

Review

Research Progress and Applications of Microbial Deodorization Technology

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Abstract

The emission of odorous gases has become a critical environmental challenge in livestock and poultry farming, organic solid waste treatment, and wastewater and sludge management, with typical pollutants including NH_3 , H_2S , and various volatile organic compounds (VOCs). Conventional physicochemical deodorization methods are limited by complex equipment, high energy consumption, and secondary pollution, whereas microbial deodorization has attracted increasing attention because of its low energy demand, environmental friendliness, and environmentally safe end products. At present, comprehensive reviews of microbial deodorization technology remain limited, particularly those addressing the differences in microbial removal mechanisms for odorous gases and their components originating from different sources. The major components, characteristics, and emission patterns of odorous gases from different sources are summarized in this paper. Recent advances in the screening and consortium construction of highly efficient deodorizing microorganisms, together with their practical applications in odor treatment, are further summarized. Furthermore, emerging metabolic engineering strategies based on genetic modification, enzyme regulation, and metabolic pathway reconstruction are discussed, highlighting their potential for enhancing microbial degradation capacity and facilitating the rational design of next-generation deodorization systems. Future research directions are also proposed to address existing challenges, thereby providing insights for the rational design and engineering application of microbial deodorization systems.

Keywords: microbial deodorization; ammonia; hydrogen sulfide; volatile organic compounds; bioreactor



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1. Introduction

Odorous gases are generated from daily human activities as well as agricultural and industrial production processes, including livestock and poultry farming (e.g., animal housing and manure storage facilities), organic solid waste treatment (e.g., municipal solid waste composting plants and sanitary landfills), and wastewater and sludge treatment (e.g., anaerobic digesters, biogas upgrading scrubbers, and sludge dewatering and composting units), all of which represent key scenarios requiring effective odor-control solutions. Common odorous compounds include NH_3 , H_2S , and volatile organic compounds (VOCs). Prolonged exposure to these odorous gases has been associated with adverse health effects, ranging from psychological distress, such as anxiety, uneasiness, and depression, to physical symptoms including eye irritation, headache, respiratory disorders, nausea, and vomiting [1]. Odorous gases also exert adverse environmental impacts. The emission of

NH₃ results in nitrogen loss [2], atmospheric H₂S contributes to the formation of photochemical smog and acid rain [3,4], and VOCs are implicated in global warming and a range of other environmental problems [5]. Therefore, the control and mitigation of odorous gas emissions have become important research priorities.

At present, physical, chemical, and biological approaches are the principal technologies used for odorous gas treatment. Physical methods include adsorption, dilution, and neutralization. Chemical methods mainly include combustion, oxidation, and absorption. Microbial deodorization, which emerged in the 1950s, is an innovative technology in which odorous compounds are degraded through the metabolic activities of microorganisms [6]. Microorganisms are characterized by rapid growth, short reproductive cycles, and strong adaptability to complex environments, enabling the production of specific enzymes for the degradation of different pollutants. Compared with physical and chemical methods, microbial deodorization offers higher removal efficiency, lower operational costs, simpler operation, and reduced secondary pollution, and has therefore been widely applied for the treatment of various odorous gases. However, reviews focusing on microbial deodorization technology remain limited, particularly those addressing the differences in microbial treatment mechanisms for odorous gases and their components from different sources.

In this review, the major sources and compositions of odorous gases are summarized, and odor emission standards in different countries and regions are compared. The mechanisms and influencing factors of microbial deodorization are comprehensively reviewed, and recent advances in the screening and consortium construction of highly efficient deodorizing microorganisms are discussed. Furthermore, the development and practical applications of microbial deodorization technologies are summarized to provide theoretical and practical guidance for the efficient and targeted treatment of odorous gases using microbial technologies.

