atmosphere

Review

Odors Emitted from Biological Waste and Wastewater Treatment Plants: A Mini-Review

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Abstract: In recent decades, a new generation of waste treatment plants based on biological treatments (mainly anaerobic digestion and/or composting) has arisen all over the world. These plants have been progressively substituted for incineration facilities and landfills. Although these plants have evident benefits in terms of their environmental impact and higher recovery of material and energy, the release into atmosphere of malodorous compounds and its mitigation is one of the main challenges that these plants face. In this review, the methodology to determine odors, the main causes of having undesirable gaseous emissions, and the characterization of odors are reviewed. Finally, another important topic of odor abatement technologies is treated, especially those related to biological low-impact processes. In conclusion, odor control is the main challenge for a sustainable implementation of modern waste treatment plants.

Keywords: odor; organic waste; composting; anaerobic digestion; biofiltration

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Citation: González, D.; Gabriel, D.; Sánchez, A. Odors Emitted from Biological Waste and Wastewater Treatment Plants: A Mini-Review. *Atmosphere* **2022**, *13*, 798. https://doi.org/10.3390/atmos13050798

Academic Editor: Jo-Chun Kim

Received: 25 April 2022
Accepted: 13 May 2022
Published: 13 May 2022

1. Introduction

Anaerobic digestion and/or composting are currently replacing incineration and landfills in the framework of waste management in modern societies. These technologies present the main advantage of energy and material recovery in a circular economy context [1,2].

Being biological technologies with clear advantages in terms of sustainability, as both treatments are focused on the organic fraction of wastes (e.g., municipal solid waste, sewage sludge, farm manures, and agricultural waste), it is evident that they imply the generation of volatile compounds that are emitted to atmosphere. Among the main gaseous emissions related to the biological treatment of organic wastes, different compounds with different effects can be found: ammonia [3,4], greenhouse gases (methane and nitrous oxide) [5,6], and a heterogeneous group of Volatile Organic Compounds (VOCs) [7,8].

This last case comprises a wide number of families such as alcohols, ketones, esters, organic acids, aldehydes, sulfurs or volatile sulfur compounds (VSCs), aromatics, terpenes, hydrocarbons, and N-compounds, among others [9]. Many VOCs have an odor. In certain circumstances, emissions of VOCs can give rise to localized odor nuisance problems, even if they are not hazardous to persons. The strength of a given compound's odor may be expressed by its odor threshold, that is, the concentration at which half the population could not detect an odor [9]. However, it is difficult to predict the odor threshold of a mixture of VOCs and other odorant compounds such as ammonia or hydrogen sulfide, since there are often complex and nonlinear synergistic effects that can alter both the strength and quality of the perceived odor. In such cases, the odor threshold of the emitted mixture must be determined by practical measurements, usually dynamic olfactometry, that is, with the involvement of odor panelists [10].

In this review, the critical aspects regarding the emissions of odors from biological waste treatment are analyzed and discussed. As odors are produced by a mixture of chemical compounds, the odor composition will be also commented. Finally, technologies for the abatement of odors will be also discussed, focusing on biological treatments.

2. How to Measure Odors

As mentioned above, odors are the result of the human perception of one or more chemical compounds. Waste treatment plants, when based on biological treatments, have several emission sources. In the case of composting, when the process takes place in windrows (static, aerated, and/or turned), these are the most obvious ones. If a biofilter is used to minimize these emissions, this can be another evident emission source [11]. However, the emissions of VOCs and other odorants during some pre- (waste conditioning) and post-treatment operations can be significant [12]. In the case of anaerobic digestion, since only closed reactors are possible, odor emissions come from complementary operations rather than the anaerobic digestion process itself: waste storage, mechanical pretreatment, fermentation preparation, or digestate dewatering [13]. It is evident that odors must be investigated according to the emission source.

2.1. Odors Sampling

Obtaining representative gaseous samples from emitting area sources is not simple. The first thing to take into account in odor sampling is to avoid any disturbance that sampling can cause on the characteristics and conditions of the source. In order to make the results comparable, investigations using different sampling methods depending on the types of sources of odor should be conducted to observe possible differences [14]. In the case of point sources, such as gas collectors, this is not a common problem. However, waste treatment plants often have several area sources. In this case, it is very difficult to cover the entire emission area during sampling. In consequence, representative sampling sites have to be established, although no regulations exist.

