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Absorption processes in reducing the odor nuisance of wastewater☆,☆☆

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ABSTRACT

Deep social awareness, especially in highly developed countries, imposes pressure on entrepreneurs and service providers, forcing them to undertake effective actions to minimize the effects of their activities also in terms of the emission of malodorous substances. The article presents information on the absorption processes harnessed in the deodorization of gases from wastewater management and the characteristics of these gases. Avoiding emissions is not always possible, hence there is a need to conduct an inventory of such gases and use deodorization methods. The specificity of gases from wastewater management and their prevalence urge the search for cheap and easy-to-use deodorization methods. It is obvious that the selection of deodorization technology is driven by many factors and should be preceded by a thorough analysis of the possibilities and limitations of various solutions. The aim of this article is, therefore, to present the characteristics of gases from wastewater management and to discuss various technologies based on absorption processes as a technology for deodorizing such gases in order to help potential investors choose an emission-reducing method suitable for particular conditions.

- Malodorous substances in wastewater management.
- Deodorization using water and chemical absorption.
- Deodorization using biological purification.

Specifications Table

Subject area:	Gas cleaning
More specific subject area:	*Deodorization*
Name of the reviewed methodology:	*Absorption*
Keywords:	*odor, absorption, deodorization technology, malodorous substances removal, malodorous gases emission limitation, deodorization, sewage treatment*
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Review question:	*1. What odor-generating compounds does wastewater management deal with?*
	2. What are the types of absorption methods used in deodorization?
	3. What are the advantages and disadvantages of each method?

☆ **Related research article** The review article describes one of the groups of deodorization methods used in the deodorization of gases from wastewater management – absorption

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Method details

Introduction

Human activity is inevitably associated with an increase in anthropopressure, whereas the civic development is accompanied by a successive degradation of the natural environment. The generation of various types of pollutants, including the emissions of undesirable gaseous components, necessitates implementing countermeasures. A certain group of contaminants includes substances with an unpleasant odor. Odor nuisance affects 13 to 20% of the European population [24]. As air quality and related odor emissions grow into extremely severe problems with the development of civilization, especially in highly developed countries, methods for reducing these emissions are increasingly being sought. The production of potentially malodorous chemicals is associated with many areas of human activity, with wastewater management being one of their most commonly mentioned sources [19,32,38,43,45]. One of the most common reasons for people's complaints about wastewater management activities is the odor nuisance of facilities dealing with this branch of economy [4,21,24,43]. This is because in the past sewage treatment plants and sewage systems were designed mainly to remove pollutants and prevent their discharge into the aquatic environment and soil, while the problem of potential air contamination has been neglected. Hence, in most cases, facilities designed for the wastewater treatment process have no comprehensive solutions to prevent odor emissions [38].

Technologies deployed to reduce malodorous substances can be broadly divided into two main groups: preventive technologies (solutions ensuring the possibility of preventing odor emissions) and technologies for deodorization of gases already generated. The preventive technologies are therefore aimed at averting the formation of odor-generating pollution. If they cannot be applied, technologies that reduce or mitigate the odor nuisance of the resulting gases need to be implemented [46]. Physical methods of diluting emitted gases can be distinguished as a separate group of methods. This group of methods is designed to dilute the emitted odorous gas sufficiently before it reaches residential areas to eliminate its odor nuisance. Odor-generating pollutants are generated but are not a nuisance outside the buffer area. The diagram below shows different ways of proceeding to reduce odor nuisance in wastewater management facilities (Fig. 1).

As with all pollutants, it is best to avoid their generation. Therefore, prevention should be the first and the key action undertaken. In the case of wastewater management, it mainly consists in maintaining sewage networks with devices, wastewater treatment plants, and facilities managing sewage sludge in good condition throughout the entire operation process.

However, if it is not possible to prevent the generation of unpleasant odors, measures should be taken to reduce, or at best completely remove odors from the resulting gases. In this case, it is very important to make the processes odor-hermetic so that it is possible to direct as many gases as possible to deodorizing installations. The collected gases can be deodorized by means of various techniques, including e.g. absorption, adsorption, incineration, non-thermal oxidation or biological treatment. Methods based on absorption processes are quite willingly used due to their high efficiency and fairly good process recognition .

Malodorous substances in sewage management

Malodorous substances appearing in the air during wastewater collection and treatment and sewage sludge neutralization are very diverse. They mainly include compounds formed upon organic matter degradation [41,43,52]. Various types of gases are emitted in the wastewater during the biodegradation processes. Odorless gases, such as carbon dioxide, methane or nitrogen, but also odorants are then generated [23]. The odor substances most frequently identified in gases from wastewater management facilities include those containing sulfur, nitrogen and volatile organic compounds such as: hydrogen sulfide, thiols, sulfides, ammonia, indole, amines, alcohols, aldehydes, ketones or fatty acids [2,4,23,32,35,42,43]. Table 1 presents the detection thresholds for the most frequently identified odor compounds.Detection thresholds for the most frequently identified odor compounds generated during wastewater collection and treatment and sewage sludge management.