2. Methods

The literature reviewed in this study were retrieved through a systematic search of the Web of Science and Scopus databases, using Boolean search strings combining core terminology relevant to microbial deodorization, such as “bio* AND odor* AND remov*”, “biofilter* AND hydrogen sulfide”, and “ammonia AND microbial AND treatment”. The search results were subsequently refined by applying inclusion criteria limited to peer-reviewed original research articles and reviews published in English, with studies unrelated to biological odor control or lacking microbial characterization data excluded. Following title and abstract screening, the retained articles were subject to full-text review, and the ultimately incorporated literature were analyzed and categorized according to the following parameters: target odorants, bioreactor configuration, dominant functional microorganisms, key metabolic enzymes, removal efficiency, and operational conditions.

3. Composition and Emission Standards of Odorous Gases from Different Sources

NH₃, H₂S, and volatile organic compounds (VOCs) are generated during livestock and poultry farming, organic solid waste treatment, and wastewater and sludge treatment, among which NH₃ and H₂S are commonly used as the primary indicators for odor assessment. The major components and emission pathways of odorous gases vary depending on their sources (Table 1). Odorous gases from livestock and poultry production are primarily generated during manure handling and are mainly composed of NH₃, H₂S, and VOCs such as naphthalene and acetaldehyde [7]. NH₃ is predominantly derived from the enzymatic hydrolysis of urea in animal urine by urease-producing microorganisms, as well as from the microbial decomposition of nitrogenous organic matter in feces [8]. H₂S is mainly

generated through the anaerobic microbial reduction of sulfate and the degradation of sulfur-containing amino acids (e.g., cysteine and methionine) under anaerobic conditions in manure pits and slurry storage facilities [9]. Among these, NH_3 exhibits the highest emission level [10], whereas H_2S emissions vary with season and livestock production type [11–14]. During organic solid waste treatment, odorous gases are mainly released during the pretreatment and composting stages [15]. Halogenated compounds account for approximately 33% of the emitted gases, followed by NH_3 (21%) and reduced sulfur compounds (14%). Higher concentrations of H_2S are more likely to be emitted during the composting of food waste [16–18]. Odorous emissions from wastewater and sludge treatment are mainly generated during the dewatering and composting processes [19]. The composition of the emitted gases changes with treatment stage, with H_2S predominating in the initial stage, VOCs (e.g., α -pinene) being dominant during the thermophilic stage, and NH_3 becoming the major component in the later stage [20–22].

Table 1. Major components and emission pathways of odorous gases from different sources [23].

Odor Source	Major Components	Emission Pathways
Livestock and poultry farming	NH_3 , H_2S , and VOCs (naphthalene, acetaldehyde, carbon disulfide, and dimethyl disulfide) NH_3 accounts for the highest proportion of emissions, whereas H_2S is emitted at the lowest level.	Decomposition of poultry manure mixed with feces, urine, feathers, bedding materials, and dust, as well as the composting of livestock and poultry manure
Organic solid waste treatment (e.g., municipal solid waste)	NH_3 , H_2S , and VOCs (ethanol, limonene, p-diethylbenzene, dimethyl sulfide, methanethiol, and ethanethiol) NH_3 accounts for approximately 21% of the emissions, whereas reduced sulfur compounds account for approximately 14%.	Waste pretreatment processes (including conveying, shredding, and screening), anaerobic digestion, and composting
Wastewater and sludge treatment	NH_3 , H_2S , and VOCs (dimethyl disulfide, eucalyptol, α -pinene, methanethiol, dimethyl sulfide, styrene, and xylene) During sludge composting, H_2S is predominantly emitted during the initial stage, VOCs are mainly released during the thermophilic stage, and NH_3 becomes the dominant emission during the late thermophilic and maturation stages.	Sludge dewatering and sludge composting processes

Odor emission standards vary considerably among countries in terms of regulatory stringency and the range of controlled odorants. As the first country to establish odor-control legislation, Japan has continuously revised its Offensive Odor Control Law, under which 22 designated odorous substances are currently regulated, with separate boundary concentration limits specified for industrial and non-industrial areas [24]. This regulatory framework is characterized by refined management, while its stringent limit values impose high requirements on the stability and efficiency of odor-control technologies. Subsequently, South Korea also established a comprehensive regulatory system for odorous pollutant emissions [25]. In contrast, the current Chinese Emission Standard for Odor Pollutants (GB 14554-93) specifies boundary emission limits for only eight odorous pollutants [26]. The comparison of threshold values for major indicators indicates that Chinese standards set relatively lenient limits, while gaps remain in pollutant coverage and differentiated regulatory requirements for different industries (Table 2).

Table 2. Comparison of odorous substance emission standards between China and Japan [26,27].

No.	Odorous Substance	Boundary Concentration Limit (mg/m ³)					
		Japan			China		
		Class I	Class II	Class III	Grade I	Grade II	Grade III
1	Ammonia	0.76	1.52	3.80	1.0	1.5	4.0
2	Methanethiol	0.0043	0.0086	0.0215	0.004	0.007	0.02
3	Hydrogen sulfide	0.030	0.091	0.304	0.03	0.06	0.32
4	Dimethyl sulfide	0.028	0.139	0.555	0.03	0.07	0.15
5	Dimethyl disulfide	0.038	0.126	0.421	0.03	0.06	0.13
6	Trimethylamine	0.013	0.053	0.185	0.05	0.08	0.15
7	Carbon disulfide	0.034	0.102	0.204	2.0	3.0	8.0
8	Styrene	1.86	3.72	9.30	3.0	5.0	8.0
9	Acetaldehyde	0.098	0.197	0.983	—	—	—
10	Propionaldehyde	0.130	0.259	1.30	—	—	—
11	n-Butyraldehyde	0.029	0.064	0.258	—	—	—
12	Isobutyraldehyde	0.064	0.225	0.644	—	—	—
13	n-Valeraldehyde	0.035	0.077	0.192	—	—	—
14	Isovaleraldehyde	0.012	0.023	0.038	—	—	—
15	Isobutanol	2.98	6.62	16.5	—	—	—
16	Ethyl acetate	11.8	19.7	78.7	—	—	—
17	Methyl isobutyl ketone	4.47	8.94	26.8	—	—	—
18	Toluene	41.1	123	247	—	—	—
19	Xylene	4.74	9.48	23.7	—	—	—
20	Propionic acid	0.099	0.231	0.661	—	—	—
21	n-Butyric acid	0.0039	0.0079	0.0236	—	—	—
22	n-Valeric acid	0.0041	0.0091	0.0182	—	—	—
23	Isovaleric acid	0.0046	0.0137	0.0182	—	—	—

4. Mechanisms and Influencing Factors of Microbial Deodorization

4.1. Mechanisms of Microbial Deodorization

Microbial deodorization is essentially a biological process in which odorous compounds (NH₃, H₂S, and VOCs) are utilized by microorganisms as energy, carbon, or nitrogen sources and are subsequently oxidized or transformed into harmless products through a series of complex biochemical reactions. This process involves a cascade of reactions, including gas-phase mass transfer, transformation at the cell surface, and intracellular metabolism. Elucidation of these underlying mechanisms is essential for the selection of efficient microbial strains and the optimization of deodorization processes.

4.1.1. NH₃ Removal: Conventional Nitrification–Denitrification and Simultaneous Heterotrophic Nitrification–Aerobic Denitrification Pathways

Microbial conversion of NH₃ is a typical biological nitrogen cycling process and has traditionally been considered to rely on sequential nitrification and denitrification, in which the coordinated activities of multiple functional microorganisms and key enzymes play essential roles [28]. This pathway is accomplished through three sequential steps involving two groups of aerobic autotrophs and anaerobic denitrifying bacteria. Ammonia-oxidizing bacteria (AOB), such as *Nitrosomonas*, catalyze the oxidation of NH₃ to hydroxylamine (NH₂OH) through the membrane-bound ammonia monooxygenase (AMO), which functions as the rate-limiting enzyme and can be inhibited by high NH₃ concentrations [29]. Hydroxylamine is subsequently oxidized to nitrite (NO₂[−]) by hydroxylamine oxidoreductase (HAO). Nitrite-oxidizing bacteria (NOB), such as *Nitrobacter*, further oxidize NO₂[−] to nitrate (NO₃[−]) via periplasmic nitrite oxidoreductase (NXR) [30]. Under oxygen-limited conditions, denitrifying bacteria (DNB) sequentially reduce nitrate to nitrogen gas (N₂) through the catalytic actions of nitrate reductase (Nar), nitrite reductase (Nir), nitric oxide reductase (Nor), and nitrous oxide reductase (Nos) (Figure 1) [30]. Beyond this classical

framework, two additional autotrophic pathways have been identified. Anaerobic ammonium oxidation (anammox), carried out by Planctomycetes such as *Candidatus Brocadia* and *Candidatus Kuenenia*, directly converts NH_4^+ and NO_2^- to N_2 under strictly anaerobic conditions without any carbon source requirement [31]. Complete ammonia oxidation (comammox), first described in certain *Nitrospira* strains, enables a single organism to independently accomplish the full NH_4^+ -to- NO_3^- conversion previously assumed to require the coordinated activities of both AOB and NOB [32]. Although both pathways have been detected in biofilters and compost matrices, their contributions to NH_3 attenuation in odor-control scenarios remain limited compared with conventional nitrification–denitrification, and their ecological roles in deodorization systems warrant further investigation. Therefore, efficient NH_3 removal depends on the establishment of alternating or spatially separated aerobic and anoxic environments that support the activities of AOB, NOB, and DNB [33].

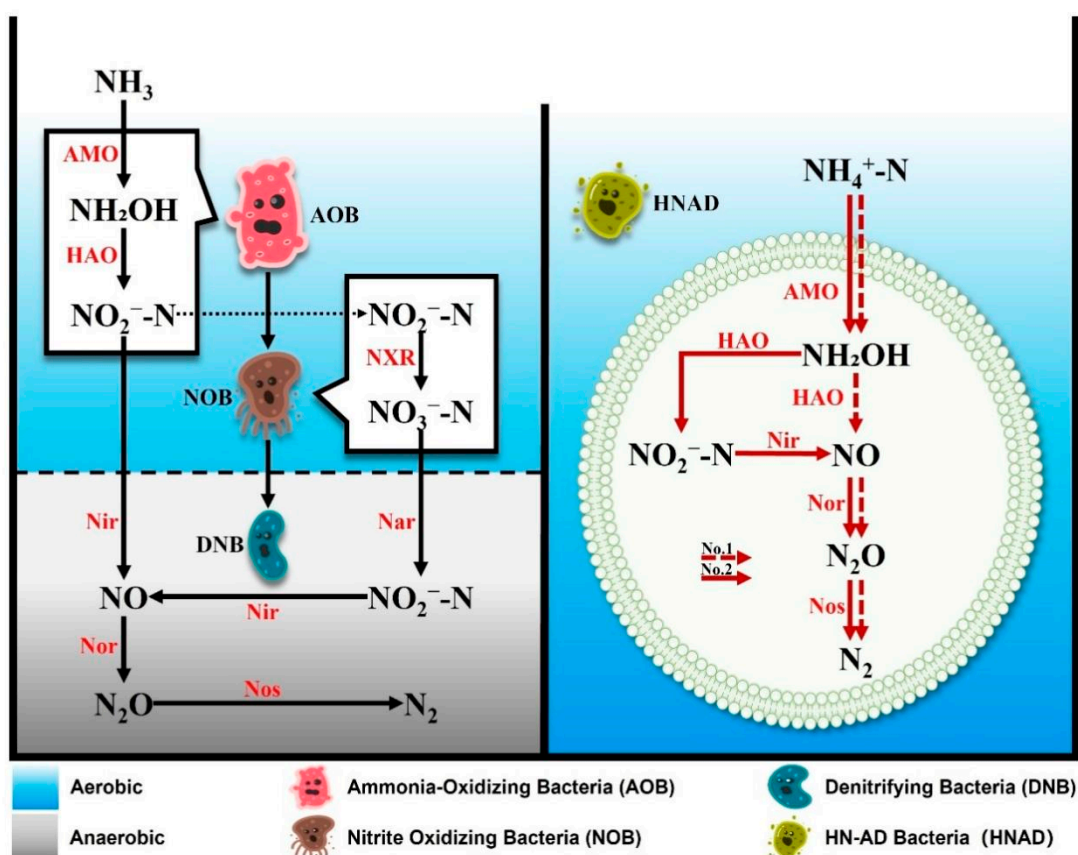


Figure 1. Removal mechanism of NH_3 .

Recent studies have demonstrated that many heterotrophic microorganisms, such as *Paracoccus* and *Halomonas*, possess genes encoding the above key enzymes and are capable of simultaneous heterotrophic nitrification and aerobic denitrification (HN-AD). Under fully aerobic conditions, NH_3 can be directly converted into gaseous end products (N_2 or N_2O), with little or no accumulation of hydroxylamine or nitrite intermediates. The nitrogen metabolic pathway of HN-AD bacteria has not yet been fully elucidated, and two putative pathways have been proposed [34]: (i) $\text{NH}_4^+ \rightarrow \text{NH}_2\text{OH} \rightarrow \text{NO}_2^- \rightarrow \text{NO} \rightarrow \text{N}_2\text{O} \rightarrow \text{N}_2$, in which transient accumulation of NO_2^- and NO_3^- has been observed before their subsequent reduction; (ii) $\text{NH}_4^+ \rightarrow \text{NH}_2\text{OH} \rightarrow \text{NO} \rightarrow \text{N}_2\text{O} \rightarrow \text{N}_2$, in which the hydroxylamine produced from NH_4^+ -N oxidation is directly converted into N_2 through the denitrification pathway (Figure 1) [35]. The isolation and screening of broad-spectrum

HN-AD microorganisms from complex environments will remain a key research priority for future biological NH_3 removal.

4.1.2. Removal of H_2S and Sulfur-Containing VOCs: Sulfur Oxidation Pathways and Sulfur Fate

The biological oxidation of sulfur-containing odorous compounds is primarily mediated by sulfur-oxidizing enzyme systems, which catalyze the sequential oxidation of sulfide to elemental sulfur, elemental sulfur to sulfite, sulfite to sulfate, and thiosulfate to sulfate (Figure 2). The key enzymes involved include sulfide:quinone oxidoreductase (Sqr), flavocytochrome c sulfide dehydrogenase (Fcc), dissimilatory sulfite reductase (Dsr), sulfur dioxygenase (Sdo), sulfite:cytochrome c oxidoreductase (SorAB), sulfite:quinone oxidoreductase (SoeABC), adenosine-5'-phosphosulfate reductase (Apr), and persulfide dioxygenase (Pdo) [36]. The oxidation of H_2S is initiated by membrane-bound Sqr, which catalyzes the two-electron oxidation of H_2S and drives the deposition of the resulting sulfane sulfur as solid-phase elemental sulfur (S^0). During this process, electrons are transferred through the quinone pool to the respiratory chain, where metabolic energy is generated [37]. A glutathione (GSH)-based sulfur transport and detoxification system is also widely present in microbial cells. Reactive sulfur generated by Sqr is rapidly conjugated with GSH to form glutathione persulfide (GSSH). This process not only maintains intracellular sulfur homeostasis but also converts inorganic sulfur into a transferable organic form. As a reactive sulfur donor, GSSH facilitates the directed transfer of sulfur among different intracellular enzyme systems and promotes its subsequent oxidation [38]. The generated S^0 may accumulate extracellularly or intracellularly, such as in the sulfur globules of *Acidithiobacillus*. This step is critical for mitigating shock loads caused by high H_2S concentrations and offers the potential for elemental sulfur recovery [39]. When H_2S concentrations are relatively low or complete oxidation is required, H_2S can be directly oxidized to sulfate (SO_4^{2-}) by the sulfur oxidation (Sox) system, such as the SoxXYZAB complex in *Arcobacter butzleri*, without the accumulation of detectable intermediates [40]. In some microorganisms, including *Thiobacillus* spp. and certain Proteobacteria, the Sox system is functionally coupled with the adenosine-5'-phosphosulfate (APS) metabolic network. In these organisms, sulfur oxidation does not completely bypass metabolic intermediates; instead, sulfate is first activated to form APS, which serves as a key metabolic intermediate before being enzymatically converted to the final sulfate product [36]. Therefore, for processes primarily targeting H_2S removal, strains possessing highly active Sqr, such as *Acidithiobacillus thiooxidans*, should be selected to achieve rapid H_2S removal and elemental sulfur recovery. In contrast, advanced treatment processes aimed at controlling total sulfur concentrations require microorganisms harboring a complete Sox system, such as *Paracoccus pantotrophus*, to accomplish complete oxidation to sulfate.

The biodegradation of sulfur-containing VOCs, such as methanethiol (CH_3SH) and dimethyl disulfide (CH_3SSCH_3), generally involves an initial activation and bond-cleavage step. Extracellular enzymes, such as methanethiol oxidase secreted by microorganisms including *Hyphomicrobium*, catalyze cleavage of the C-S bond to produce H_2S or other low-molecular-weight sulfur compounds. These inorganic sulfur species are subsequently oxidized through the Sqr/Sox-mediated pathways described above [41]. This mechanism explains the transient increase in H_2S concentration that is frequently observed in the outlet gas of biotrickling filters treating sulfur-containing VOCs. Accordingly, the construction of microbial consortia comprising specialized VOC-degrading microorganisms capable of C-S bond cleavage and highly efficient sulfur-oxidizing bacteria responsible for H_2S removal represents an effective strategy for the complete and stable elimination of sulfur-containing VOCs, such as *Acidithiobacillus thiooxidans* and *Thiobacillus thioparus* [42].

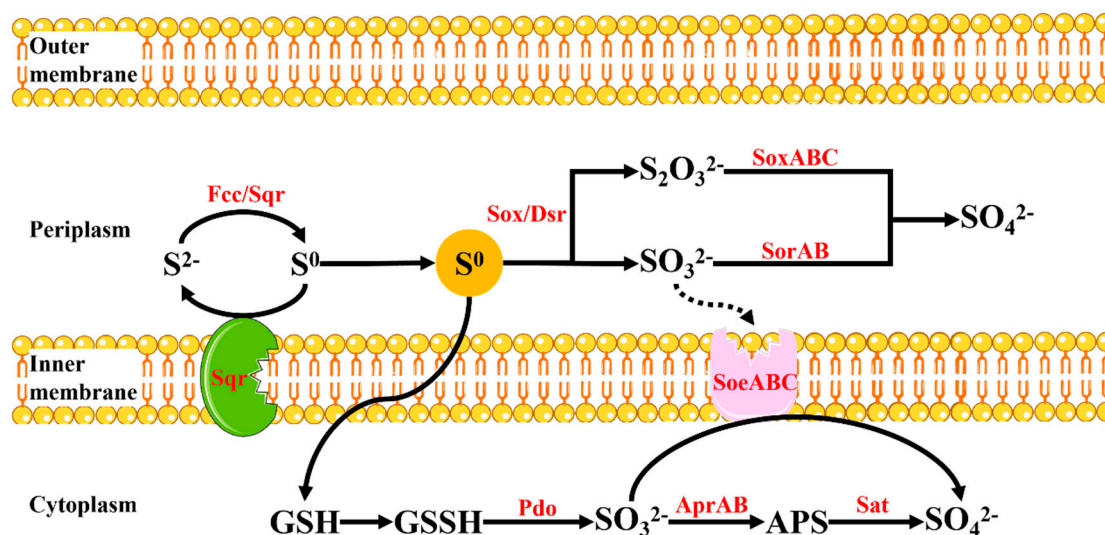


Figure 2. Removal mechanisms of H₂S and sulfur-containing VOCs.

4.1.3. Removal of Non-Sulfur VOCs: Assimilatory and Dissimilatory Metabolism as Carbon Sources

Non-sulfur VOCs, such as benzene, toluene, and styrene, serve as carbon and energy sources for microorganisms, and their degradation efficiency depends on the coupling between mass transfer and initial oxidation reactions. For aromatic compounds, dioxygenases can simultaneously incorporate two oxygen atoms into the benzene ring, resulting in ring cleavage and the formation of cis,cis-muconic acid, whereas monooxygenases introduce one oxygen atom per catalytic cycle, producing phenolic or alcohol intermediates [43]. These initial products subsequently enter central metabolic pathways, such as the tricarboxylic acid (TCA) cycle, where they are completely mineralized to CO₂ and H₂O [44]. For alkanes, degradation begins with terminal hydroxylation, in which alkane hydroxylase (AlkB) serves as the rate-limiting enzyme initiating the process by oxidizing alkanes to alcohols (Figure 3). Alcohol dehydrogenase (ADH) and aldehyde dehydrogenase (ALDH) then sequentially convert alcohols to aldehydes and carboxylic acids, which are ultimately funneled into central metabolic pathways [45]. The intrinsic hydrophobicity of pollutants, which determines gas–liquid mass transfer rates, and their molecular structural complexity, which affects the catalytic accessibility of oxygenases, together constitute the rate-limiting factors in the degradation process [46]. Therefore, both fundamental research and practical applications are required. On one hand, strains capable of producing efficient broad-spectrum oxygenases should be screened and engineered. These enzymes possess broad substrate spectra and can catalyze the oxidation of structurally diverse VOCs, rather than acting on merely one substrate. For example, the toluene dioxygenase (TDO) encoded by the todC1C2BA operon in *Pseudomonas putida* F1 can oxidize not only toluene but also benzene, ethylbenzene, naphthalene, and several chlorinated aromatic compounds, making it a representative broad-spectrum oxygenase applicable to mixed aromatic VOC treatment scenarios [47]. On the other hand, mass transfer should be enhanced by adding hydrophobic packing materials (e.g., activated carbon and diatomite) or surfactants, and co-metabolism strategies using easily degradable substrates (e.g., glucose) should be explored to initiate the transformation of recalcitrant VOCs such as trichloroethylene [48].

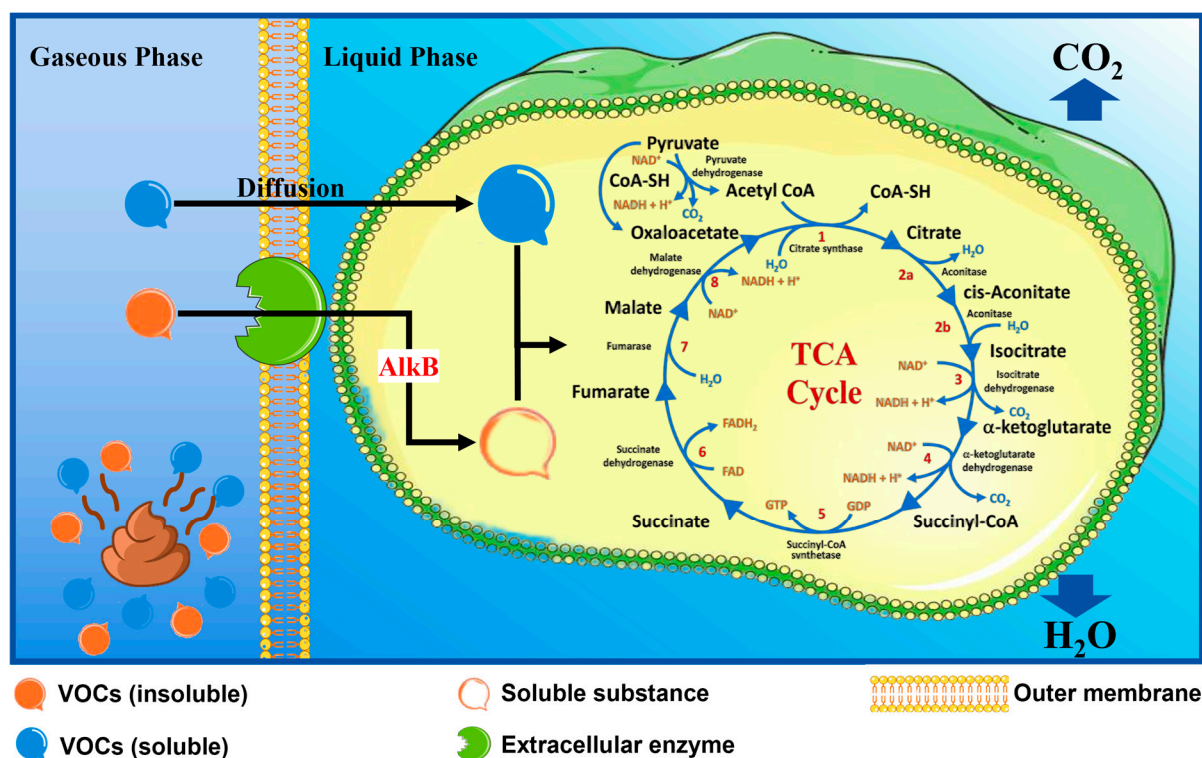


Figure 3. Removal mechanism of sulfur-free VOCs.

4.2. Influencing Factors of Microbial Deodorization

The efficiency of microbial deodorization systems is jointly regulated by key environmental parameters, including temperature, pH, moisture content, and aeration rate. These parameters influence microbial community structure, metabolic activity, and mass transfer processes, thereby collectively determining the overall removal efficiency of odorous compounds [49]. Temperature is a key variable governing microbial metabolic activity. The biodegradation of NH₃, H₂S, and VOCs generally exhibits high activity within the mesophilic range of 20–45 °C, whereas excessively high temperatures (>45–50 °C) significantly inhibit the activity of most mesophilic microorganisms, resulting in reduced deodorization efficiency [50–52]. System pH affects the bioavailability of odorous compounds by altering their ionic forms and enzymatic activity [53]. Although near-neutral conditions (pH 7–8) generally favor the synergistic metabolism of mixed microbial consortia, NH₃ degradation may be more efficient under mildly acidic conditions, whereas H₂S removal typically exhibits higher mass transfer efficiency under alkaline conditions. Fungi-dominated systems also show unique advantages for VOC degradation under acidic conditions [53–55]. Aeration rate not only supplies oxygen required for aerobic microorganisms but also serves as a carrier for heat dissipation and volatile compound removal [56]. Moderate or intermittent aeration has been shown to effectively reduce NH₃ and H₂S emissions by creating favorable microenvironments. However, excessive aeration, while beneficial for controlling certain VOCs, may negatively affect overall system performance by altering microbial community structure and the moisture balance within the reactor [57–60]. In addition, moisture content is a fundamental parameter influencing the physical structure of composting systems and microbial activity, as it directly affects oxygen diffusion efficiency and microbial mobility. In solid-phase composting systems treating organic substrates such as animal manure, municipal solid waste, and sewage sludge, a moisture content of 50–70% is generally considered optimal for microbial degradation activity, as it simultaneously satisfies the requirements for substrate solubilization, microbial mobility, and adequate oxygen diffusion through the porous matrix [61]. For liquid-phase bioreactor

systems such as bioscrubbers and biotrickling filters, moisture is non-limiting by design [62]. Instead, other parameters including pH, dissolved oxygen, and nutrient concentrations become the primary controlling factors [63]. Deviations from the optimal moisture range in solid-phase systems may inhibit specific metabolic pathways, including nitrification and sulfate reduction, thereby promoting the accumulation and release of odorous compounds such as NH_3 and H_2S [64–67].

5. