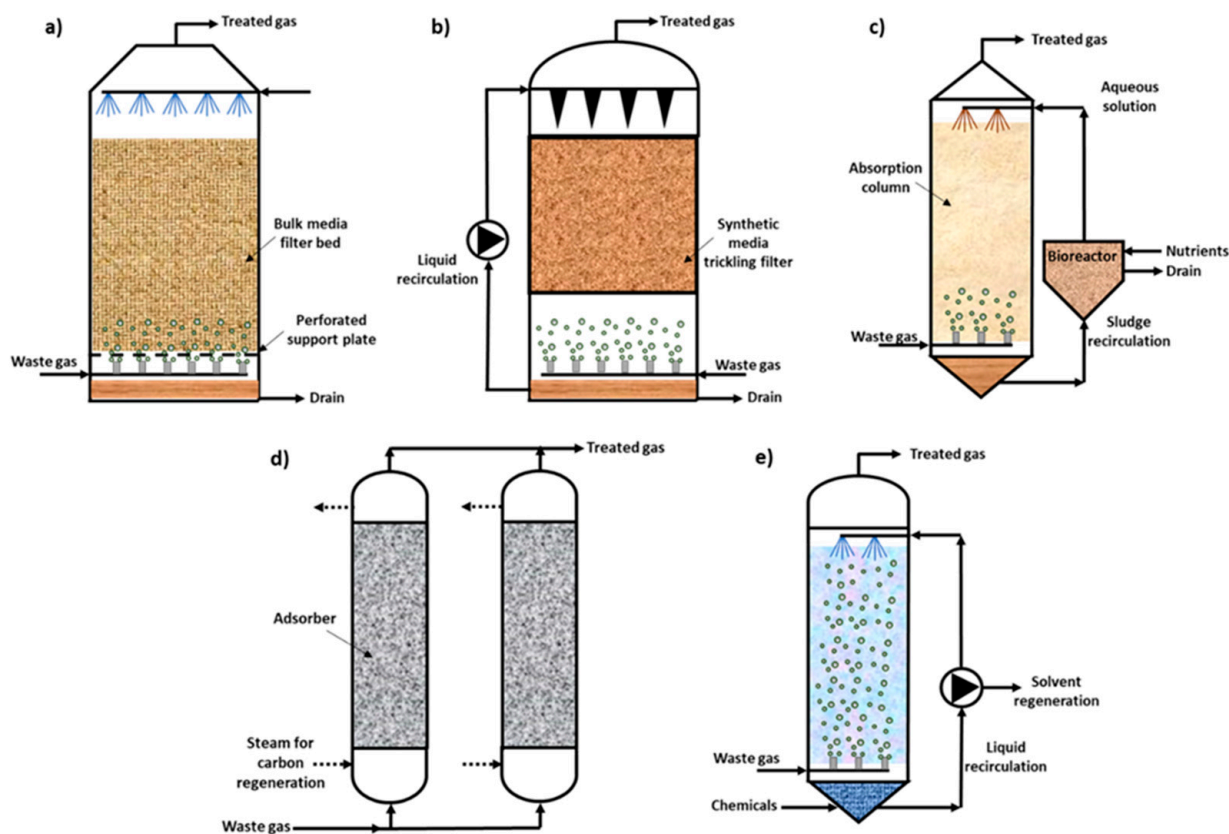


Figure 3. Odor abatement technologies: (a) biofilter, (b) bio-trickling filter, (c) bio-scrubber, (d) adsorption system and (e) chemical scrubber.

4. Full-Scale OTTs in WWTPs

Only a few reviews [6,12] explored, collected and summarized chemical/physical and biological technologies for the treatment of odorous emission. Figure 3 reports the configuration of the main chemical/physical and biological technologies applied in WWTPs for the treatment of odorous compounds emissions.

Biologically based odor treatment technologies, such as biofilters, biotrickling filters, and bioscrubbers have gained more and more popularity due to their lower O&M cost, reduced energy and chemical consumption and the absence of expensive adsorbent materials. Biotechnologies also have a more environmentally friendly profile because pollutants are finally converted into innocuous compounds such as CO₂, H₂O and biomass at ambient pressure and temperature. *Best Available Techniques (BAT) Reference Document for Common Waste water and Waste gas Treatment/Management Systems in the Chemical Sector* (2016) reported an overview of end-of-pipe odor treatment techniques. This document reported the advantages of biofiltration, including (i) low shift of pollution to any other media, (ii) few chemical agents added, and (iii) low energy consumption. Moreover, it also suggested the combination of biofiltration and bioscrubbing since the bioscrubber may act as a humidifier and degrade a high portion of the odorous load.

In a biofilter system (Figure 3a), the odorants are forced through a packed bed (compost, peat, bark or a mixture of these) on which the microorganisms are attached as a biofilm. The pollutants are absorbed by the filter material and degraded by the biofilm.

In BTF (Figure 3b), the odorous gas is forced through a packed bed filled with a chemically inert carrier material that is colonized by microorganisms, similar to trickling filters in wastewater treatment. The liquid medium is recirculated over the packed bed and the pollutants are first taken up by the biofilm on the carrier material and then degraded by the microorganisms. The liquid medium can be recirculated continuously or discontinuously and in a co- or countercurrent to the gas stream. Flow directions will not affect the efficiency of the process.

In BS (Figure 3c), the pollutant is adsorbed in an aqueous phase in an absorption tower then converted by the active microorganisms into CO₂, H₂O and biomass in a separate activated sludge unit. The effluent is circulated over the absorption tower in a co- or countercurrent direction to the gas stream.

Physical/chemical technologies consist of two types of reactors, namely adsorption systems and chemical scrubbing. Adsorption systems (Figure 3d) generally consist of static beds of granular materials in vertical cylindrical columns. Among purification methods, adsorption is simple and easy to apply to real-scale wastewater treatment plants [59]. Several sorbents have been studied, including fly ash, carbon, activated carbon, polymers, carbon-coated polymers, ceramics, micro- and mesoporous materials, metal-organic frameworks, natural zeolites, and synthetic zeolites. Chemical scrubbers (Figure 3e) are among the most mature abatement techniques employed in WWTPs due to the extensive experience and high robustness as well as the short gas retention time (as low as 1–2.5 s). The most common configuration (Figure 3) is a vertical shell with gas flow going up through packing and the liquid solution (depending on the target compounds) going down. The liquid solution is usually circulated over the packing by pumping from a collection sump in the bottom of the tower, while chemicals are added either in the sump or in the recirculation piping.

To the best of our knowledge, the current work is the first review paper to analyze and compare more than 50 full-scale odor treatment technologies (chemical/physical and biological) applied in WWTPs. The main characteristics of full-scale OTTs found in the scientific literature are reported and critically analyzed for each treatment method.

4.1. Biofilter

Different studies [60–63] reported H₂S and NH₃ as the main pollutants removed by the biofilters (BFs). In the Subiaco Wastewater Treatment Plant (Western Australia, the waste gas flowrate of 65,000 m³ h⁻¹, 75 ppm H₂S and 5 ppm NH₃), a biofilter installed after the acid scrubber to promote the formation of a biofilm for H₂S removal, was then moved to the inlet of the scrubber to treat H₂S and NH₃ mixtures [63]. BFs were also used to treat odors from the sludge thickeners, effluent channel and influent splitter box at the Mill Creek WWTP of the Metropolitan Sewer District of Greater Cincinnati [64] and in Shandong, China with PU packing materials [65]. The REs, in terms of H₂S and NH₃

concentrations, to be higher than 90%. The removal yields thus reduced odor emissions to under detection limits. Compared to scrubber operations which entail using of acid/alkali as scrubbing media, BFs can provide less negative environmental impacts because water is added instead of chemicals and small amounts of leachate are produced. However, the capital and operating costs must require further investigation to consider this target. High concentrations of H₂S were detected at pumping stations in the WWTP of the City of Birmingham (Alabama), at a WWTP of South Walton (Florida) and at Etaples-Le Touquet's WWTP (Artois-Picardie Region, France) [66]. The H₂S levels fluctuations ranged between 4–26 ppm. A total of six BF units were installed at the Birmingham WWTP (waste gas flowrate of 51,000 m³ h⁻¹), while BF with inorganic bed media was utilized in Le Touquet's WWTP. REs higher than 99% were obtained by utilizing the biofilters. Owing to the significant waste gas volume to treat and considering that these sites were mostly located in sensitive areas, even a slight exceeding of the threshold limits due to accidental leaks may be annoying and, consequently, strict monitoring is required also using a dispersion model [67], and/or, multiple BF units in series can be installed to increase the treatment efficacy [68].

Some papers dealt with the use of different packing materials to enhance biofiltration in municipal WWTP including peat [69] (Charguia, Tunisia with inlet H₂S concentrations ranging between 200–1300 mg m⁻³), seashells [70] (Lake Wildwood WWTP, California with 55,200 L h⁻¹ of wastewater flowrate and air flowrate of 28,300 L min⁻¹), polyurethane foam [65] (Shandong, China, H₂S, NH₃ and VOC inlet concentrations were 0.5–28.4, 0.9–34.3 and 0–0.9 mg m⁻³, respectively), advanced biofiltration with organic and inorganic phase in the medium [71] (Mallorca, Spain with air flow rate of 15,000 m³ h⁻¹), packed waste straw and cortex [72] (refinery WWTP in Shanghai, China). Using the modified packing materials, biofiltration was demonstrated to be an optimum OTT by having 90–99% RE. The goal of the authors was to provide a nutrient-rich environment for the bacteria in the packing material, which may increase the efficiency of the process. However, the efficiencies were dependent on the different operating conditions since the packing materials are sensitive to shock loadings. In a real case scenario, the H₂S inlet loads fluctuate, and sometimes, the loading rates overcome the microbial activity capacities. This scenario is challenging because the microbial population in the medium must be enough and must not be as a limiting factor [32]. Moreover, some articles assess removal yields in terms of odor concentrations measured with dynamic olfactometry in OUE m⁻³ [71,73]. In Harnaschpolder WWTP, a full-scale biofilter (headworks and the sludge handling units air flowrate: 60,000 m³ h⁻¹ and activated sludge including aerobic and anaerobic tanks air flowrate: 70–100,000 m³ h⁻¹) is applied [73], while in Middelfart's municipal waste water treatment plant (Norway), a BF is implemented in order to treat 1500 m³ h⁻¹ of odorous emissions from headworks and primary treatment areas [71]. Both BFs have performance higher than 96% RE. BFs were able to withstand an acidic environment without adding NaOH or NaOCl. Even though the filter must be periodically replaced and there are savings in chemical consumption, this phenomenon can bring to the production of high amount of acid leachate that might be difficult to dispose of.

Evaluating the studies, the type of packing material influenced the efficiency of biofilter, as well as other parameters such as pH and moisture content. Heterotopic bacteria are the dominant microorganisms. Moisture levels in the packing materials must be maintained only at the ideal point because, at low levels, the microbial activity might decrease, while at high levels, anaerobic zones can be present and decrease the amount of oxygen for biological activity, affecting OTT's performances. The bed must be continuously aerated to avoid anaerobic conditions. Table 4 summarizes the mean removal efficiencies of malodorous compounds using plant-scale biofilters.

Table 4. Operating parameters and performances of pilot plant-scale applications of biofilters.

Location	EBRT [s]	Air Flowrate	EC VOC	RE [%] VOC	EC H ₂ S	RE [%] H ₂ S	EC NH ₃	RE [%] NH ₃	Odor Reduction	RE [%] Odor	Reference/s
'Subiaco, Australia	9.33	45 (50,000)	—	—	45	92	0.00043	100	—	—	[60,63]
'City of Birmingham, Alabama, U.S.A.	—	51,000	—	—	—	99	—	—	—	—	[74]
'Baltimore County, Maryland, U.S.A.	24	17,000	—	—	—	99	—	—	—	—	
'Mill Creek, Cincinnati, Ohio, U.S.A.	—	10,000	—	95	—	99	—	—	—	—	[61]
'Beijing, China	60	250	—	—	2.53	90	0.41	95	—	—	[65]
'Penn Valley, California (Lake Wildwood WWTP)	—	1680	—	—	—	99	—	—	—	99	[70]
'Al-Nasiriyah, Iraq	40	5000	—	—	12	98	5	95	—	—	[75]
'Carson, California, U.S.A.	60	34,000	—	—	—	70	—	80	—	—	[74]
'Mallorca, Spain	—	15,000	—	90	—	—	—	97	9500	95	[71]
'Middelfart, Denmark	—	1500	—	95	—	98	—	—	12,000	99	
'Brownsville, Texas, U.S.A.	60	10	—	—	99	99	—	—	—	—	[76]
'Shandong, China	30	828	—	95	—	98	—	80	—	—	[65]
'Ohio, U.S.A.	56	9000	—	—	14	95	—	—	—	—	[64]
'Shanghai, China	120	500	120	500	0.2	90	0.4	98	—	—	[72]
'Etaples-Le Touquet, France	6	250	—	—	—	99	—	—	—	—	[66]
'Charguia, Tunisia	60	—	—	—	58	99	—	—	—	—	[69]

Note: Unit for EC: $\text{g m}^{-3} \text{h}^{-1}$; Unit for Odor Concentration: $\text{OU}_E \text{m}^{-3}$ Unit for volumetric air flowrate: $\text{m}^3 \text{h}^{-1}$. WWTPs types: (') municipal WWTP.

4.2. Biotrickling Filter

Kasperczyk et al. [38] tested a semi-industrial scale biotrickling filter in a WWTP in Poznań (Poland) for the treatment of odor in the exhaust air with 440 ppm_v H₂S and 240 ppm_v VOCs at maximum. The authors used biocatalysts such as *Pseudomonas fluorescens* bacteria and bacterial strains *Thiobacillus* sp. to promote the formation of the BTF's biofilm to metabolize the odorants. Yang et al. [16] studied biotrickling filters in a chemical fiber WWTP at both lab- and pilot-scale to degrade TVOCs. At the laboratory scale, the degradation seemed to be due to the combination of adsorption and biological reactions (i.e., 90% RE on the fourth day and a declined during the fifth to eighth day). However, in the pilot-scale WWTP, RE was affected by the EBRT, since REs decreased by more than 40% when the EBRT was reduced to 32 s. This condition might be due to the scale-up of the BTF. Furthermore, Wu et al. [77] achieved 95% of RE in a pilot-scale BTF in a Singapore WWTP, while Cox et al. [78] obtained 98% of RE for H₂S and VOCs at the Hyperion WWTP in Los Angeles, (California). Chen et al. [79] achieved RE of 96% in BTF using activated carbon-loaded polyurethane packing materials to remove H₂S in the upper layer and modified organism-suspended fillers in the lower layer, with EBRTs lower than 1 min.

The BTFs in the investigated studies [9,44,75,76] demonstrated high efficiencies (higher than 85% of RE). Guerrero and Bevilacqua [80] evaluated the performance of a BTF to treat H₂S emissions from a UASB reactor. Only 50.9% of RE for H₂S was obtained in the experiment, carried out on a real case scenario (brewery WWTP) with EBRT of 1.6 min and, thus, values were higher than in other studies. This condition in the scenario might be due to the type of microorganisms in the packing materials utilized. These were an autotrophic H₂S-degrading culture obtained from the anaerobic sludge of the UASB reactor of the WWTP, sensitive to a temperature lower than 29 °C.

Biotrickling filters are capable of treating high inlet loads compared to other OTTs, but their efficacy is still strongly dependent on the type of packing material. In fact, the study of Lakey [81], reported that a BF in the WWTP of Perth (Australia) with an inlet air flowrate of 79,000 m³ h⁻¹ achieved a H₂S RE of 99.5% and a VOCs RE of 95%. The replacement of chemical scrubbers with BTFs can be thus considered economically viable

since the theoretical consumption of need chemicals for the absorption and oxidation of both H₂S and VOCs [82].

Plastic fibers (i.e., polyurethane foams) are preferred in some studies to enhance the BTFs' removal performances [65,83]. In terms of operation, the BTF requires relatively low power, since only the pumping phase requires energy and an aeration blower is not needed. Moreover, less sludge is produced than by suspended-growth systems. Despite the high manufacturing costs of this technology, their life span is longer than ordinary packing material. On the other hand, the clogging incidence is expected and the packing material's porosity has to be periodically maintained by back-washing. The generated sludge needs further treatment and disposal and the final effluent must be treated in the WWTP [83].

Table 5 summarizes the mean removal efficiencies of malodorous compounds using pilot plant-scale application of bio-trickling filters.

Table 5. Operating parameters and performances of pilot plant scale applications of biotrickling filters.

Location	EBRT [s]	Air Flowrate	EC VOC	RE [%] VOC	EC H ₂ S	RE [%] H ₂ S	EC NH ₃	RE [%] NH ₃	Odour Reduction	RE [%] Odour	Reference/s
'Singapore	20	—	—	—	95	—	—	—	—	—	[77]
Huntington Beach, California, U.S.A.	—	—	—	—	30	—	—	—	—	80	[56,84]
Huntington Beach, California, U.S.A.	—	—	—	—	60	—	—	—	—	40	
Poznań, Poland	30	10	90	18	85	—	—	—	—	—	[38]
'China	—	—	—	39.95	99	—	—	—	—	—	[79]
"China	—	—	90	—	—	—	100	—	—	—	[16]
'South Walton, Florida, U.S.A.	2000	—	—	—	99	—	—	—	—	90	[74]
Singapore	2000	—	—	—	99	—	—	—	—	90	
'Beenyup, Perth, Australia	79,000	—	95	—	99	—	100	15,500	15,500	95	[81]
'Poland	—	—	—	—	99	—	—	20,000	20,000	90	[85]
'Manresa, Barcelona, Spain	1200	3.3	46	—	—	13	82	—	—	—	[86]
'California, U.S.A.	16,300	—	—	90	98	—	—	—	—	85	[87]
'Pusan, South Korea	12,000	—	95	—	—	—	—	—	—	—	[74]
'Kayang, Seoul, South Korea	30,000	—	—	—	99.8	—	96.7	—	—	—	
'Moscow, Russia	10,000	—	—	—	95	—	—	—	—	—	[88]
'Los Angeles, California, U.S.A.	2500	—	—	10	99	—	—	—	—	99	[74]
"*Cuoiodapur, Pisa, Italy	8000	—	—	90	80	—	—	—	—	—	[89]
'Nieuwe Waterweg, Hoogheemraadschap van Delfland, Netherlands	3500	—	—	55	98	—	—	—	—	—	[73]
'Harnaspolder	800	—	—	—	—	—	—	20,000	20,000	96	
'Hyperion Treatment Plant, California, U.S.A.	600	1.5	40	13	98	—	—	—	—	97	[78]
'Jacksonville, Florida, U.S.A.	845	—	—	50	99	—	—	—	—	—	[90]
"*Araraquara, Sao Paulo, Brazil	—	—	—	2	70	—	—	—	—	—	[80]
'London, United Kingdom	2450	—	—	5	98	—	—	100,000	100,000	93	[91]
'Cubelles-Cunit WWTP, Barcelona, Spain	10,000	2	70	10	85	—	—	25,000	25,000	90	[82]

Note: Unit for EC: g m⁻³ h⁻¹; unit for odor concentration: OU_E m⁻³; unit for volumetric air flowrate: m³ h⁻¹. WWTP types: (') municipal WWTP, (") chemical fiber, (*') tannery WWTP, (**') brewery WWTP.

4.3. Scrubber System

Baawain et al. [45] reported the application of a chemical wet scrubber (with two identical parallel-train cross-flow systems) as OTT in Al-Ansab WWTP (Oman), with wastewater flowrate of 2300 m³ h⁻¹, waste gas flowrate of 160,000 m³ h⁻¹ and H₂S inlet concentrations of 65–170 ppm. The removal efficiency ranged between 80 and 96%, but declined to 67% during the maintenance period. Meanwhile, some papers investigated the

usage of oxidants in the scrubbing medium to enhance wet scrubbing efficiency. For example, Kerc and Olmez [92] analyzed different scrubbing compounds (i.e., water, ozonated water, caustic and ozone injected caustic) to remove H₂S in Tuzla WWTP (Istanbul, Turkey) in which 99% RE was achieved using caustic scrubbing and ozonation, while Yang et al. [93] utilized peroxymonosulfate (PMS) as an oxidant for odor reduction (e.g., methyl mercaptan, CH₃SH(G)) in a wet scrubbing process. Furthermore, in Orange County Sanitation District, California, Zhou et al. [56] used both chemicals and bioscrubbers in one plant (headworks and primary treatment) and another (headworks), respectively, while Biard et al. [94] investigated a conventional chemical scrubber to treat H₂S using NaOH and NaOCl solution.

Zhou et al. [56] revealed that chemical scrubbers and biofilters performed best among other odor control technologies (OCTs), while Kerc and Olmez [92] offered ozonation as an effective scrubbing enhancement. However, the cost of installation and complexity of the operation must be taken into account. To accelerate the mass transfer of gas pollutant to a liquid solution, Yang et al. [93] showed that synthetic oxidants can be applied. The approach of Kerc and Olmez [92] and Yang et al. [93] offered a promising technique to enhance the efficiency of wet scrubbing, but the production of byproducts in the liquid solution has to be further investigated.

Wet treatment techniques such as scrubbers in odor control are mostly applied because the gaseous pollutant can be dissolved in liquid phase and temporarily stabilized for further treatment [5]. Chemical scrubbers have the ability to deal with a wide range of gas pollutants from sulfur to acidic gases and can tolerate fluctuating temperatures, which is ideal for operation in almost any environment. However, they require periodic maintenance and suffer from corrosion due to chemical attacks. Table 6 summarizes the mean removal efficiency of malodorous compounds using pilot plant-scale application by scrubber.

Table 6. Operating parameters and performances of pilot plant-scale applications of scrubbers.

LOCATION	Waste Air Flowrate	RE [%] H ₂ S	RE [%] Odor	Reference/s
'Fountain Valley, California, U.S.A.	—	70	70	[56,84]
'Al-Ansab, Oman	160,000	100	—	[45,95]
'Damhusaaen, Copenhagen, Denmark	6000	99	—	[96]
'Mill Creek, Cincinnati, Ohio, U.S.A.	17,000	95	—	[61]
'Tuzla, Istanbul, Turkey	360	99	—	[92]
'France	2800	95	—	[94]

Note: WWTPs type: (') municipal WWTP.

4.4. Combined OTT

Integrated OTTs designs are implemented to address situations in which different typologies of odor compounds or high inlet loads are present. These cases are usually detected in refineries where high odorant concentrations, mainly BTEX, are present and, thus, a combination of different OTTs is [29,95,96]. Rada et al. [97] utilized a bioscrubber, two biotrickling filters and a biofilter with an overall RE higher than 70% to remove benzene (C₆H₆), while Torretta et al. [98] implemented water scrubbing followed by biofilter (Italy) with an overall RE of almost 95% (benzene inlet concentration of 12.4 mg m⁻³, benzene outlet concentration of 1.02 mg m⁻³, toluene inlet concentration of 11.1 mg m⁻³, toluene outlet concentration of 0.25 mg m⁻³, ethylbenzene inlet concentration of 2.7 mg m⁻³, ethylbenzene outlet concentration of 0.32 mg m⁻³, xylene inlet concentration of 9.5 mg m⁻³, xylene outlet concentration of 0.26 mg m⁻³). Another study of Raboni et al. [29] implemented water scrubbing as pretreatment, followed by a biotrickling filter and a biofilter (inlet air flowrate of 600 m³ h⁻¹, Refinery WWTP in Milan, Italy) with an overall RE of 96%, while Zhou et al. [56] used bioscrubbers and biotrickling filters at

the headworks and primary treatment units respectively, with a RE of 50–70% in terms of odour removal.

Torretta et al. [98] and Raboni et al. [29] utilized water scrubbing without adding chemicals (i.e., NaOH or NaOCl) with low REs (lower than 50% of total BTEX removal) since BTEX have moderate solubility in water. However, this condition might lead to the fact that the leachate is less dangerous than using chemicals and the lifespan of the wet scrubber is higher due to fewer corrosion problems. Biological methods (i.e., biofilters) can be regarded as polishing techniques or can be installed in points where the odor threshold is low (i.e., headworks) [73]. Lafita et al. [73] converted chemical scrubbers with biofilters to biotrickling filters (air flowrate of 2000–3500 m³ h⁻¹) with 95% RE in terms of H₂S removal at Hoogheemraadschap van Delfland WWTP (Netherlands). Municipal WWTPs have lower loads of sulfide and VOCs compared to refineries. Consequently, Martinez et al. [99] and Jones et al. [76] utilized the combination of a biotrickling filter and a biofilter to treat H₂S and VOCs (>91.00% RE of H₂S and >74.00% for VOCs) in real urban WWTPs. The biological systems successfully removed low concentrations of VOCs in the presence of highly fluctuating H₂S concentrations, but chemical scrubbing still needed pretreatment in heavy industries (i.e., refineries) that are characterized by high levels of odorous gases. Although chemical scrubbing is complex in terms of NaOH handling and material corrosion, biofilters' efficiency may be affected by the pressure drops due to compaction, water retention and excessive microbial growth that may cause clogging.

Other conventional methods are still used by some research such as air stripping [100] and carbon adsorption (at bioscrubber outlet) [84,101]. Finke et al. [101] managed odor emissions by a bioscrubber followed by four activate carbon filters (air flowrate of 52,000 m³ h⁻¹) in Merrimac WWTP (Gold Coast, Australia) with a 99.5% RE for VOCs, while a combination of absorption and a bioscrubber with 99% RE for H₂S was achieved by Hansen and Rindel [102] in a WWTP in Copenhagen (Denmark) (inlet flowrate of 6000 m³ h⁻¹). Behnami et al. [100] implemented a steam stripping technique which has been demonstrated as an effective solution for the pretreatment of the waste gas prior to biofiltration in a WWTP in East Azerbaijan (Iran) with a flowrate of 4800 m³ d⁻¹. The method was able to achieve a higher removal of VOCs. Further research must be carried out for H₂S loads fluctuation. Table 7 summarizes the mean removal efficiency of malodorous compounds using pilot plant-scale applications with a combination of different OTTs.

Table 7. Operating parameters and performances of pilot plant-scale applications of combination of OTTs.

LOCATION	EBRT (s)	Waste Air Flowrate	EC VOC	RE (%) VOC	EC H ₂ S	RE (%) H ₂ S	Odor Reduction	RE (%) Odor	Reference
*Milan, Italy	90	800	1	90	—	—	—	—	[29]
*Italy	—	600	—	90	—	—	—	—	[97]
‘Stuttgart-Büsnau, Germany	—	750	—	80	—	—	5000	90	[103]
‘Brownsville, Texas, U.S.A.	14	252	12	80	—	90	—	—	[99]
*Southern Italy	30	600	4.5	94	—	—	—	—	[98]
‘Merrimac, Australia	—	52,000	—	77	—	99	64,000	98	[101]

Note: Unit for EC: g m⁻³ h⁻¹; unit for odor concentration: OU_E m⁻³; unit for volumetric air flowrate: m³ h⁻¹. WWTP types: (‘) municipal WWTP, (*) refinery WWTP (CAS), (**) oil refinery WWTP (CAS).

5. Photo-Bioreactor Based on Algae–Bacteria Synergism

Environmentally friendly technology for the abatement of all types of emissions coming from plants are necessary to achieve the 17 sustainable development goals (SDGs) of the United Nations [104]. Biotechnologies have gained popularity thanks to the improvements driven by scientists. They contribute to the development of more robust and cost-effective

biotechnologies. Algae-based technologies use low-cost materials and are proven to be effective at laboratory scale as odor control processes in WWTPs [104]. The synergism between algae and bacteria biodegrades H₂S and VOCs while CO₂ biofixation occurs in open and closed photobioreactors has been studied and proved [30,31,105]. Biotechnologies used to treat odorous compounds released in the atmosphere [105]. Algal-bacteria photo-bioreactors could be an optimum choice due to the simultaneous treatment of odor compounds (e.g., VOC and H₂S) contained in waste gas and the capture of CO₂ [106].

Table 8 reports data from the scientific literature that prove the applicability of algal-bacteria photobioreactors for the biodegradation of contaminants emitted in the atmosphere from the wastewater treatments process. Moreover, due to the photosynthetic activities of microalgae, CO₂ biofixation is possible, while odorants (e.g., H₂S and VOCs) are oxidized.

Table 8. CO₂ biofixation efficiency and H₂S and VOC removal efficiencies of algal-bacteria photobioreactors.

Description	CO ₂ Biofixation Efficiency [%]	H ₂ S RE [%]	VOCs RE [%]	Reference
Algal-bacteria, tubular photo-bioreactor	79 ± 15	-	89 ± 3	[30]
Algal-bacteria, air lift photo-bioreactor	≈65	≈98	-	[107]
Algal, open photobioreactors	≈98	100	-	[108]
Algal-bacteria, open photobioreactors (HRAP)	99.5 ± 0.2	99.3 ± 0.8	97 ± 1	[109]

The algal biomass generated could be used to produce valuable byproducts (e.g., biofuel, fertilizers, pharmaceuticals, biopolymers, etc.) [110,111]. Even though it has been studied at a laboratory scale and demonstrated good efficiency in terms of oxidation of odorant compounds (e.g., VOCs and H₂S), a scaled-up analysis is needed for the evaluation of the robustness at full-scale application on a WWTPs with a real mixture of odorants.

6. Odor Emission Management in WWTPs

6.1. Sensitive Analysis

The empty-bed residence time (EBRT), removal efficiency (RE), elimination capacity (EC) and odor reduction of different OTTs were compared.

The empty bed residence time (EBRT) is defined as the contact time between the gaseous emissions and the biofilter media. EBRT is considered one of the principal operational parameters that influence the performance of gaseous compounds treatment technologies, particularly when hydrophobic odor compounds such as VOCs are involved [112].

Figure 4 presents the average OTTs' EBRT organized for the different full-scale technologies examined. Biofilters are operated at an average EBRT of 48 ± 30 s, which is considered the highest among odor treatment technologies, depending on the type of packing material and the contaminant inlet load. On the other hand, the bioscrubbers showed the lowest EBRT (7.5 ± 2.5 s). Biotrickling filters and the chemical scrubbers showed an EBRT of 22.2 ± 26.2 s and 20 ± 8.1 s, respectively.

Tables 9 and 10 depict respectively the average performance in terms of RE [%] and EC [g m⁻³ h⁻¹] of target odorants (VOC, H₂S and NH₃) for each OTT typology. Biofilter exhibit VOCs, H₂S and NH₃ RE [%] of 89.2 ± 8.9, 96.1 ± 5.1 and 93.0 ± 6.4, respectively. According to the data reported in Table 6, the bioscrubber and chemical scrubber are able to oxidize mainly VOCs and H₂S. The bioscrubber showed REs of 83.5 ± 6.5 and 76.0 ± 17.2%, respectively. On the other hand, chemical scrubbers demonstrated a VOCs RE of 94% and an H₂S RE of 92.8 ± 10.6%. Biotrickling filters have been proven to be one of the most promising technologies for odorant treatment showing VOCs, H₂S and NH₃ RE [%] of 77.6 ± 18.8, 92.3 ± 17.2 and 94.67 ± 7.4, respectively. Reporting the data in terms of EC, relevant results were achieved by biofilters and biotrickling filters obtaining H₂S EC of 31.7 ± 31.2 and 34.8 ± 31.2 g m⁻³ h⁻¹, respectively.

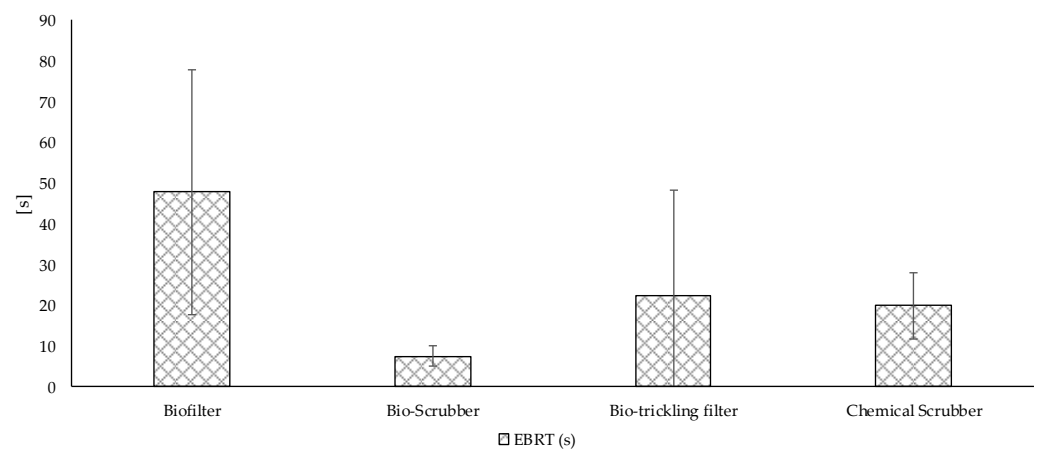


Figure 4. Average of EBRT of full-scale OTT application applied in WWTPs.

Table 9. Removal efficiency (RE) of VOCs, H₂S and NH₃ of full-scale OTTs applications applied in WWTPs.

OTTs	RE VOCs [%]	RE H ₂ S [%]	RE NH ₃ [%]
Biofilter	89.2 ± 8.9	96.1 ± 5.1	93.0 ± 6.4
Bioscrubber	83.5 ± 6.5	76.0 ± 17.2	n.a.
Biotrickling filter	77.6 ± 18.8	92.3 ± 17.2	94.7 ± 7.4
Chemical scrubber	94.0 ± 0.0	92.8 ± 10.6	n.a.

Table 10. Elimination capacity (EC) of VOCs, H₂S and NH₃ of full-scale OTTs applications applied in WWTPs.

OTTs	EC VOCs [g m ⁻³ h ⁻¹]	EC H ₂ S [g m ⁻³ h ⁻¹]	EC NH ₃ [g m ⁻³ h ⁻¹]
Biofilter	0.2 ± 0.0	31.7 ± 31.2	1.43 ± 2.1
Bioscrubber	n.a.	n.a.	n.a.
Biotrickling filter	5.0 ± 4.4	34.8 ± 31.2	13.0 ± 0.0
Chemical scrubber	4.5 ± 0.0	n.a.	n.a.

Limited results are reported in terms of $OU_E m^{-3}$ for the evaluation of OTT performance and some of them reported results only in terms of RE of odors. As reported in Table 11, biofilter and biotrickling exhibit an average RE in terms of odor equal to $97.7 \pm 1.9\%$ and $87.7 \pm 15.6\%$, respectively. The bioscrubber and the chemical scrubber demonstrated an RE of $89 \pm 9\%$ and $70 \pm 0\%$.

Table 11. Average of odor reduction [OUE m⁻³] and odor RE [%] of full-scale OTTs applications applied in WWTPs.

OTTs	Odor Reduction [OUE m ⁻³]	RE Odor [%]
Biofilter	10,750 ± 1250	97.7 ± 1.9
Bioscrubber	64,000 ± 1250	89.0 ± 9.0
Biotrickling filter	30,916.7 ± 6755.7	87.7 ± 15.6
Chemical scrubber	n.a.	70.0 ± 0.0

6.2. Cost Analysis

The operational and investment costs of the full-scale OTT assessed are reported in Table 12. High chemical and water requirements are necessary for the absorption of

odorants in chemical scrubbers; thus, it is less sustainable than others even with competitive investment costs. Adsorption systems have a lower investment cost per unit flow rate (5–12 EUR m⁻³ h⁻¹), but a very high operating cost (10–200 EUR m⁻³ h⁻¹) compared to the other technologies because of the periodic replacement of adsorptive material. Biofilters generally need more land than other options; however, its low investment (6–15 EUR m⁻³ h⁻¹) and operating costs (2–4 EUR m⁻³ h⁻¹) ensures a cost-effective technology. The investment cost (8–28 EUR m⁻³ h⁻¹) of BTFs is mainly related to the packing material used in the design (e.g., inorganic salts, polyurethane foam, activated carbon fibers, multisurface hollow balls etc.). However, the competitive operating cost (3–6 EUR m⁻³ h⁻¹) and the capability to treat high-load odorants ensure BTF as one of the most diffused technologies. Bioscrubbers, due to the high investment cost (10–32 EUR m⁻³ h⁻¹) and lower robustness at high loading rates, are not widely implemented for the treatment of malodorous emissions coming from WWTPs.

Table 12. Investment and operating cost for full-scale application.

Technology		Investment Cost	Operating Cost	References
Chemical/physical	Chemical scrubber	15–30 € m ⁻³ h ⁻¹	5–6 € m ⁻³ h ⁻¹	[113]
	Adsorption	5–12 € m ⁻³ h ⁻¹	10–200 € m ⁻³ h ⁻¹	[113,114]
Biological	Biofilter	6–15 € m ⁻³ h ⁻¹	2–4 € m ⁻³ h ⁻¹	[46,114]
	Biotrickling filter	8–28 € m ⁻³ h ⁻¹	3–6 € m ⁻³ h ⁻¹	[6,54,115]
	Bioscrubber	10–32 € m ⁻³ h ⁻¹	3–5 € m ⁻³ h ⁻¹	[6,54]

The wide variation of the investment and operating costs reported in Table 9 depends on several factors such as flow rate (investment cost per m⁻³ h⁻¹ decrease with increasing the working flow rate), EBRT (increasing EBRT significantly increases the investment and operating costs, especially in biofilters and BTF), packing material (in adsorption systems depending on the type of packing material) and odorant load.

Several obsolete chemical scrubbers applied in WWTPs have been upgraded to biological systems. Gabriel and Deshusses [116] developed a general procedure for the conversion of chemical scrubber to BTF, successfully showing a reduction of operating cost.

7. Future Perspective

Several pilot-scale applications of OTTs in WWTPs were critically examined. The greater importance of treating odors, key atmospheric pollutants in the urban water cycle, has boosted advancements in full-scale technologies for odor removal. Chemical/physical systems were developed and gradually replaced by low-cost and environmental friendly biologically based processes. Biofilters dominate among conventional odor treatment applications, but more sophisticated types of biotechnologies such as biotrickling filters and bioscrubbers have gained attention in real case applications. The data reported in Tables 4–7 confirmed that the biotrickling filter is one of the most reliable technologies due to the efficiency of treating VOCs, H₂S and NH₃ to reduce odor emissions from WWTPs. These results also confirmed BTFs' moderate investment and operational costs and lower land requirements than biofilters.

Algal-bacteria-based processes are emerging as a promising solution to convert the traditional biotechnologies implemented to control odorous emissions in WWTPs, with a high-potential hybrid configuration of photo-bioreactors and a membrane. Algal-based biotechnologies have indeed been confirmed as effective solutions to increase the sustainability of the management of odor treatment facilities in the urban water cycle. These aforementioned innovative solutions promise to be a turning point for environmentally friendly development and the circular economy when applied at real scale wastewater treatment plants. The use of algae biomass for the production of valuable bioproducts, such as biofuels opens a new prospect of converting WWTPs into green biorefineries.

Author Contributions: Conceptualization, V.S., T.Z., G.O. and V.N.; methodology, V.S., M.G.G., G.O., T.Z. and V.N.; validation, G.O., A.B., T.Z., V.B., and V.N.; formal analysis, V.S., M.G.G., G.O. and A.B.; investigation, V.S., M.G.G., G.O. and A.B.; resources, T.Z., V.B. and V.N.; data curation, V.S., M.G.G., G.O. and A.B.; writing—original draft preparation, V.S., T.Z., M.G.G. and G.O.; writing—review and editing, V.S., M.G.G., G.O., A.B., T.Z., C.-W.L., V.B. and V.N.; visualization, V.S., M.G.G. and G.O.; supervision, T.Z., V.B. and V.N.; project administration, T.Z., V.B. and V.N.; funding acquisition T.Z. and V.N. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by University of Salerno, grant number (FARB) 300393FRB18NADDE, 300393FRB19NADDE, 300393FRB20NADDE, 300393FRB19ZARRA and 300393FRB20ZARRA.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: The authors would thank to: (i) University of Salerno (FARB grants: 300393FRB18NADDE, 300393FRB19NADDE, 300393FRB20NADDE, 300393FRB19ZARRA and 300393FRB20ZARRA); (ii) Inter-University Centre for Prediction and Prevention of Relevant Hazards (Centro Universitario per la Previsione e Prevenzione Grandi Rischi, C.U.G.RI.); (iii) Sponge S.r.l., Academic Spin Off of the University of Salerno.

Conflicts of Interest: The authors declare no conflict of interest.

References

- Belgiorno, V.; Naddeo, V.; Zarra, T. *Odour Impact Assessment Handbook*; John & Wiley Sons, Inc.: Hoboken, NJ, USA, 2012.
- Senatore, V.; Zarra, T.; Buonerba, A.; Ho, K.; Shadi, C.; Gregory, W.H. Indoor versus outdoor transmission of SARS-COV-2: Environmental factors in virus spread and underestimated sources of risk. *Euro-Mediterr. J. Environ. Integr.* **2021**, *6*, 1–9. [[CrossRef](#)]
- Blackman, A.; Li, Z.; Liu, A.A. Efficacy of Command-and-Control and Market-Based Environmental Regulation in Developing Countries. *Annu. Rev. Resour. Econ.* **2018**, *10*, 381–404. [[CrossRef](#)]
- Naddeo, V.; Korshin, G. Water, energy and waste: The great European deal for the environment. *Sci. Total Environ.* **2020**, *764*, 142911. [[CrossRef](#)]
- Zarra, T.; Galang, M.G.; Ballesteros, F.; Belgiorno, V.; Naddeo, V. Environmental odour management by artificial neural network—A review. *Environ. Int.* **2019**, *133*, 105189. [[CrossRef](#)]
- Lebrero, R.; Bouchy, L.; Stuetz, R.; Muñoz, R. Odor Assessment and Management in Wastewater Treatment Plants: A Review. *Crit. Rev. Environ. Sci.* **2011**, *41*, 915–950. [[CrossRef](#)]
- Ravina, M.; Bruzzese, S.; Panepinto, D.; Zanetti, M. Analysis of separation distances under varying odour emission rates and meteorology: A WWTP case study. *Atmosphere* **2020**, *11*, 962. [[CrossRef](#)]
- Ravina, M.; Panepinto, D.; Mejia Estrada, J.; De Giorgio, L.; Salizzoni, P.; Zanetti, M.; Meucci, L. Integrated model for estimating odor emissions from civil wastewater treatment plants. *Environ. Sci. Pollut. Res.* **2020**, *27*, 3992–4007. [[CrossRef](#)] [[PubMed](#)]
- Yang, K.; Li, L.; Wang, Y.; Xue, S.; Han, Y.; Liu, J. Airborne bacteria in a wastewater treatment plant: Emission characterization, source analysis and health risk assessment. *Water Res.* **2019**, *149*, 596–606. [[CrossRef](#)] [[PubMed](#)]
- Berenjian, A.; Chan, N.; Malmiri, H.J. Volatile Organic Compounds removal methods: A review. *Am. J. Biochem. Biotechnol.* **2012**, *8*, 220–229. [[CrossRef](#)]
- Wysocka, I.; Gębicki, J.; Namieśnik, J. Technologies for deodorization of malodorous gases. *Environ. Sci. Pollut. Res.* **2019**, *26*, 9409–9434. [[CrossRef](#)]
- Ren, B.; Zhao, Y.; Lyczko, N.; Nzihou, A. Current Status and Outlook of Odor Removal Technologies in Wastewater Treatment Plant. *Waste and Biomass Valorization* **2019**, *10*, 1443–1458. [[CrossRef](#)]
- Zarra, T.; Naddeo, V.; Belgiorno, V.; Reiser, M.; Kranert, M. Odour monitoring of small wastewater treatment plant located in sensitive environment. *Water Sci Technol* **2008**, *58*, 89–94. [[CrossRef](#)]
- Zarra, T.; Naddeo, V.; Belgiorno, V. Characterization of odours emitted by liquid waste treatment plants (LWTPs). *Glob. Nest J.* **2016**, *18*, 721–727. [[CrossRef](#)]
- Zarra, T.; Giuliani, S.; Naddeo, V.; Belgiorno, V. Control of odour emission in wastewater treatment plants by direct and undirected measurement of odour emission capacity. *Water Sci. Technol.* **2012**, *66*, 1627–1633. [[CrossRef](#)] [[PubMed](#)]
- Yang, Z.; Li, J.; Liu, J.; Cao, J.; Sheng, D.; Cai, T. Evaluation of a pilot-scale bio-trickling filter as a VOCs control technology for the chemical fibre wastewater treatment plant. *J. Environ. Manage.* **2019**, *246*, 71–76. [[CrossRef](#)] [[PubMed](#)]
- Bokowa, A.; Diaz, C.; Koziel, J.A.; McGinley, M.; Barclay, J.; Schaubberger, G.; Guillot, J.-M.; Sneath, R.; Capelli, L.; Zorich, V.; et al. Summary and Overview of the Odour Regulations Worldwide. *Atmosphere* **2021**, *12*, 206. [[CrossRef](#)]
- Brancher, M.; Griffiths, K.D.; Franco, D.; de Melo Lisboa, H. A review of odour impact criteria in selected countries around the world. *Chemosphere* **2017**, *168*, 1531–1570. [[CrossRef](#)]
- Naddeo, V.; Zarra, T.; Belgiorno, V.; Giuliani, S. Odour Impact Assessment in Industrial Areas. *Chem. Eng. Trans.* **2012**, *30*, 85–90.

20. Wiley, P.E. Reduction of hydrogen sulfide gas in a small wastewater collection system using sodium hydroxide. *Water Environ. Res.* **2019**, *91*, 483–490. [[CrossRef](#)]
21. Frutos, O.D.; Quijano, G.; Pérez, R.; Muñoz, R. Simultaneous biological nitrous oxide abatement and wastewater treatment in a denitrifying off-gas bioscrubber. *Chem. Eng. J.* **2016**, *288*, 28–37. [[CrossRef](#)]
22. Alfonsín, C.; Lebrero, R.; Estrada, J.M.; Muñoz, R.; Kraakman, N.J.R.; Feijoo, G.; Moreira, M.A.T. Selection of odour removal technologies in wastewater treatment plants: A guideline based on Life Cycle Assessment. *J. Environ. Manage.* **2015**, *149*, 77–84. [[CrossRef](#)]
23. Talaiekhazani, A.; Bagheri, M.; Goli, A.; Talaei Khoozani, M.R. An overview of principles of odor production, emission, and control methods in wastewater collection and treatment systems. *J. Environ. Manage.* **2016**, *170*, 186–206. [[CrossRef](#)] [[PubMed](#)]
24. Nowak, D.J.; Crane, D.E.; Stevens, J.C. Air pollution removal by urban trees and shrubs in the United States. *Urban For. Urban Green.* **2006**, *4*, 115–123. [[CrossRef](#)]
25. Rousseille, F.; Ventura, A. Masking agent efficiency on odor removal from WWTP sludge drying process. *Water Pract. Technol.* **2018**, 1–10. [[CrossRef](#)]
26. Bindra, N.; Dubey, B.; Dutta, A. Technological and life cycle assessment of organics processing odour control technologies. *Sci. Total Environ.* **2015**, 527–528, 401–412. [[CrossRef](#)] [[PubMed](#)]
27. Estrada, J.M.; Kraakman, N.J.R.; Lebrero, R.; Muñoz, R. Integral approaches to wastewater treatment plant upgrading for odor prevention: Activated Sludge and Oxidized Ammonium Recycling. *Bioresour. Technol.* **2015**, *196*, 685–693. [[CrossRef](#)] [[PubMed](#)]
28. Beigi, B.H.M.; Thorpe, R.B.; Ouki, S.; Winter, P.; Waalkens, A. Hydrogen sulphide and VOC removal in biotrickling filters: Comparison of data from a full-scale, low-emission unit with kinetic models. *Chem. Eng. Sci.* **2019**, *208*, 115033. [[CrossRef](#)]
29. Raboni, M.; Torretta, V.; Viotti, P. Treatment of airborne BTEX by a two-stage biotrickling filter and biofilter, exploiting selected bacterial and fungal consortia. *Int. J. Environ. Sci. Technol.* **2017**, *14*, 19–28. [[CrossRef](#)]
30. Oliva, G.; Ángeles, R.; Rodríguez, E.; Turiel, S.; Naddeo, V.; Zarra, T.; Belgiorno, V.; Muñoz, R.; Lebrero, R. Comparative evaluation of a biotrickling filter and a tubular photobioreactor for the continuous abatement of toluene. *J. Hazard. Mater.* **2019**, *380*, 120860. [[CrossRef](#)] [[PubMed](#)]
31. Muñoz, R.; Meier, L.; Diaz, I.; Jeison, D. A review on the state-of-the-art of physical/chemical and biological technologies for biogas upgrading. *Rev. Environ. Sci. Biotechnol.* **2015**, *14*, 727–759. [[CrossRef](#)]
32. Oliva, G.; Zarra, T.; Naddeo, V.; Munoz, R.; Lebrero, R.; Ángeles, R.; Belgiorno, V. Comparative analysis of AOPs and biological processes for the control of VOCs industrial emissions. *Chem. Eng. Trans.* **2018**, *68*, 451–456. [[CrossRef](#)]
33. Conti, C.; Guarino, M.; Bacenetti, J. Measurements techniques and models to assess odor annoyance: A review. *Environ. Int.* **2020**, *134*, 105261. [[CrossRef](#)] [[PubMed](#)]
34. Blanco-Rodríguez, A.; Camara, V.F.; Campo, F.; Becherán, L.; Durán, A.; Vieira, V.D.; de Melo, H.; Garcia-Ramirez, A.R. Development of an electronic nose to characterize odours emitted from different stages in a wastewater treatment plant. *Water Res.* **2018**, *134*, 92–100. [[CrossRef](#)]
35. Huang, B.; Lei, C.; Wei, C.; Zeng, G. Chlorinated volatile organic compounds (Cl-VOCs) in environment - sources, potential human health impacts, and current remediation technologies. *Environ. Int.* **2014**, *71*, 118–138. [[CrossRef](#)]
36. Giuliani, S.; Zarra, T.; Naddeo, V.; Belgiorno, V. A novel tool for odor emission assessment in wastewater treatment plant. *Desalin. Water Treat.* **2015**, *55*, 712–717. [[CrossRef](#)]
37. Zarra, T.; Reiser, M.; Naddeo, V.; Belgiorno, V.; Kranert, M. Odour emissions characterization from wastewater treatment plants by different measurement methods. *Chem. Eng. Trans.* **2014**, *40*, 37–42. [[CrossRef](#)]
38. Kasperczyk, D.; Urbaniec, K.; Barbusinski, K.; Rene, E.R.; Colmenares-Quintero, R.F. Application of a compact trickle-bed bioreactor for the removal of odor and volatile organic compounds emitted from a wastewater treatment plant. *J. Environ. Manage.* **2019**, *236*, 413–419. [[CrossRef](#)] [[PubMed](#)]
39. Fisher, R.M.; Alvarez-Gaitan, J.P.; Stuetz, R.M. Review of the effects of wastewater biosolids stabilization processes on odor emissions. *Crit. Rev. Environ. Sci. Technol.* **2019**, *49*, 1515–1586. [[CrossRef](#)]
40. Ramírez, N.; Cuadras, A.; Rovira, E.; Borrull, F.; Marcé, R.M. Chronic risk assessment of exposure to volatile organic compounds in the atmosphere near the largest Mediterranean industrial site. *Environ. Int.* **2012**, *39*, 200–209. [[CrossRef](#)]
41. Hazrati, S.; Rostami, R.; Fazlzadeh, M.; Pourfarzi, F. Benzene, toluene, ethylbenzene and xylene concentrations in atmospheric ambient air of gasoline and CNG refueling stations. *Air Qual. Atmos. Heal.* **2016**, *9*, 403–409. [[CrossRef](#)]
42. Senatore, V.; Oliva, G.; Zarra, T.; Belgiorno, V.; Naddeo, V. Bio-scrubber coupled with ozonation for enhanced VOCs abatement. In Proceedings of the 16th International Conference on Environmental Science and Technology, Rhodes, Greece, 4–7 September 2019; pp. 9–10.
43. Comia, J.; Oliva, G.; Zarra, T.; Naddeo, V.; Ballesteros, F.C.; Belgiorno, V. *Degradation of Gaseous VOCs by Ultrasonication: Effect of Water Recirculation and Ozone Addition*. *BT-Frontiers in Water-Energy-Nexus—Nature-Based Solutions, Advanced Technologies and Best Practices for Environmental Sustainability*; Naddeo, V., Balakrishnan, M., Choo, K.-H., Eds.; Springer International Publishing: Cham, Switzerland, 2020; pp. 333–336.
44. US EPA. Toxicological Review of Hydrogen Sulfide (CAS No. 7783-06-4). *Summ. Inf. Integr. Risk Inf. Syst.* **2003**, 74.
45. Baawain, M.; Al-Mamun, A.; Omidvarborna, H.; Al-Sulaimi, I.N. Measurement, control, and modeling of H₂S emissions from a sewage treatment plant. *Int. J. Environ. Sci. Technol.* **2019**, *16*, 2721–2732. [[CrossRef](#)]

46. Kraakman, N.J.R.; Estrada, J.M.; Lebrero, R.; Cesca, J.; Muñoz, R. Evaluating odour control technologies using reliability and sustainability criteria - A case study for water treatment plants. *Water Sci. Technol.* **2014**, *69*, 1426–1433. [[CrossRef](#)]
47. Alinezhad, E.; Haghighi, M.; Rahmani, F.; Keshizadeh, H.; Abdi, M.; Naddafi, K. Technical and economic investigation of chemical scrubber and bio-filtration in removal of H₂S and NH₃ from wastewater treatment plant. *J. Environ. Manage.* **2019**, *241*, 32–43. [[CrossRef](#)]
48. Ksibi, M. Chemical oxidation with hydrogen peroxide for domestic wastewater treatment. *Chem. Eng. J.* **2006**. [[CrossRef](#)]
49. Kartika, R. Role of Panellists Variation in Determining Odour Hedonic Scale Odour quantification. *Int. J. Appl. Eng. Res.* **2018**, *13*, 10611–10617.
50. Schmidt, D.R.; Member, A.; Engineer, A.E.; Clanton, C.J. Air quality and emissions from livestock and poultry production/waste management systems. In *Book: Animal Agriculture and the Environment: National Center for Manure and Animal Waste Management White Papers*; MidWest Plan Service: Ames, IA, USA, 2003; Volume 19, pp. 347–360.
51. Iftekhhar, M.S.; Burton, M.; Zhang, F.; Kininmonth, I.; Fogarty, J. Understanding Social Preferences for Land Use in Wastewater Treatment Plant Buffer Zones. *Landsc. Urban Plan.* **2018**, *178*, 208–216. [[CrossRef](#)]
52. Tadda, M.A.; Ahsan, A.; Shitu, A.; Elsergany, M.; Arunkumar, T.; Jose, B.; Razzaque, M.A.; Nik, N.N. A review on activated carbon: Process, application and prospects. *J. Adv. Civ. Eng. Pract. Res.* **2016**, *2*, 7–13.
53. Oliva, G.; Zarra, T.; Pittoni, G.; Senatore, V.; Galang, M.G.; Castellani, M.; Belgiorno, V.; Naddeo, V. Next-generation of instrumental odour monitoring system (IOMS) for the gaseous emissions control in complex industrial plants. *Chemosphere* **2021**, *271*, 129768. [[CrossRef](#)]
54. Oliva, G.; Zarra, T.; Massimo, R.; Senatore, V.; Buonerba, A.; Belgiorno, V.; Naddeo, V. Optimization of classification prediction performances of an instrumental odour monitoring system by using temperature correction approach. *Chemosensors* **2021**, *9*, 147. [[CrossRef](#)]
55. Giuliani, S.; Zarra, T.; Naddeo, V.; Belgiorno, V. Measurement of odour emission capacity in wastewater treatment plants by multisensor array system. *Environ. Eng. Manag. J.* **2013**, *12*, 173–176.
56. Zhou, Y.; Hallis, S.A.; Vitko, T.; Suffet, I.H.M. Identification, quantification and treatment of fecal odors released into the air at two wastewater treatment plants. *J. Environ. Manage.* **2016**, *180*, 257–263. [[CrossRef](#)]
57. Naddeo, V.; Zarra, T.; Oliva, G.; Kubo, A.; Ukida, N.; Higuchi, T. Odour measurement in wastewater treatment plant by a new prototype of e.nose: Correlation and comparison study with reference to both European and Japanese approaches. *Chem. Eng. Trans.* **2016**, *54*, 85–90. [[CrossRef](#)]
58. Hayes, J.E.; Fisher, R.M.; Stevenson, R.J.; Mannebeck, C.; Stuetz, R.M. Unrepresented community odour impact: Improving engagement strategies. *Sci. Total Environ.* **2017**, *609*, 1650–1658. [[CrossRef](#)]
59. Piechota, G. Multi-step biogas quality improving by adsorptive packed column system as application to biomethane upgrading. *J. Environ. Chem. Eng.* **2021**, *9*, 105944. [[CrossRef](#)]
60. Cadee, K.; Wallis, I. Odour containment and ventilation at Perth's major WWTPs. *Water* **2007**, *34*, 54–60.
61. Gao, L.; Keener, T.C.; Zhuang, L.; Siddiqui, K.F. A technical and economic comparison of biofiltration and wet chemical oxidation (scrubbing) for odor control at wastewater treatment plants. *Environ. Eng. Policy* **2001**, *2*, 203–212. [[CrossRef](#)]
62. Zheng, T.; Li, L.; Chai, F.; Wang, Y. Factors impacting the performance and microbial populations of three biofilters for co-treatment of H₂S and NH₃ in a domestic waste landfill site. *Process Saf. Environ. Prot.* **2021**, *149*, 410–421. [[CrossRef](#)]
63. Rabbani, K.A.; Charles, W.; Kayaalp, A.; Cord-Ruwisch, R.; Ho, G. Pilot-scale biofilter for the simultaneous removal of hydrogen sulphide and ammonia at a wastewater treatment plant. *Biochem. Eng. J.* **2016**, *107*, 1–10. [[CrossRef](#)]
64. Zhuang, L.; Keener, T.C.; Siddiqui, K.F. Long-term evaluation of an industrial-scale biofilter for odor control at a large metropolitan wastewater treatment plant. *Environ. Prog.* **2001**, *20*, 212–218. [[CrossRef](#)]
65. Liu, J.; Yang, K.; Li, L.; Zhang, J. A full-scale integrated-bioreactor with two zones treating odours from sludge thickening tank and dewatering house: Performance and microbial characteristics. *Front. Environ. Sci. Eng.* **2017**, *11*, 6. [[CrossRef](#)]
66. Patria, L.; Cathelain, M.; Laurens, P.; Barbere, J.P. Odour removal with a trickling filter at a small WWTP strongly influenced by the tourism season. *Water Sci. Technol.* **2001**, *44*, 243–249. [[CrossRef](#)]
67. Donaldson, F.H.; Dilego, T.J.; Higgins, M.S.; Padewski, E.A.; Peluso, J.S. Assessing and managing PCCP water transmission mains—Baltimore County, Maryland—A case study. In *Proceedings of the 2006 Pipeline Division Specialty Conference-Pipelines*, Chicago, IL, USA, 2 August 2006.
68. Abdel-Jabbar, N.; Ahmed, W.; Shareefdeen, Z. System identification and control of a biotrickling filter. *Chem. Prod. Process Model.* **2015**, *10*, 39–53. [[CrossRef](#)]
69. Omri, I.; Aouidi, F.; Bouallagui, H.; Godon, J.J.; Hamdi, M. Performance study of biofilter developed to treat H₂S from wastewater odour. *Saudi J. Biol. Sci.* **2013**, *20*, 169–176. [[CrossRef](#)]
70. Abraham, S.; Joslyn, S.; Suffet, I.H. Treatment of odor by a seashell biofilter at a wastewater treatment plant. *J. Air Waste Manag. Assoc.* **2015**, *65*, 1217–1228. [[CrossRef](#)]
71. Almarcha, D.; Almarcha, M.; Nadal, S.; Poulssen, A. Assessment of odour and VOC depuration efficiency of advanced biofilters in rendering, sludge composting and waste water treatment plants. *Chem. Eng. Trans.* **2014**, *40*, 223–228. [[CrossRef](#)]
72. Xie, B.; Liang, S.B.; Tang, Y.; Mi, W.X.; Xu, Y. Petrochemical wastewater odor treatment by biofiltration. *Bioresour. Technol.* **2009**, *100*, 2204–2209. [[CrossRef](#)]

73. Lafita, C.; Peña-Roja, J.M.; Sempere, F.; Waalkens, A.; Gabaldón, C. Hydrogen sulfide and odor removal by field-scale biotrickling filters: Influence of seasonal variations of load and temperature. *J. Environ. Sci. Heal. Part A Toxic/Hazardous Subst. Environ. Eng.* **2012**, *47*, 970–978. [[CrossRef](#)]
74. Shareefdeen, Z.; Herner, B.; Singh, A. Biotechnology for air pollution control—An overview. *Biotechnol. Odor Air Pollut. Control.* **2005**, 3–15. [[CrossRef](#)]
75. Ghawi, A.H. Design of Biofilter Odor. *J. Ecol. Eng.* **2018**, *19*, 7–15.
76. Jones, K.D.; Yadavalli, N.; Karre, A.K.; Paca, J. Microbial monitoring and performance evaluation for H₂S biological air emissions control at a wastewater lift station in South Texas, USA. *J. Environ. Sci. Heal. Part A Toxic/Hazardous Subst. Environ. Eng.* **2012**, *47*, 949–963. [[CrossRef](#)]
77. Wu, L.; Loo, Y.Y.; Koe, L.C.C. A pilot study of a biotrickling filter for the treatment of odorous sewage air. *Water Sci. Technol.* **2001**, *44*, 295–299. [[CrossRef](#)] [[PubMed](#)]
78. Cox, H.H.J.; Deshusses, M.A.; Converse, B.; Schroeder, E.D.; Vosooghi, D.; Samar, P.; Iranpour, R. Odor and Voc Treatment By Biotrickling Filters: Pilot Scale Studies At the Hyperion Treatment Plant. *Proc. Water Environ. Fed.* **2012**, *2001*, 297–315. [[CrossRef](#)]
79. Chen, Y.; Wang, X.; He, S.; Zhu, S.; Shen, S. The performance of a two-layer biotrickling filter filled with new mixed packing materials for the removal of H₂S from air. *J. Environ. Manage.* **2016**, *165*, 11–16. [[CrossRef](#)] [[PubMed](#)]
80. Guerrero, R.B.S.; Bevilacqua, D. Biotrickling Filtration of Biogas Produced from the Wastewater Treatment Plant of a Brewery. *J. Environ. Eng.* **2015**, *141*, 04015010. [[CrossRef](#)]
81. Lakey, M.; Manager Victoria, G.; Pitt, M.; Manager, G.; TeQ Limited, C.; Michael Pitt, V. Dual phase biotrickling filter treatment of H₂S and VOC's. *Water Ind. Oper. Work.* **2011**, *31*, 80–86.
82. Santos, A.; Guimerà, X.; Dorado, A.D.; Gamisans, X.; Gabriel, D. Conversion of chemical scrubbers to biotrickling filters for VOCs and H₂S treatment at low contact times. *Appl. Microbiol. Biotechnol.* **2015**, *99*, 67–76. [[CrossRef](#)] [[PubMed](#)]
83. Lebrero, R.; Rodr, E.; De Juan, C.; Norden, G.; Rosenbom, K. Comparative Performance Evaluation of Commercial Packing Materials for Malodorants Abatement in Biofiltration. *Appl. Sci.* **2021**, *11*, 2966.
84. Vitko, T.; Cowden, S.; Erdal, Z.; Witherspoon, J.; Suffet, I.H. Innovative odor mapping and management method sets the stage for targeted foul air treatment. In Proceedings of the WEFTEC 2016-89th Water Environment Federation Annual Technical Exhibition and Conference, Milwaukee, WI, USA, 21–24 March 2016; 2016.
85. Grzelka, A.; Romanik, E.; Miller, U. Odour nuisance assessment of the food industry wastewater treatment plant. *E3S Web Conf.* **2019**, *100*, 00024. [[CrossRef](#)]
86. Dorado, A.D.; Gabriel, D.; Gamisans, X. Biofiltration of WWTP sludge composting emissions at contact times of 2-10 s by structured/unstructured packing materials. *Process Biochem.* **2015**, *50*, 1405–1412. [[CrossRef](#)]
87. Gabriel, D.; Deshusses, M.A. Performance of a full-scale biotrickling filter treating H₂S at a gas contact time of 1.6 to 2.2 seconds. *Environ. Prog.* **2003**, *22*, 111–118. [[CrossRef](#)]
88. Popov, V.; Khomenkov, V.; Zhukov, V.; Cavanagh, M.; Cross, P. Design, construction and long-term performance of novel type of industrial biotrickling filters for VOC and odour control. **2005**, 257–262. Available online: <https://ruc.udc.es/dspace/bitstream/handle/2183/11451/CC-79%20art%2033.pdf> (accessed on 25 November 2021).
89. Spennati, F.; Mannucci, A.; Mori, G.; Giordano, C.; Munz, G. Moving Bed BioTrickling Filters: An innovative solution for hydrogen sulphide removal from gas streams. *Desalin. Water Treat.* **2017**, *61*, 215–221. [[CrossRef](#)]
90. le Roux, L.D.; Johnson, M.E. Performance of High-Rate Biotrickling Filter Under Ultra-High H₂S Loadings at a Municipal WWTP. *Proc. Water Environ. Fed.* **2012**, *2010*, 691–701. [[CrossRef](#)]
91. Sempere, F.; Winter, P.; Waalkens, A.; Hühnert, N.; Cranshaw, I.; Beigi, B.; Thorpe, R.B. Treatment of discontinuous emission of sewage sludge odours by a full scale biotrickling filter with an activated carbon polishing unit. *Water Sci. Technol.* **2018**, *77*, 2482–2490. [[CrossRef](#)] [[PubMed](#)]
92. Kerc, A.; Olmez, S.S. Ozonation of odorous air in wastewater treatment plants. *Ozone Sci. Eng.* **2010**, *32*, 199–203. [[CrossRef](#)]
93. Yang, S.; Li, Y.; Wang, L.; Feng, L. Use of peroxymonosulfate in wet scrubbing process for efficient odor control. *Sep. Purif. Technol.* **2016**, *158*, 80–86. [[CrossRef](#)]
94. Biard, P.-F.; Couvert, A.; Renner, C.; Zozor, P.; Bassivière, S.; Levasseur, J.-P. Hydrogen sulphide removal in waste water treatment plant by compact oxidative scrubbing in Aquilair Plus™ process. *Water Pract. Technol.* **2009**, *4*, 1–9. [[CrossRef](#)]
95. Baawain, M.; Al-Mamun, A.; Omidvarborna, H.; Al-Jabri, A. Assessment of hydrogen sulfide emission from a sewage treatment plant using AERMOD. *Environ. Monit. Assess.* **2017**, *189*, 263. [[CrossRef](#)]
96. Hansen, N.G.; Rindel, K. Bioscrubbing: An effective and economic solution to odour control at sewage-treatment plants. *Water Environ. J.* **2001**, *15*, 141–146. [[CrossRef](#)]
97. Rada, E.C.; Raboni, M.; Torretta, V.; Copeli, S.; Ragazzi, M.; Caruson, P.; Istrate, I.A. Removal of benzene from oil refinery wastewater treatment plant exhausted gases with a multi-stage biofiltration pilot plant. *Rev. Chim.* **2014**, *65*, 68–70.
98. Torretta, V.; Collivignarelli, M.C.; Raboni, M.; Viotti, P. Experimental treatment of a refinery waste air stream, for BTEX removal, by water scrubbing and biotrickling on a bed of *Mitilus edulis* shells. *Environ. Technol. (United Kingdom)* **2015**, *36*, 2300–2307. [[CrossRef](#)]
99. Martinez, A.; Rathibandla, S.; Jones, K.; Cabezas, J. Biofiltration of wastewater lift station emissions: Evaluation of VOC removal in the presence of H₂S. *Clean Technol. Environ. Policy* **2008**, *10*, 81–87. [[CrossRef](#)]

100. Behnami, A.; Zoroufchi Benis, K.; Shakerkhatibi, M.; Derafshi, S.; Chavoshbashi, M.M. A systematic approach for selecting an optimal strategy for controlling VOCs emissions in a petrochemical wastewater treatment plant. *Stoch. Environ. Res. Risk Assess.* **2019**, *33*, 13–29. [[CrossRef](#)]
101. Finke, G.; Oliver, P.; Thomas, M.; Evanson, I. Environmentally sustainable odour control for the Merrimac WWTP upgrade. *Chemeca* **2008**, 1996–2005.
102. Hansen, N.G.; Rindel, K. Bioscrubbing, an effective and economic solution to odour control at wastewater treatment plants. *Water Sci. Technol.* **2000**, *41*, 155–164. [[CrossRef](#)]
103. Dobsław, D.; Schulz, A.; Helbich, S.; Dobsław, C.; Engesser, K.H. VOC removal and odor abatement by a low-cost plasma enhanced biotrickling filter process. *J. Environ. Chem. Eng.* **2017**, *5*, 5501–5511. [[CrossRef](#)]
104. Senatore, V.; Buonerba, A.; Zarra, T.; Oliva, G.; Belgiorno, V.; Boguniewicz-Zablocka, J.; Naddeo, V. Innovative Membrane Photobioreactor for Sustainable CO₂ Capture and Utilization. *Chemosphere* **2021**, *273*, 129682. [[CrossRef](#)] [[PubMed](#)]
105. Rajamanickam, R.; Baskaran, D.; Kaliyamoorthi, K.; Baskaran, V.; Krishnan, J. Steady State, transient behavior and kinetic modeling of benzene removal in an aerobic biofilter. *J. Environ. Chem. Eng.* **2020**. [[CrossRef](#)]
106. Ángeles Torres, R.; Marín, D.; Rodero, M. Biogas treatment for H₂S, CO₂, and other contaminants removal. In *From Biofiltration to Promising Options in Gaseous Fluxes Biotreatment*; Elsevier: Amsterdam, The Netherlands, 2020; ISBN 9780128190647.
107. Lebrero, R.; Ángeles, R.; Pérez, R.; Muñoz, R. Toluene biodegradation in an algal-bacterial airlift photobioreactor: Influence of the biomass concentration and of the presence of an organic phase. *J. Environ. Manage.* **2016**, *183*, 585–593. [[CrossRef](#)] [[PubMed](#)]
108. Meier, L.; Stará, D.; Bartacek, J.; Jeison, D. Removal of H₂S by a continuous microalgae-based photosynthetic biogas upgrading process. *Process Saf. Environ. Prot.* **2018**, *119*, 65–68. [[CrossRef](#)]
109. Franco-Morgado, M.; Toledo-Cervantes, A.; González-Sánchez, A.; Lebrero, R.; Muñoz, R. Integral (VOCs, CO₂, mercaptans and H₂S) photosynthetic biogas upgrading using innovative biogas and digestate supply strategies. *Chem. Eng. J.* **2018**, *354*, 363–369. [[CrossRef](#)]
110. Vermi, M.; Corpuz, A.; Borea, L.; Senatore, V.; Castrogiovanni, F.; Buonerba, A.; Oliva, G.; Ballesteros, F.; Zarra, T.; Belgiorno, V.; et al. Wastewater treatment and fouling control in an electro algae-activated sludge membrane bioreactor. *Sci. Total Environ.* **2021**, *786*, 147475. [[CrossRef](#)]
111. Pahunang, R.R.; Buonerba, A.; Senatore, V.; Oliva, G.; Ouda, M.; Zarra, T.; Muñoz, R.; Puig, S.; Ballesteros, F.C.; Li, C.W.; et al. Advances in technological control of greenhouse gas emissions from wastewater in the context of circular economy. *Sci. Total Environ.* **2021**, *792*, 148479. [[CrossRef](#)]
112. Ángeles, R.; Oliva, G.; Zarra, T.; Naddeo, V.; Belgiorno, V.; Muñoz, R.; Lebrero, R. Comparative evaluation of a biotrickling filter and a tubular photobioreactor for the continuous abatement of toluene. *Chem. Eng. Trans.* **2018**, *68*, 463–468. [[CrossRef](#)]
113. Stanley, W.B.M.; Muller, C.O. Choosing an Odor Control Technology – Effectiveness and Cost Considerations. *Proc. Water Environ. Fed.* **2012**, *2002*, 259–276. [[CrossRef](#)]
114. Shammay, A.; Sivret, E.C.; Le-Minh, N.; Lebrero Fernandez, R.; Evanson, I.; Stuetz, R.M. Review of odour abatement in sewer networks. *J. Environ. Chem. Eng.* **2016**, *4*, 3866–3881. [[CrossRef](#)]
115. Tomàs, M.; Fortuny, M.; Lao, C.; Gabriel, D.; Lafuente, J.; Gamisans, X. Technical and economical study of a full-scale biotrickling filter for H₂S removal from biogas. *Water Pract. Technol.* **2009**, *4*, wpt2009026. [[CrossRef](#)]
116. Gabriel, D.; Deshusses, M.A. Retrofitting existing chemical scrubbers to biotrickling filters for H₂S emission control. *Proc. Natl. Acad. Sci. USA* **2003**, *100*, 6308–6312. [[CrossRef](#)]