The most frequently described and mentioned in the literature are sulfur compounds, especially hydrogen sulfide [3,4,23,27,45]. They are estimated to account for approximately 45% of the compounds responsible for the olfactory experience caused by transport and wastewater treatment. In oxygenated wastewater, sulfur most often occurs in the form of a sulfate ion and, as reported by Paing et al. [28] its concentration ranges from 10 to even 400 mg/dm^3. Under anaerobic conditions, when the wastewater is poorly aerated (e.g. wastewater in sewage systems with a low flow rate and quite high temperature), these compounds are converted into sulfides upon the action of sulfate-reducing bacteria [20,29]. The wastewater pH value is essential as well. At pH of about 7 and under reducing conditions, sulfur will occur in the wastewater in the form of hydrogen sulfide and hydrosulfides. An increase in pH facilitates hydrogen sulfide conversion into hydrosulfides. This phenomenon is illustrated by the following equations [32,48].

$$H_2S_{(g)} \leftrightarrow H_2S_{(aq)} \overset{pK_{a1}=7}{\leftrightarrow} HS^- \quad (1)$$

$$\mathrm{H_2S} \leftrightarrow \mathrm{H^+} + \mathrm{HS^-} \quad (2)$$

$$K_{a1} = \frac{C_{H^+} \cdot C_{HS^-}}{C_{H_2S_{(aq)}}} \quad (3)$$

However, only hydrogen sulfide poses an odor-generating problem, as it can pervade from the wastewater to the gas phase and constitute an odor nuisance (Eq. (1)). Its concentration above the wastewater surface almost always exceeds the olfactory detection

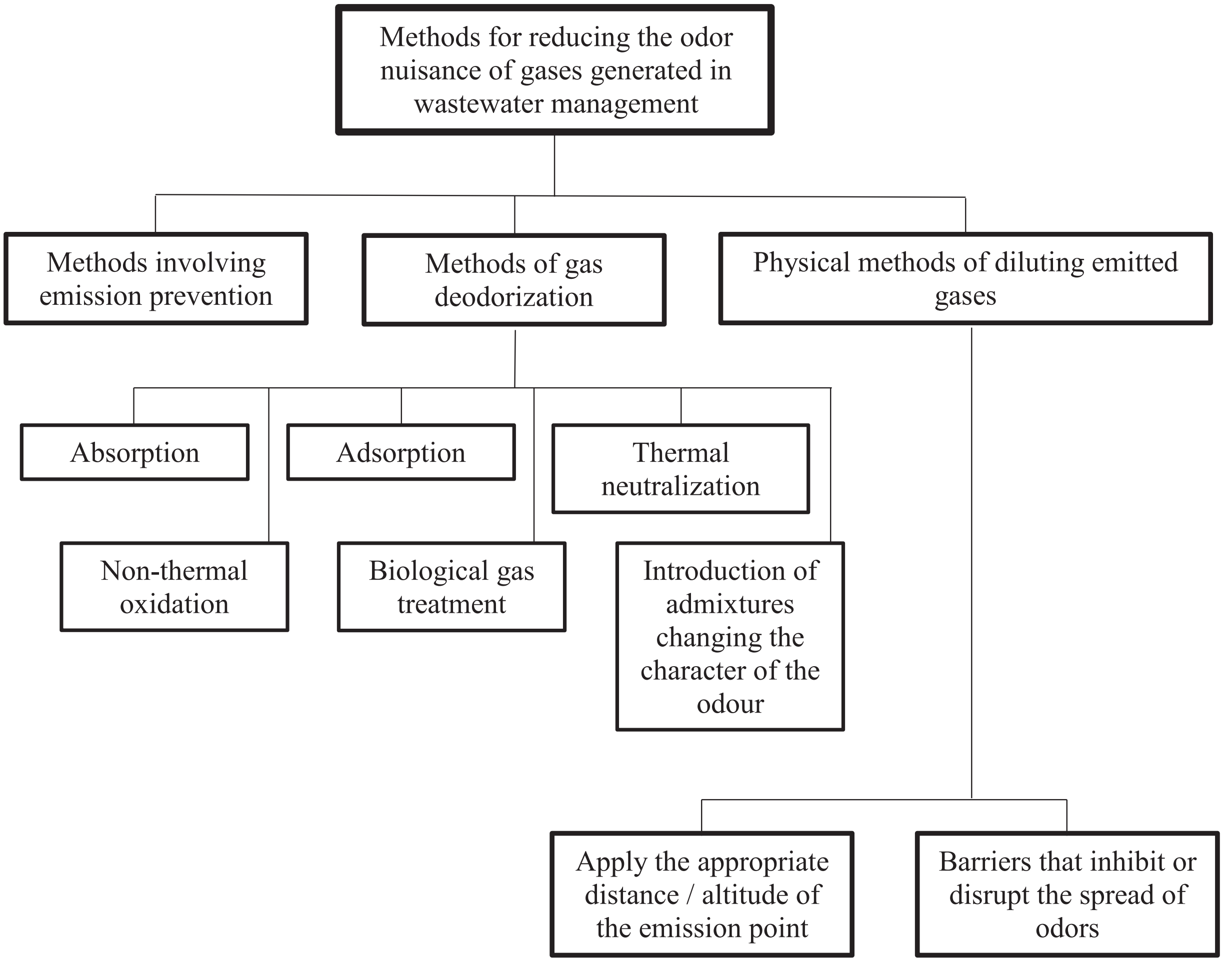

Fig. 1. Methods for reducing the odor nuisance of gases generated in wastewater management.

threshold, and often also the lowest permissible instantaneous concentration (14 mg/m^3) [21,40]. The amount of hydrogen sulfide generated from wastewater and emitted to the air depends, among other things, on the temperature, pH or the presence of wastewater turbulence [30,32,43,49,50].