Accordingly, several approaches can be found in the literature. For example, in biofilters, a relatively common strategy is to cover the entire surface to reduce it to a point source [15], although, in this case, disturbances of the gas flow must be carefully observed and avoided. Other authors have used a wind tunnel device [16,17] to obtain representative air samples for odor analysis at different points of plants treating municipal solid waste (MSW) or anaerobic treatment ponds. In these cases, the air samples were collected by sucking the air with a depression pump inside inert bags for further analysis. Figure 1 shows one of the most typical devices called a dynamic flux chamber.

Figure 1. Dynamic flux chamber for the collection of odors in a biofilter surface (Source: the authors).

Another possibility is to measure the velocity of air emitted using high precision anemometers [16]. Finally, Cadena et al. [18] proposed a methodology to obtain representative gaseous emission samples from surfaces in waste treatment plants. The methodology consisted of determining the air velocity and the concentration of selected compounds in a matrix of points on the emitting surface. Air samples were collected in inert bags for odor analysis. The product of odor concentration and air velocity results in odor mass flow released per area unit. Regardless of the strategy used, it is evident that having a wide number of measurements (at different days, seasons, weather conditions, etc.) will result in more reproducible and realistic odor data.

2.2. Odor Measurement

Although several approaches have been used to measure odor, in recent years, the European standard EN 13725:2003 has been extensively used in the European Union and other countries such as Chile, Australia, and Colombia. Today, this standard (that has been recently updated) "BS EN13725:2022—Stationary source emissions. Determination of odour concentration by dynamic olfactometry" is the most used methodology in the world to measure odor concentration [19]. The odor concentration is defined as the number of European odor units in a cubic meter of gas at standard conditions (temperature of 273.15 K and pressure of 10^5 Pa). Therefore, the odor concentration is measured in "European Odour Units per cubic meter" and its symbol is "ou_E/m^3". The odor concentration is calculated from the number of times that an odorous gas has to be diluted in order to reach the odor threshold of a group of people or panel specially trained and selected.

Although widely accepted as standard, not all the studies related to waste treatment use it. Other alternative measures have been used, such as the number of times that the concentration of an odorant exceeds the threshold values, normally together with the hedonic tone. These approaches are less informative than the odor units, since it is difficult to measure and interpret synergic odor effects, typically found in complex odor mixtures [20].

On the other hand, there have been recent experiences with portable field olfactometers for assessing the odor nuisance of odor sources, such as wastewater treatment plants (WWTPs) or municipal solid waste treatment facilities (MSWTFs), and validating the odor dispersion modelling results. From these, the equipment most used are the Nasal Ranger® [21,22] and the Scentroid SM100 portable olfactometer [23,24], which work by gradually diluting an odorous gas with clean odorless air in known ratios until the perception of an odor change to obtain the odor concentration. These portable devices have been described as robust and reliable tools to obtain valuable information on source odor concentration, being a cost-effective alternative for odor investigations.

2.3. Electronic Noses

An electronic nose offers potential as a portable, rapid, cost-effective, and noninvasive field diagnostic technique for initial screening to detect odor problems. Essentially, electronic noses consist of an array of nonspecific chemical sensors, which interact with the different VOCs in the sample. The signal is analyzed with pattern recognition and multivariate statistical techniques to differentiate and classify samples according to their volatile composition.

Although not completely accepted as a substitute for dynamic olfactometry, several works have highlighted the use of electronic noses for the monitoring of odors in waste treatment plants. In fact, the combination of the two approaches is claimed to have advantages for the measurable and objective evaluation of the odor nuisance [25]. Specifically, Jonca et al. (2022) present a recent review on the use of electronic noses in waste treatment plants, focusing on the development of these apparatuses for the constant monitoring of waste treatment processes (composting, anaerobic digestion, and biofiltration, among others) [26]. The conclusion is that electronic noses are promising tools for the control of the waste treatment process and odor impact assessment; however, "current trends clearly stand that maximum information on the odorous samples investigations is achieved when olfactometry, gas chromatography coupled to mass spectrometry (GC-MS) and e-noses are used as complementary approaches to a given problem" [22]. Other authors have also demonstrated the usefulness of electronic noses in several waste treatment plants, such as composting [27], anaerobic digestion [28], biofiltration [29], landfill [30], complete plants [31], and even biodiesel production facilities [32].

3. Odor-Producing Chemicals

Although odors are often produced by a mixture of different compounds such as VOCs, ammonia, or hydrogen sulfide, there exists a large amount of data about the threshold odor values of several odorants found in waste treatment plants. For instance, the Scottish Environment Protection Agency (2010) published an excellent "Odour Guidance" with detailed information about the characteristic of some odorant compounds, including their threshold value, the hedonic tone, and their possible effects on health depending on their concentration [33]. From this and other sources of information about these compounds, a set of characteristics can be discussed:

1. Some of the threshold values are extremely low; that is, the human nose is a powerful analytical device.
2. Not all the compounds are toxic or, if they are, the concentrations must be very high.
3. A common lack of these tables is the absence of a critical property: biodegradability, which is crucial when a biological treatment for the abatement of these compounds is to be applied.

Table 1 presents a summary of the main compounds found in biological treatment plants and their main characteristics.

Table 1. Summary of the main odorants emitted from waste treatment plants.

Compound	Detection Threshold (ppm_V) *	Type of Odor
Ammonia	0.039	Stringent
Hydrogen sulfide	0.00047	Rotten eggs
Methyl mercaptan	0.0011	Rotten cabbage
Ethylamine	0.026	Fishy, bitter
Dimethyl amine	0.047	Fishy, pungent
Acetaldehyde	0.004	Fruity
Ethyl mercaptan	0.002	Rotten cabbage
Dimethyl sulfide	0.001	Rotten vegetables
Dimethyl disulfide	0.001	Garlic-like
Diethyl sulfide	0.0008	Garlic-like
Butyl mercaptan	0.0005	Garlic-like
Acetic acid	0.008	Vinegar, acidic
Propionic acid	0.0057	Rancid, acidic
α-pinene	0.011	Herbal
Limonene	0.038	Orange
Butyric acid	0.00019	Sweat
Skatole (3-methylindole)	0.012	Feces

* Values can differ considerably from different sources. Data from [34,35]. Created by the authors.

As observed, some of the most unpleasant odorants can be emitted from waste treatment plants. This is the reason for typical odor nuisances reported near these facilities. In any case, it is worthwhile to note two important things: (i) most of these products are reported as nontoxic (except hydrogen sulfide and ammonia) even at high concentrations, and (ii) the synergic effect of the mixture of these compounds can significantly alter the threshold value.

4. Odors from Waste Treatment Plants

4.1. Composting

Composting and its related operations are probably the most reported regarding gaseous emissions and, particularly, odors. However, there are more onerous processes in terms of odors, such as anaerobic processes, landfills, sewage collection units, or animal waste processing plants, especially fish waste. It is important to know that the composting process has well-defined treatment stages: pretreatment, thermophilic phase, maturation, and post-treatment. In this case, it is obvious that these stages will produce different types of odors. However, it must be taken into account that these stages are not clearly differentiated in full-scale composting plants and sometimes overlap. In such cases, the most efficient monitoring of odors should be their evolution in time [3,7,18]. At the same time, this technology is being applied to a wide variety of organic waste [36] and even for soil remediation purposes [37,38]. Therefore, the odors will be also different. Table 2 exemplifies the characteristics of relevant organic odorants emitted from composting units. The main odorants are those found with the highest concentrations and significantly above their odor detection threshold.

Table 2. Relevant organic odorants and families reported in composting processes of MSW or sewage sludge.

Waste Type	Location	Main Odorant Families	Main Odorants (Concentrations, ppm_v)	Ref.
MSW	Composting	aromatic HC aliphatic HC ketones terpenes	2-butanone (1.46–4.90) Toluene (0.19–1.04) Limonene (0.22–1.01)	[39]
MSW	Compost maturation	ketones terpens alcohols	n-butanol (3.47) Methyl ethyl ketone (0.8) Limonene (1.93)	[40]
MSW	Indoor air composting hall	aromatic HC, aliphatic HC, terpenes S compounds	Decane (0.47–0.60) Toluene (0.38–0.72) Limonene (1.87–3.11) H_2S (0.8–0.9) DMS (0.11–0.30)	[12]
Sewage sludge	Dynamic windrows	aldehydes ketones S compounds carboxylic acids	Isovaleraldehyde (0.04) 2-butanone (0.46–0.52) DMS (0.55–1.15) DMDS (0.40–1.39) Butyric acid (0.09–15)	[41]
Sewage sludge	Composting	S-compounds terpens esters	Pinenes (α and β) (0.1–2.8) Limonene (0.01–10) DMS (0.08–1.2) DMDS (0.3–18) Ethyl isovalerate (0.1–2.8)	[7]
Sewage sludge	Composting	S compounds terpenes	DMS (NA) DMDS (NA) Limonene (NA) α-pinene (NA)	[42]

NA—not available.

4.1.1. Food Waste

Food waste or, in general, the organic fraction of municipal solid waste (OFMSW) is mainly transformed into composting. Composting can be performed in windrows or in-vessel systems, which can obviously affect the odor emission. Most of the papers published present data on the concentration of typical odorants (especially ammonia), their effect on health, and some strategies of mitigation. However, the chemicals related to odors during the composting of food waste are a wide variety of chemical compounds: ammonia, amines, acetic acid, and multiple volatile organic compounds (hydrocarbons, ketones, esters, terpenes, and S-compounds) [43]. For instance, the co-composting process of kitchen waste and garden waste are reported as a good strategy to decrease the emissions of ammonia and hydrogen sulfide, as well as enhancing compost maturity [44]. In fact, several studies point to a correlation between waste stability and odor [10,45], which is an interesting aspect to consider in the biological stages of an organic waste treatment. In fact, Gutiérrez et al. (2017) presented a successful correlation between Oxygen Uptake Rate (OUR) and odor emissions (in this case, measured as odor units) when using different substrates, including the OFMSW and other substrates [46]. Another topic that is presented in composting is the use of additives to minimize the odor emissions. For instance, Yuan et al. (2015) used a specific bulking agent, dry cornstalks, which were pretreated with ferric chloride ($FeCl_3$) during the composting of kitchen waste. The authors conclude that this strategy resulted in a significant decrease in the amounts of ammonia and hydrogen sulfide emitted [47]. Other works have been published in the field of biodrying, a technology based on the same principles as composting [48], with the same conclusion about the use of additives [49].

Regarding odor units, other papers have been published. Colón et al. (2017) presented a complete study on indoor air in modern complex mechanical-biological treatment plants treating mixed municipal solid waste and source-selected OFMSW by composting and anaerobic digestion, observing different patterns during one complete working day, with terpenoids, aromatic and aliphatic hydrocarbons being the VOCs more often detected in odors [7]. This fact has an evident importance on the ventilation required in facilities working with the OFMSW.

Other works present extensive studies on the impact of implementing deodorization systems in complex waste treatment plants including composting but a large number of other operations, apart from the biological process itself [43]. In fact, most of the papers related to odor emissions in composting are focused on deodorization, a point that will be treated later in this review.

4.1.2. Sewage Sludge

Although less studied, composting is also a technology for the treatment and stabilization of sewage sludge. However, in the last decades, and due to the proliferation of anaerobic digestion of wastewater sludge, composting has been increasingly limited to the stabilization of digested sludge. In both cases (sewage sludge and anaerobically digested sludge), benefits from the composting include stabilization, lower phytotoxicity and, what is very important, the reduction in unpleasant odors in its application to soil as organic fertilizer [50]. However, the studies of odor emissions during sewage or digested sludge composting are relatively scarce. In fact, some of the works published are related to the emission of certain compounds, especially hydrogen sulfide, which is produced when anaerobic zones appear in the compost matrix, although ammonia is also often studied. In general, S-compounds are discussed as the most problematic in terms of odors during the composting of sewage sludge [51,52].

Again, in the case of sewage sludge, the correlation between stabilization and the decrease in odor emissions is also observed, especially in the case of ammonia and hydrogen sulfide, the most commonly reported malodors chemicals [53].

Finally, it is important to note that the studies including odor units during the composting of sewage sludge are scarce. Particularly, Gonzalez et al. (2019) reported a complete characterization of the VOCs and odor units emitted from a sewage sludge full-scale composting plant. Odor emission factors (OEF) were determined during the progressive stabilization of sewage sludge due to the composting process, resulting in a range of 10^6 odor units per kg of composted dry mass [7]. The authors also systematically studied the main VOCs detected in odors, which were isovaleraldehyde, indole, skatole, butyric acid, dimethyl sulfide, and dimethyl disulfide. In another study by the same authors, the odor emission factors, when composting sewage sludge at a pilot scale, were in the range of 10^7 odor units per kg of composted dry mass, whereas the major odor contributors identified were dimethyl disulfide, eucalyptol, and α-pinene [54].

4.1.3. Manure

The term "manure" is somewhat confusing, as it includes different materials in terms of moisture, chemical composition, stability, etc. Therefore, the reader must be careful when consulting studies in this framework. This can be applied to odor units (where the studies are scarce) and, in general, gaseous emissions to the atmosphere. At the same time, this type of waste is often processed some time after its production, which implies a storage period, which again is critical for the emissions during composting. In this regard, Blazy et al. (2015) correlated the chemical composition and the odor concentration of emissions produced during the storage and composting of pig slaughterhouse sludge [55]. The results were positive, as a satisfying correlation between chemical composition and odor concentration was obtained. A relevant aspect from this study is that only three compounds among the 66 identified (trimethylamine, hydrogen sulfide, and methanethiol), accounted for the prediction of odor concentration measured during the composting and storage of this waste.

In other studies, manure has been co-composted with other complementary wastes, given the evident lack of porosity and excess of nitrogen and waste found in most of these materials. For example, Toledo et al. (2020) presented a study composting a complex mixture of chicken manure, *alperujo* (olive pomace paste), olive leaves/pruning, and cereal straw at full-scale, where low odor emissions were reported because of the use of lignocellulosic substrates jointly with manure [56]. In a similar work, Zang et al. (2016) reported the effects of the mix ratio, moisture content, and aeration rate on sulfur odor emissions during pig manure composting [57]. Other particular points that are very commonly treated are the study of emissions of anaerobically digested manures [58], where the emissions of some malodourous compounds can be enhanced, and the study of inoculants to decrease the amount of odor units of these materials, although sometimes no quantitative data are provided [59].

4.2. Anaerobic Digestion

Anaerobic digestion is an alternative technology based on biological processes when the main objective is to transform organic waste into biogas, whose high percentage of methane (40–60%) makes it a highly attractive renewable energy source [1]. Nevertheless, it is important to note that anaerobic digestion and composting are complementary technologies that, properly combined, can result in higher material and energy recovery than that of both technologies separately considered [60]. Another important question is that of anaerobic digestion, which, as a net energy producing process, is often considered in global warming studies, and, in consequence, only greenhouse gases are monitored [61].

Regarding odors, as anaerobic digestion is a strict anaerobic process, it is evident that it takes place in enclosed reactors, except in the case of landfills, which are out of the scope of this paper. This is the reason why odors are practically restricted to the complementary operations rather than the process itself: organic waste preconditioning, digested material dewatering, etc. For example, Wisniewska et al. (2020) monitored odors and malodorous compounds in different parts of an anaerobic digestion plant treating food waste. The authors concluded that the zone of waste collection was the main emissions source of the plant [62]. In another similar study [63], waste storage, fermentation preparation, and digestate dewatering were the main emission odor sources in a Polish MSW biogas treatment plant, with ranges of 4 to 78 ou/m^3 for fermentation preparation and from 8 to 448 ou/m^3 for digestate dewatering.

Another important issue is the odor associated with the material during the anaerobic digestion. In fact, the odors emitted when applying digested materials to soil as organic amendments are one of the main concerns related to the use of these materials. In this case, similar to that observed in the composting field, several studies have pointed that odors are strongly correlated to the stability of the material [45,64]. Thus, materials that are partially digested tend to produce more unpleasant odors than those with a low level of biodegradability [65].

5. Odors from Wastewater Treatment Plants

Although less studied, wastewater treatment plants (WWTP) are obviously emitting sources of odors. Although the odorant compounds can be similar to those observed in waste treatment plants, it is evident that the emissions sources are different, as the configuration of the plant is also different. In open-to-air WWTP, pretreatment units, primary settlers, biological aerated reactors, or the sludge treatment (dewatering, anaerobic digestion, etc.) can be effective emissions sources [66]. Accordingly, typical odor collection devices must be adapted (Figure 2).

Figure 2. Dynamic flux chamber for the collection of odors in a WWTP (pretreatment). Source: the authors.

Regarding odor emissions generated in WWTPs, scientific studies generally focus on the emission of specific odorant compounds, such as hydrogen sulfide (due to its odorant as well as its corrosive nature), ammonia, and volatile organic compounds; however, works targeting actual odor concentration, odor emission rates, and odor emission factors from full-scale WWTPs are scarce. Capelli et al. (2009) integrated odor emission data obtained from 17 different Italian WWTPs differing in constructional and processing features, treating mostly urban wastewaters, and found odor concentrations ranging from 845 to 3840 ou/m^3 depending on the emission source considered. From these data, the authors were able to demonstrate that the main odor sources of a WWTP were found among the pretreatment units, specifically at the primary sedimentation step, and that, generally, the odor emission tended to decrease along the depuration cycle [67]. This behavior has also been observed by other authors, who also correlated these higher odor emissions at pretreatment units with an increased presence of H_2S, NH_3, and different VOC families with a low odor detection threshold such as VSCs or ketones [66,68,69]. Recently, De Sanctis et al. (2022) assessed the impact of implementing MULESL technology (MUch LEss SLudge; patent WO2019097463), which aims to reduce sludge generation and the discharge of contaminants of emerging concern (CEC) when treating part of the inlet wastewater from Putignano's WWTP. It was found that, apart from reducing sludge generation and increasing CEC removal, odor emissions associated with this novel technology were reduced by a percentage of

45% with respect to the those associated with the traditional treatment at Putignano's WWTP [70]. As explained by the authors, the highest odor concentrations associated to the MULESL technology were found at the initial step of the process, when pumping the sewage (1714 $\pm$ 1496 ou/m^3), and then they were gradually reduced to low values (499 $\pm$ 357 ou/m^3) as the process went on.

On the other hand, many works dealing with odor and odorant emissions from WWTPs focused on the design and development of the so-called electronic noses in order to facilitate and automate odor emission quantification and, consequently, odor emission dispersion [71–73]. Typically, the compounds monitored by this kind of system are VOCs, VSCs, and nitrogen compounds, which are the typical odor precursors found in WWTP gaseous emissions. Together with odor concentration measurements, the main aim is to be able to correlate the concentration of different groups of odorant compounds with the odor concentration to finally obtain an electronic system independent of human panels that enables odor emission assessment in WWTPs. In this sense, Burgués et al. (2021) developed an e-nose mounted on a small drone which was capable of generating real-time aerial maps of the odor emissions in WWTPs, using a set of 21 gas sensors together with four environmental parameters sensors to highly correlate the concentrations of H_2S, NH_3, mercaptans, amines, and different VOCs with odor concentrations measured by the dynamic olfactometry of field samples [71,72]. As stated before, the conclusion is that electronic noses are helpful tools for odor impact assessment; however, it is also clear that maximizing the odor information in terms of olfactometric analysis together with powerful analysis by GC-MS and electronic noses is the way to follow for a proper odor emission characterization [26].

Finally, many of the odor emission studies carried out in WWTPs have the ultimate objective of predicting how these odors will impact the surroundings and citizens nearby the facilities, and, subsequently, what actions can be implemented to mitigate these impacts. In this line, air dispersion modeling applied to odor impact assessment is a tool that has been under constant improvement for the last decades, correlating pollutant and/or odor emission data from the emission sources with meteorological data or models to predict the atmospheric dispersion of these pollutants. From the different air dispersion models available, experience has shown that the most appropriate for these purposes are the Gaussian models (e.g., AERMOD) and CALPUFF [74,75]. In this sense, it is important to use as much site-specific data as possible to obtain realistic results. For example, to improve the regulatory framework on odor emissions in Chile, Varela-Bruce and Antileo (2021) gathered experimental olfactometric data from 41 Chilean WWTPs to generate a database on odor emission factors for specific units found in WWTPs. Recently, this database served as the basis to implement a CALPUFF odor dispersion model to assess the odor impact on the surroundings of the Temuco WWTP, concluding that the creation and use of the Chilean specific database showed much more realistic results than the ones obtained using standard databases [76]. In another recent study, Zarra et al. (2021) compared different odor assessment approaches for odor nuisance characterization in an urbanized area near by a full-scale WWTP, concluding that even though air dispersion modeling is a powerful tool for odor nuisance prediction, the fact of coupling and integrating it with other approaches such as field inspections through (i) trained assessors or (ii) questionnaire-based surveys would make the assessment outcomes much more realistic [77].

6. Odors Abatement

Traditionally, odor abatement has been carried out using physical–chemical technologies such as chemical absorption (scrubbing) and adsorption. The former is the most widespread technology at industrial scale, mostly favorable for medium- to highly-soluble compounds (dimensionless Henry coefficient lower than 1). Adsorption is a technology favorable for poorly soluble compounds, such as many hydrophobic VOC (dimensionless Henry coefficient above 1). In both cases, either chemicals' consumption in scrubbing or adsorbent replacement or regeneration make such technologies much more expensive than biological processes in terms of operational expenditures (OPEX). Although other common gas treatment technologies such as incineration or condensation could be used, they are also not economical in practice. Incineration needs natural gas to be added due to the low concentrations of odorant flows, whereas condensation costs either by pressure increase or cooling are not justified unless valuable chemicals can be recovered. However, practitioners still need to be convinced that emerging biological processes are a real alternative for odor abatement.

Biological gas treatment can be carried out with a range of configurations of bioreactors in practice. In all cases, the catalyst for odor stabilization is a microbial culture able to grow under the operating conditions in the bioreactor. However, mainly biofilters and biotrickling filters are used at full-scale for odor abatement. The reasons for that are essentially the higher construction costs of bioscrubbers compared to biofilters or biotrickling filters, as bioscrubbers are constituted by an absorption unit for pollutant capture followed by a reaction unit were biodegradation of pollutants takes place. Additionally, the odor is mainly made of very low concentrations of often poorly soluble compounds, which are not suitable to be treated in bioscrubbers where the absorption unit operates under larger L/G ratios (ca. 5–10 times larger) compared to biofilters and biotrickling filters. Thus, out of the large list of factors affecting the biofiltration performance in biofilters and biotrickling filters such as pH, temperature, or nutrient availability; the watering rate, in combination with an adequate gas contact time, is the most critical factor for a proper performance in the removal of odorants [78], as mass transport from the gas to the biofilm (biofilters) or liquid phase (biotrickling filters) is directly dependent on the thickness of the water layer over the biofilm. Selection of the most appropriate configuration is still challenging, but only a few works have systematically addressed that topic. Shammay et al. (2019) proposed a selection flowchart for the treatment of sewer network emissions [79]. Although H_2S removal is properly accomplished by biofilters, biotrickling filters, and activated carbon adsorbers, fluctuating loads and the presence of other odorants make selection complex. Often a combination of different configurations in-series is an appropriate alternative [66,80].

6.1. Biofilters

Biofilters are packed bed type bioreactors in which a complex microbiota grows as a biofilm on the surface of a packing material, which is simply continuously wetted through water humidity condensation or intermittently watered in case of evaporation. Most applications use one single or a combination of organic packing materials such as peat, compost, or wood chips [81], even though some authors have proven that the use of sole plastic materials such as polyethylene films may be also effective for inorganic odorants such as H_2S and NH_3 [82]. The packing material exerts an influence on the performance of biofilters [83]. Gas contact times below 10–15 s are enough for medium-to-highly soluble odorants such as H_2S, NH_3, or alcohols, whereas gas contact times above 25–30 s are required to remove odorant VOCs. However, determining an appropriate watering rate is challenging and often depends on the optimum results in adhoc field testing. As a proper starting point for testing, watering rates in the order of 0.1–0.3 $m^3 \cdot m^{-2} d^{-1}$ are suggested for odor removal in biofilters. Further research is needed to establish the potential correlations of the impact of the watering frequency and rate over biofilters' performance.

Application of biofilters as an alternative for odor abatement has been extensively reviewed in the past [84]; however, novel applications and opportunities are still arising [85]. Liu et al. (2021) proposed recently a novel three-stage integrated biofilter combining an acidophilic bacterial-based section for S and N removal and fungal-based and heterotrophic bacteria-based sections for the treatment of organic odorants such as VOCs from MSW treatment facilities [86]. Stratification of the bed in different sections was demonstrated as a compact efficient alternative as previously proposed by other authors from a modeling point of view [87]. New opportunities from knowledge findings in the biofiltration field can still be explored. Yao et al. (2019) showed that methanethiol removal in a biofilter was increased when methane was present [88], which may be useful for properly designing and exploiting the performance in odor mitigation of biocovers of landfills [89], which share many similarities with odor-abatement biofilters from other waste treatment facilities such as MSWTF.

6.2. Biotrickling Filters

Biotrickling filters (BTFs) are conceptually similar to biofilters except for the packing materials used, usually inert materials such as plastic or polyurethane foam fillings, and for the fact that a liquid phase is continuously trickled over the bed. Consequently, BTFs are more suitable for medium-to-high solubility compounds, such as H_2S, NH_3, or soluble VOCs such as alcohols and some carboxylic acids or ketones. Their main advantage over biofilters is that they can be built with a taller bed (4–6 m in height), opposite to biofilters often built with 1–1.5 m in height to avoid bed compaction that leads to channeling. Together with the shortest gas contact time needed for relatively soluble compounds (often below 5–10 s), this make BTFs a much more compact technology.

In recent decades, BTFs have gained much more interest since Gabriel and Deshusses demonstrated in 2003 the outstanding performance of a polyurethane packed BTF for the removal of H_2S as the main target odorant in WWTPs at gas contact times around 2 s [90]. A range of applications have been developed since then targeting the design of more compact units able to deal with larger pollutant concentrations and gas flow rates including the treatment of odorant concentration levels of VOCs. Strategies such as intermittent trickling of water in the removal of H_2S [91], the effect of natural stratification in multilayer BTFs for simultaneous H_2S and VOCs removal [92], or the optimization of the process parameters such as the packing material configuration and liquid recirculation [93] and the usage of additives, microbial inoculation, and pretreatment techniques to lower odor emission during the process have been recently explored with successful results [94].

Despite BTFs' benefits in terms of controllability and footprint amongst others, still, biofilters are the preferred configuration at industrial scale, as they are the less expensive configuration among biofiltration technologies [95]. This is particularly important when large gas flowrates, above 40,000–60,000 $m^3 \cdot h^{-1}$, have to be treated. Such high flow rates require the use of parallel BTF units, thus leading to much less competitive installations as BTFs present 30–50% larger capital expenditures (CAPEX) than biofilters. However, at the low-end of the range of gas flowrates BTFs offer much more appealing benefits both technically and economically.

6.3. Odor Abatement in In-Series Configurations

Because of the complexity of the emissions in many waste treatment facilities and despite recent advances, single-type configurations are usually not able to cope with the more and more restrictive limits in terms of odorant emissions. If bioprocesses are considered, the most widespread combination of technologies for odor treatment at full-scale is the use of in-series chemical scrubbers for VICs' (volatile inorganic compounds) removal (mainly NH_3 and H_2S) followed by biofilter for VOCs' removal. Alternatives such as the use of plasma systems [96] or the combination of adsorption and biotrickling filtration [97] have been also explored with interesting results.

However, several authors have shown that either converting chemical scrubbers to BTFs for VICs' removal [90,98], combining a BTF followed by a biofilter for complex odorants abatement at WWTP [66], or even using in-series BTFs for S-compounds' removal may be also effective for biobased-only odor abatement, while, at the same time, a much more sustainable and economical alternative [99].

7. Conclusions

From this review, it is important to highlight the following conclusions:

(1) Odors are a very important measure to characterize waste and wastewater treatment plants, sometimes being an indicator of some problems in the performance of the plant.

(2) Odors should be measured by dynamic olfactometry to gauge the real effect that they provoke on society. Other types of measures, such as electronic noses, are in a developmental stage, because of the complex mixtures that constitute odors from waste management plants.
(3) Odors are not synonymous with toxicity. Although the main contributors of odors in waste and wastewater treatment plants are VOCs (especially nitrogen and sulfur compounds), the complete composition must be determined to calculate toxicity values.
(4) Among the available technologies for odor abatement, biological treatments such as biofiltration and modifications are the most sustainable in terms of environmental impact and economic cost.

Author Contributions: Conceptualization, A.S. and D.G. (David Gabriel); methodology, D.G. (Daniel González); formal analysis, D.G. (David Gabriel); investigation, A.S. and D.G. (David Gabriel); writing—review and editing, A.S., D.G. (David Gabriel) and D.G. (Daniel González). All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

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

Abbreviations

BTF	Biotrickling filter
CAPEX	Capital expenditures
CEC	Contaminants of emerging concern
GC-MS	Gas chromatography coupled to mass spectrometry
MSW	Municipal solid waste
MSWTF	Municipal solid waste treatment facility
OEF	Odor emission factor
OFMSW	Organic fraction of municipal solid waste
OPEX	Operational expenditures
OUR	Oxygen uptake rate
VOC	Volatile organic compound
VSC	Volatile sulfur compound
WWTP	Wastewater treatment plant

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