So far, a number of biochemical reactions mediated by microorganisms that lead to hydrogen sulfide formation have also been identified [14,43]. One of them is the reaction (Eq. (4)) in which microorganisms convert sulfate VI ion (with organic carbon and water being necessary) into hydrogen sulfide, producing a bicarbonate ion [43].

$$SO_4^{2-} + 2C + 2H_2O \rightarrow 2HCO_3^- + H_2S \quad (4)$$

Another reaction (Eq. (5)) requires a strongly acidic environment. During its course, sulfate VI ion is also converted to hydrogen sulfide as presented below [43].

$$SO_4^{2-} + 10H^+ \rightarrow H_2S + 4H_2O \quad (5)$$

Microorganisms can also transform elemental sulfur into hydrogen sulfide. The course of this reaction is shown in Eq. (6) [43].

$$S + 2H^+ \rightarrow H_2S \quad (6)$$

It is noteworthy that hydrogen sulfide is a hazardous compound. At concentrations of 60 ÷ 70 mg/m^3, it is irritating to the eyes, whereas several hours of contact with this gas at its concentrations of 140 ÷ 210 mg/m^3 causes poisoning, and a at concentration above 700 mg/m^3 can even be fatal. The odor of hydrogen sulfide is only noticeable in a certain concentration range, and is no longer perceivable at concentrations above 100 mg/m^3 [40].

Not only sulfur compounds present in the wastewater are responsible for its odor nuisance. Depending on wastewater type, various other malodorous substances will also be produced. For example, large amounts of lactose, proteins or fats can be expected in dairy sewage. Their ratios, pH, temperature and the redox potential will affect the biodegradation of such a material and the possibility of generation of odor-causing compounds. Under reducing conditions, proteins are broken down mainly to ammonia and amino acids.

Table 1
Detection thresholds for the most frequently identified odor compounds generated in wastewater management.

Name	Semi-structural/summary formula	Detection threshold [ppb]	Description of the smell	Bibliographic source
hydrogen sulphide	H_2S	0.47	rotten eggs	[38]
	$/H_2S$	0.018		[23]
sulphur dioxide	SO_2	10	pungent, garlic	[38]
	$/SO_2$			
methyl mercaptan	CH_3SH	0.07	rotten cabbage	[38]
	$/CH_4S$	0.001		[23]
dimethyl sulphide	$(CH_3)_2S$	0.21	rotten vegetables, garlic	[38]
	$/C_2H_6S$	0.004		[23]
ammonia	NH_3	10	pungent, irritating	[38]
	$/NH_3$	5.75		[23]
methylamine	CH_3NH_2	470	fish	[38]
	$/CH_5N$	0.02		[23]
dimethylamine	$(CH_3)_2NH$	340	fish	[38]
	$/C_2H_7N$			
trimethylamine	$(CH_3)_3N$	4	fish	[38]
	$/C_3H_9N$	1.7		[23]
acetic acid	CH_3COOH	1000	vinegar	[38]
	$/C_2H_4O_2$			
indole	-	0.0014	fecal, repulsive	[38]
	$/C_8H_7N$	0.000032		[23]
skatole	-	0.006	fecal	[38]
	$/C_9H_9N$	0.000565		
benzene	-	270	paint thinner	[38]
	$/C_6H_6$			
toluene	$C_6H_5CH_3$	46	fruity, paint, pungent, rubber	[38]
	$/C_7H_8$			
xylene	$C_6H_4(CH_3)_2$	38	plastic	[38]
	$/C_8H_{10}$			
ethyl mercaptan	C_2H_5SH	0.0011	leek,	[23]
	$/C_2H_6S$		onion	
n-propanethiol	$CH_3(CH_2)_2SH$	0.001		[23]
	$/C_3H_8S$			
n-butanethiol	$CH_3(CH_2)_3SH$	0.0014		[23]
	$/C_4H_{10}S$			
diethyl sulphide	$(C_2H_5)_2S$	0.004		[23]
	$/C_4H_{10}S$			
diethyl disulphide	$(C_2H_5)_2S_2$	0.00043		[23]
	$/C_4H_{10}S_2$			
pyridine	-	0.084		[23]
	$/C_5H_5N$			
acetamide	CH_3CONH_2	60		[23]
	$/C_2H_5NO$			
butyric acid	C_3H_7COOH	0.004		[23]
	$/C_4H_8O_2$			
valerian acid	$CH_3(CH_2)_3COOH$ $/C_5H_{10}O_2$	0.005	unpleasant, sweet, honey	[23]
phenol	C_6H_5OH	0.109		[23]
	$/C_6H_6O$			
p-cresol	$CH_3C_6H_4OH$	0.0018		[23]
	$/C_7H_8O$			

Under similar conditions, lactose decomposes to form propionic acid, ethanol and acetates. On the other hand, fats are broken down into glycerol and fatty acids [17]. Most of these newly formed compounds have quite low olfactory thresholds, which triggers the problem of odor nuisance in such wastewater.

Wastewater treatment plants are undoubtedly the cause of emissions of malodorous substances, the concentrations of which vary at different points in the treatment process. The type and amount of odorants released into the air is determined by the type of degrading matter, but also by the stage and conditions of the biodegradation. First of all, the odor nuisance is caused by the raw sewage inflow zones, facilities separating primary sludge, and sludge treatment zones (Table 2).

The most common sources of emissions are, therefore, the catchment points of slurry tankers, the main collector, grates and sieves, a floating slurry and fat separation station, fermentation tanks, drip plots, lagoons, and sewage sludge treatment rooms [3,4,21,26,53,54].

It is estimated that as much as 52% of emissions are caused by raw wastewater and thickening of sewage sludge, and that about 40% are related to sludge neutralization [38].

Table 2
Odor emissions from selected wastewater treatment plants.

Object name	Emission value [$ou_E \cdot m^{-2} \cdot h^{-1}$]	Bibliographic source
primary sedimentation	10 000	[38]
sludge-digestion tanks	8 200	[38]
sludge thickening and dewatering facilities	2500	[38]
denitrification (anoxic) tanks	730	[38]
nitrification (aerobic) tanks	510	[38]

Table 3
Average percentage distribution of odor emissions during waste water treatment processes.

Object name	Average percentage distribution of odour emission	Bibliographic source
grit chamber	22%	[38]
primary sedimentation	12%	[38]
aeration	9%	[38]
secondary sedimentation	3%	[38]
sludge dewatering thickener	33%	[38]
sludge storage digester	21%	[38]

Table 4
Olfactory thresholds (at normal pressure $p = 1.01325 \cdot 10^5$ Pa) and Henry's constant for selected malodorous compounds [34],[46].

Malodours compounds	Henry's constant [Pa]	Olfactory thresholds [Pa] at normal pressure $p = 1.01325 \cdot 10^5$ Pa
acetaldehyde	$3.749 \cdot 10^5$	0.000152
acetic acid	$0.010 \cdot 10^5$	0.048636
acetone	$1.824 \cdot 10^5$	4.255650
acrylonitrile	$6.181 \cdot 10^5$	0.162120
ammonia	$0.963 \cdot 10^5$	1.722525
butanoic acid	$0.030 \cdot 10^5$	0.000405
carbon disulphide	$1013.250 \cdot 10^5$	0.021278
dimethyl sulphide	$111.458 \cdot 10^5$	0.000304
dimethylamine	$1.317 \cdot 10^5$	0.034451
formaldehyde	$0.018 \cdot 10^5$	0.081060
hydrogen sulphide	$557.288 \cdot 10^5$	0.000042
methanethiol	$141.855 \cdot 10^5$	0.000007
methylamine	$0.608 \cdot 10^5$	0.476228

Table 5
Efficiency of selected chemical absorption processes.

Absorber type	Absorbent - aqueous	Efficiency (substance to be removed)	Bibliographic source
cross	NaOH, NaClO	80-90% (H_2S)	[6]
parallelflow	NaOH, NaClO	above 90% (H_2S)	[10]
		above 99% (H_2S);	[33]
		87% (CH_3SH)	[33]
counterflow with filling	NaOH, NaClO	above 99% (H_2S);	[11]
		95% (H_2S);	[16]
		82-90 % (H_2S);	[47] [53]
		50-70% (fecal odors)	[11]
		above 99% (CH_3SH)	
counterflow	O_3	99% (H_2S)	[22]
counterflow with filling	$2KHSO_5 \cdot KHSO_4 \cdot K_2SO_4$	above 95% (CH_3SH)	[57]
counterflow	H_2O_2	90% (organic sulphides); 85%-99% ($(CH_3)_2S$)	[39]
counterflow	Cl_2	99% (malodorous compounds)	[12]
counterflow with filling	NaClO	97% (malodorous compounds)	[12]
counterflow	NaClO + exposure UV	99.9% (H_2S); 99.6% (CH_3SH); 99.3% ($(CH_3)_2S$)	[12]
counterflow	NaClO + filling containing NiO_2	~100% (malodorous compounds)	[12]
counterflow	NaBrO	95% (malodorous compounds)	[12]
counterflow with filling	I degree ClO_2 II degree $Na_2S_2O_3$	90% (malodorous compounds)	[12]
counterflow	NaOH, $KMnO_4$	99.9 % (malodorous compounds)	[12]

Reducing the odor nuisance of gases generated in the wastewater management

Article 13 of the Directive of the European Union ([1], L 312/3) recommends the Member States should take the necessary measures to ensure that waste management is carried out without endangering human health, with no threat posed to the environment, and without causing nuisance due to noise or odors. The emerging regulations of this type spur the interest of both domestic and foreign authorities in the problem of odors [38]. They encourage to take actions aimed at reducing the odor nuisance of gases. The first step should undoubtedly attempt to significantly mitigate or even prevent the formation of malodorous pollutants via the implementation of preventive technologies. Sometimes, however, it is difficult or even impossible to arrest emissions. Then, deodorization methods or, in some cases, physical methods of diluting emitted gases (barriers or high chimneys), need to be implemented. In densely populated areas, the primary strategy is to make the treatment processes odor-hermetic, followed by collection and then transport of contaminated gases to deodorization systems [8,38] As already mentioned, methods based on sorption processes, including absorption, are among the frequently deployed solutions for deodorizing gases derived from wastewater management. A range of methods based on absorption processes is listed below. According to the division of methods presented in the introduction, all methods should be classified as methods of gas deodorization.

Absorption

Absorption, in addition to adsorption, is one of the most common gas deodorization technologies harnessed in wastewater treatment plants [4,38]. Additionally, it is a fairly well recognized method characterized by high reliability and a short gas retention time (only 1–2.5 s) [38]. The absorption process is carried out in devices called absorbers, with a very different design (e.g., spray scrubbers, packed columns, plate columns or barbotage absorbers - where the absorption liquid is the solid phase and purified gas is the dispersed phase) [5,23,37,46].

The most common design is the counterflow vertical spray absorber, where the absorbent is typically fed at the top of the device and circulated. Absorbers of this type are used when the main mass transfer resistances appear on the gas side. Packed absorbers are most often applied if the mass transfer resistances are similar in both phases, whereas barbotage absorbers are deployed if the main mass transfer resistances are on the liquid side [46].

The absorption processes are based on the solubility of odor-causing pollutants in the absorption liquid. The gaseous pollutant is dissolved in the liquid phase and temporarily stabilized for further purification [38]. Absorption is the process of absorbing a gaseous substance (absorbate) by a liquid or solid substance (absorbent), i.e. mass exchange between the gas and the liquid or the solid phases. Along with adsorption, it belongs to sorption processes. Unlike adsorption, however, it is a process that takes place in the entire volume of the sorbent, and mass transport depends primarily on the contact surface between the gas to be treated and the absorbent, and on the solubility of the absorbate in the absorbent ([37,58]). It is quite important to analyze the kinetics of the absorption process in order to determine the required contact time of the liquid and gas phases. The kinetics largely determines the size of the absorption devices and, obviously, the cost of the entire process.

The mass transfer flux ($\dot{n}$) (the flow of odorants between the gas and liquid phases) is described in the Eq. (7) shown below [15].

$$\dot{n} = K_g \cdot A \cdot \Delta\pi \tag{7}$$

where:

- K_g– *mass transfer coefficient (depending on the mass transfer coefficients in the gas and liquid phase and on the constant gas-liquid balance), which depends on many factors, including diffusion coefficients, viscosity, density as well as the nature of the flow of both the purified gas and the liquid absorptive.*
- A – *surface area of mass transfer, which depends on the type of absorber and its dimensions.*
- $\Delta\pi$– *the mean driving force, which depends on a difference of component concentration in the purified gas and in the equilibrium state (according to Henry's law defined for the actual concentration of a component in the absorption liquid).*

The Henry's law (Eq. (8)) describes the equilibrium process of mass flux between phases [37,46].

$$p_A = H \cdot x_A \tag{8}$$

where:

- p_A– *partial pressure (resilience) of component "A" in the gas at equilibrium,*
- H – *Henry's constant,*
- x_A– *concentration (mole fraction) of component "A" in the liquid at equilibrium.*

The Henry's constant depends on the process temperature, the type of absorbed component, and the type of absorbent. Water or water enriched with chemical compounds serve most often as the absorption liquid.

Water absorption

0presents exemplary values of the Henry's constant of the component absorption in water and the partial pressure corresponding to the olfactory threshold of selected malodorous compounds.

Table 6
Optimal parameters of the absorption liquid for most microorganisms used in deodorization processes.

Parameter name	Parameter value/ range of values	Unit	Bibliographic source
temperature	30 - 40	^0C	[23],[31],[36]
pH	5 - 8	pH	[36],[44]
wavelength of harmful radiation	230-275	nm	[23],[31]
proportions between biogenic elements	100:5:1	-	[23],[31]

Although the Henry's constant value indicates a high absorbate partition coefficient between the liquid and gas phases, it is often insufficient due to the height of the odorant's olfactory threshold. In such a case, the absorption process would require a large volume of absorbent to achieve a satisfactory effect.

Chemical absorption

In order to increase the process efficiency, water is enriched with various chemical compounds. The spectrum of these compounds is quite broad and determined individually for a given type of gas. The substances that are commonly used include, for example: O_3, H_2O_2, NaClO, $NaClO_2$, BaClO, $KMnO_4$, NaOH, CaCl(ClO), $Ca(ClO)_2$, and Cl_2. This type of absorption process is also called chemical absorption. Chemical absorbers (called chemical scrubbers) are capable of dealing with a wide range of gaseous pollutants and can also tolerate temperature fluctuations. A certain drawback of their use, however, is the increased susceptibility to corrosion due to contact with chemicals. The effectiveness of selected processes using chemical absorption is presented below [51]. Depending on the process conditions and the absorbed pollutant type, the efficiency ranges from 50% to even 100%. However, it should be remembered that even such high values may be insufficient in the case of gas deodorization. Even small amounts of an odorant can cause intense olfactory sensations. In addition, a spent absorbent is left after the process. It must be regenerated or finally disposed [46], which often increases operating and investment costs.

Absorbent can be regenerated with either physicochemical or biological methods, with the latter perceived as more environmentally friendly.

Biological purification

As already mentioned, one of the methods of regenerating the absorbent is through biological processes. Absorption coupled with biological regeneration of absorbents is carried out in installations called bioscrubbers. Deodorization in bioscrubbers consists in transporting the mass of odor-causing pollutants from the treated gas to the absorption liquid (most often water) containing suspended microorganisms (the so-called activated sludge). The deodorization process takes place in two stages. The first stage entails the absorption of the odor-causing pollutant in the absorbent, whereas the second one includes its biodegradation due to the activity of microorganisms [18].

The biological purification of gases is possible if the pollutants are biodegradable substances and the treated gases do not contain substances toxic to microorganisms. It is permissible to purify gases containing toxic substances if their concentration is low and does not destroy the biological material [7]. The gas parameters must guarantee the biological activity of the microorganisms as they determine the parameters of the absorption liquid colonized by the microorganisms (Table 6).

The process temperature is essential in this case, as it should not cause abrupt changes in the absorbent's temperature [13,23,31,37]. The pH value is equally important, although it is also possible to bio-purify acid gases with an appropriate sorbent adaptation [9]. In addition, the appropriate proportions and availability of biogenic elements, lack or sufficiently low concentrations of toxins, and reduction of harmful UV radiation are required. It is also important to maintain sufficiently stable parameters to prevent their rapid changes. If the parameters need to be modified, the modifications should to be made slowly so that the microorganisms have a chance to adapt to the new conditions.

The most important thing, however, is that odor-causing pollutants be at least little soluble in the absorbent, which is at the same time the living environment of microorganisms. The process of absorbent regeneration (degradation of odor-causing pollutants) takes place thanks to the microorganisms suspended in it. These microorganisms use odor-causing pollutants for their biological processes. In this way, they acquire the energy and metabolites necessary for their life processes, boosting their biomass (an increase in the amount of microorganisms in the sorbent). Therefore, excess biomass should be systematically removed [37]. Bioscrubbers are often coupled with an absorbent regeneration tank (activated sludge), in which the sorbent regeneration can be intensified through, e.g., the aeration processes, the addition of nutrients (the proportions in the treated gas are not always optimal for the growth of microorganisms) or absorption liquid pH adjustment [37].

The above process is carried out mainly in countercurrent flow. If the bioscrubbers contain filling, it is sometimes run with cross-flow. The filling is used to increase the contact surface between the liquid and gas phases [37]. Then, the processes of absorption into the absorption liquid are coupled with the sorption processes on the filling covered with a layer of a biofilm colonized by microorganisms. The process of pollutant degradation takes via two pathways: thanks to microorganisms suspended in the absorption liquid and thanks to microorganisms colonizing the biofilm.

If the bio-scrubbers contain filling, its overgrowth should be prevented. Therefore, it is additionally required to remove the excessive amount of microorganisms from the filling surface - bed rinsing stage. Satisfactory results are also obtained when using a floating filling, like e.g., a filling suspended in a fluidized phase, where its elements collide with each other and remove excess biofilm from its surface. The operating parameters of the packed bioscrubber are: linear gas flow rate from 0.5 to 2.5 m/ with approximately 20-60 m^3 of the absorbent per m^2 of the filling [37].

Barbotage reactors can also be used for biological gas purification, but then the flow rate of the gas to be treated should be low [25]. In this case, e.g. activated sludge (water with microorganisms suspended in it) can serve as the solid phase.

A quite significant disadvantage of the biological methods is the operational risk, which is one of the largest among all deodorization methods deployed ([25,55]). Nevertheless, due to their low costs, biological processes are among the methods most frequently used in the deodorization of odor-causing pollutants from wastewater treatment plants ([3,56,53]).

Summary

Reducing the odor nuisance from wastewater management is becoming a challenge, especially in highly developed countries. Taking action requires an inventory of the problem. The range of odor-generating compounds present in gases from wastewater management is very extensive, and their olfactory thresholds are often very low. Interactions between the individual components of the malodorous gas make it very difficult to solve the problem. Therefore, it seems that the use of coupled techniques: quantitative and qualitative chemical analysis and olfactometry, can provide the right choice of a deodorization method and the assessment of its effectiveness.

Firstly, preventive methods should be implemented in order to deal with the problem of odor nuisance. Only when they fail, the methods of deodorizing the generated gases should be harnessed. This often requires process containment, collection and transfer of gases to deodorizing installations. In the case of gases from wastewater management, most frequently applied solutions are the sorption methods, including absorption processes. These are simple technologies that do not require highly qualified personnel to operate. Simple absorption in water, often enriched with various chemicals or microorganisms, proves viable. The absorption processes ensure high efficiency with relatively low operating costs. One of the most important costs of the process is the regeneration of the sorbent or its utilization. Considering the environmental concerns, there is a trend towards biological regeneration methods. Therefore, installations based on bioscrubbers, often also coupled with sludge regeneration tanks, are becoming quite common.

Ethics statements

My work does not include data collected from social media platforms.

CRediT author statement

Izabela Wysocka - Preparation and execution of the article in full

Declaration of Competing Interest

Please **tick** the appropriate statement below (please do not delete either statement) and declare any financial interests/personal relationships which may affect your work in the box below.

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

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Please declare any financial interests/personal relationships which may be considered as potential competing interests here.

Data availability

No data was used for the research described in the article.

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References

[1] Dz. Urz. UE 2008, L 312/3. Dyrektywa Parlamentu Europejskiego i Rady 2008/98/WE z dnia 19 listopada 2008 r. w sprawie odpadów oraz uchylająca niektóre dyrektywy.
[2] E. Agus, L. Zhang, D. Sedlak, A framework for identifying characteristic odor compounds in municipal wastewater effluent, Water Res. 46 (2012) 5970–5980.
[3] C. Alfonsín, R. Lebrero, J.M. Estrada, R. Muñoz, N.J.R. Kraakman, G. Feijoo, M.T. Moreira, Selection of odour removal technologies in wastewater treatment plants: a guideline based on life cycle assessment, J. Environ. Manag. 149 (2015) 77–84.
[4] E. Alinezhad, M. Haghighi, F. Rahmani, H. Keshizadeh, M. Abdi, K. Naddafi, Technical and economic investigation of chemical scrubber and bio-filtration in removal of H2S and NH3 from wastewater treatment plant, J. Environ. Manag. 241 (2019) 32–43.
[5] M. Azizi, P. Biard, A. Couvert, M. Ben Amor, Simulation of hydrogen sulphide absorption in alkaline solution using a packed column, Environ. Technol. 35 (2014) 3105–3115.

[6] M. Baawain, A. Al-Mamun, H. Omidvarborna, I.N. Al-Sulaimi, Measurement, control, and modeling of H2S emissions from a sewage treatment plant, Int. J. Environ. Sci. Technol. 16 (2019) 2721–2732.
[7] K. Barbusinski, K. Kalemba, D. Kasperczyk, K. Urbaniec, V. Kozik, Biological methods for odor treatment - a review, J. Clean. Prod. 152 (2017) 223–241.
[8] B.H.M. Beigi, R.B. Thorpe, S. Ouki, P. Winter, A. Waalkens, Hydrogen sulphide and VOC removal in biotrickling filters: comparison of data from a full-scale, low-emission unit with kinetic models, Chem. Eng. Sci. 208 (2019) 115033.
[9] M. Ben Jaber, A. Couvert, A. Amrane, F. Rouxel, P. Le Cloirec, E. Dumont, Biofiltration of high concentration of H2S in waste air under extreme acidic conditions, New Biotechnol. 33 (2016) 136–143.
[10] P.F. Biard, A. Couvert, C. Renner, P. Zozor, S. Bassivière, J.P. Levasseur, Hydrogen sulphide removal in waste water treatment plant by compact oxidative scrubbing in Aquilair Plus^{TM} process, Water Pract. Technol. 4 (2009) wpt2009023.
[11] C. Bonnin, Les Sources de Nuisances Olfactives Dans les Stations de Traitement des Eaux Residuaires et Leur Traitement par Lavage à L'eau Chlorée en Milieu Basique, University of Rennes, France, Rennes, France, 1991.
[12] S. Bursa, M. Kicińska, J. Kośmider, M. Stanisz-Lewicka, Dezodoryzacja gazów i ścieków, Część II. Dezodoryzacja na Drodze Chemicznego Utleniania, Politechnika Szczecińska, Instytut Inżynierii Chemicznej i Chemii Fizycznej., 1986.
[13] Y. Chen, X. Wang, S. He, S. Zhu, S. Shen, The performance of a two-layer biotrickling filter filled with new mixed packing materials for the removal of H2S from air, J. Environ. Manag. 165 (2016) 11–16.
[14] T.E. Chestnutt, M.T. Bach, D.W. Mazyck, Improvement of thermal reactivation of activated carbon for the removal of 2-methylisoborneol, Water Res. 41 (2007) 79–86.
[15] K. Freudenthal, R. Otterpohl, J. Behrendt, Absorption of odorous substances using selective gas–liquid separation processes, Waste Manag. (Oxf.) 25 (9) (2005) 117–126.
[16] L. Gao, T.C. Keener, L. Zhuang, K.F. Siddiqui, A technical and economic comparison of biofiltration and wet chemical oxidation (scrubbing) for odor control at wastewater treatment plants, Environ. Eng. Policy 2 (2001) 203–212.
[17] A. Grala, M. Zieliński, M. Dudek, M. Dębowski, Efektywność oczyszczania ścieków mleczarskich w reaktorze beztlenowym o przepływie pionowym, Inż. Ekol. 22 (2010) 97–105.
[18] J. Hernandez, J. Lafuente, O. Prado, D. Gabriel, Simultaneous removal of H2S, NH3, and ethyl mercaptan in biotrickling filters packed with poplar wood and polyurethane foam: Impact of pH during startup and crossed effects evaluation, Water Air Soil Pollut. 223 (2012) 3485–3497.
[19] G. Hudon, C. Guy, J. Hermia, Measurement of odor intensity by an electronic nose, J. Air Waste Manag. Assoc. 50 (2000) 1750–1758.
[20] T. Hvitved-Jacobsen, J. Vollertsen, N. Tanaka, An integrated aerobic/anaerobic approach for prediction of sulfide formation in sewers, Water Sci. Technol. 41 (2000) 107–115.
[21] G. Jiang, D. Melder, J. Keller, Z. Yuan, Odor emissions from domestic wastewater: a review, Crit. Rev. Environ. Sci. Technol. 47 (2017) 1581–1611.
[22] A. Kerc, S.S. Olmez, Ozonation of odorous air in wastewater treatment plants, Ozone Sci. Eng. 32 (2010) 199–203.
[23] J. Kośmider, B. Mazur-Chrzanowska, B. Wyszyński, Odory, Wydawnictwo Naukowe PWN, Warszawa, 2002.
[24] R. Lebrero, L. Bouchy, R. Stuetz, R. Munoz, Odor assessment and management in wastewater treatment plants: a review, Crit. Rev. Environ. Sci. Technol. 41 (2011) 915–950.
[25] R. Lebrero, E. Rodríguez, M. Martin, P.A. García-Encina, R. Muñoz, H2S and VOCs abatement robustness in biofilters and air diffusion bioreactors: a comparative study, Water Res. 44 (2010) 3905–3914.
[26] P. Lewkowska, B. Cieślik, T. Dymerski, P. Konieczka, J. Namieśnik, Characteristics of odors emitted from municipal wastewater treatment plant and methods for their identification and deodorization techniques, Environ. Res. 151 (2016) 573–586.
[27] G.M. Nisola, E. Cho, J.D. Orata, M.C.F.R. Redillas, D.M.C. Farnazo, E. Tuuguu, W.J. Chung, NH3 gas absorption and bio-oxidation in a single bioscrubber system, Process Biochem. 44 (2009) 161–167.
[28] J. Paing, B. Picot, J.P. Sambuco, A. Rambaud, Sludge accumulation and methanogenic activity in an anaerobic lagoon, Water Sci. Technol. 42 (2000) 247–255.
[29] A.K. Parande, P.L. Ramsamy, S. Ethirajan, C.R.K. Rao, N. Palanisamy, Deterioration of reinforced concrete in sewer environments, Proc. Inst. Civ. Eng. Munic. Eng. 159 (2006) 11–20.
[30] L. Pol, P. Lens, A. Stams, G. Lettinga, Anaerobic treatment of sulphate-rich wastewaters, Biodegradation 9 (1998) 213–224.
[31] T. Ralebitso-Senior, E. Senior, R. Di Felice, K. Jarvis, Waste gas biofiltration: Advances and limitations of current approaches in microbiology, Environ. Sci. Technol. 46 (2012) 8542–8573.
[32] B. Ren, Y. Zhao, N. Lyczko, A. Nzihou, Current status and outlook of odor removal technologies in wastewater treatment plant, Waste Biomass Valoriz. 10 (2019) 1443–1458.
[33] C. Sanchez, A. Couvert, A. Laplanche, C. Renner, New compact scrubber for odour removal in wastewater treatment plants, Water Sci. Technol. 54 (2006) 45–52.
[34] R. Sander, Compilation of Henry's law constants (version 4.0) for water as solvent, Atmos. Chem. Phys. 15 (2015) 4399–4981.
[35] G. Schauberger, M. Piringer, W. Knauder, E. Petz, Odour emissions from a waste treatment plant using an inverse dispersion technique, Atmos. Environ. 45 (2011) 1639–1647.
[36] M. Schlegelmilch, J. Streese, W. Biedermann, T. Herold, R. Stegmann, Odour control at biowaste composting facilities, Waste Manag. (Oxf.) 25 (2005) 917–927.
[37] M. Schlegelmilch, J. Streese, R. Stegmann, Odour management and treatment technologies: an overview, Waste Manag. (Oxf.) 25 (2005) 928–939.
[38] V. Senatore, T. Zarra, M.G. Galang, G. Oliva, A. Buonerba, C.W. Li, V. Belgiorno, V. Naddeo, Full-scale odor abatement technologies in wastewater treatment plants (WWTPs): a review, Water 13 (2021) 3503.
[39] A.F.E. Sims, Odour control with hydrogen peroxide, Prog. Water Technol. 12 (1980) 609–620.
[40] J. Stetkiewicz, Siarkowodór. Dokumentacja dopuszczalnych wielkości narażenia zawodowego, Podstawy i Metod. Oceny Śr. Pracy 4 (2011) 97–117.
[41] R. Stuetz, Odours in wastewater treatment measurement, modelling and control, Water Intelligence Online 4, 2005.
[42] Y. Takuwa, T. Matsumoto, K. Oshita, M. Takaoka, S. Morisawa, N. Takeda, Characterization of trace constituents in landfill gas and a comparison of sites in Asia, J. Mater. Cycles Waste Manag. 11 (2009) 305–311.
[43] A. Talaiekhozani, M. Bagheri, A. Goli, M.R. Talaei Khoozani, An overview of principles of odor production, emission, and control methods in wastewater collection and treatment systems, J. Environ. Manag. 170 (2016) 186–206.
[44] M. Wierzbińka, W.E. Modzelewski, The use of biofilters for deodorisation of the noxious gases, Ecol. Eng. 41 (2015) 125–132.
[45] I. Wysocka, Wykorzystanie Korozji Żelaza w Ograniczaniu Emisji Zapachowych /Utilizing Iron Corrosion in Reducing Odour Emissions, Wydawnictwo Polskiej Akademii Nauk, Warszawa, 2020.
[46] I. Wysocka, J. Gębicki, J. Namieśnik, Technologies for deodorization of malodorous gases, Environ. Sci. Pollut. Res. Int. 26 (2019) 9409–9434.
[47] T. Vitko, H. Suffet, Y. Zhou, S. Abrahams, 2014 OCSD Odor control master plan, in: Proceedings of the Water Environment Federation, 2014, 2014, pp. 1–17.
[48] W. Yang, J. Vollertsen, T. Hvitved-Jacobsen, Anoxic sulfide oxidation in wastewater of sewer networks, Water Sci. Technol. 52 (2005) 191–199.
[49] C. Yongsiri, J. Vollertsen, T. Hvitved-Jacobsen, Hydrogen sulfide emission in sewer networks: a two-phase modeling approach to the sulfur cycle, Water Sci. Technol. 50 (2004) 161–168.
[50] C. Yongsiri, J. Vollertsen, T. Hvitved-Jacobsen, Influence of wastewater constituents on hydrogen sulfide emission in sewer networks, J. Environ. Eng. 131 (2005) 1676–1683.
[51] T. Zarra, M.G. Galang, F. Ballesteros, V. Belgiorno, V. Naddeo, Environmental odour management by artificial neural network – a review, Environ. Int. 133 (2019) 105189.
[52] L. Zhang, P. De Schryver, B. De Gusseme, W. De Muynck, N. Boon, W. Verstraete, Chemical and biological technologies for hydrogen sulfide emission control in sewer systems: a review, Water Res. 42 (2008) 1–12.
[53] Y. Zhou, S.A. Hallis, T. Vitko, I.H. Suffet, Identification, quantification and treatment of fecal odors released into the air at two wastewater treatment plants, J. Environ. Manag. 180 (2016) 257–263.

[54] J. Zwoździak, M. Dziewa, Ł. Szałata, K. Kwiecińska, M. Cuske, A. Piechocka, M. Bartosik, Lista Substancji i Związków Chemicznych, Które są Przyczyną Uciążliwości Zapachowej, Narodowy Fundusz Ochrony Środowiska i Gospodarki Wodnej, 2016.
[55] J.M. Estrada, N.J.R. Kraakman, R. Lebrero, R. Muñoz, A sensitivity analysis of process design parameters, commodity prices and robustness on the economics of odour abatement technologies, Biotechnology Advances 30 (2012) 1354–1363.
[56] F. Lucernoni, F. Tapparo, L. Capelli, S. Sironi, Evaluation of an odour emission factor (OEF) to estimate odour emissions from landfill surfaces, Atmospheric Environment 144 (2016) 87–99.
[57] S. Yang, Y. Li, L. Wang, L. Feng, Use of peroxymonosulfate in wet scrubbing process for efficient odor control, Separation and Purification Technology 158 (2016) 80–86.
[58] I. Wysocka, J. Namieśnik, Technologie dezodoryzacji gazów złowonnych, Analityka: Nauka i Praktyka 4 (2018) 42–48.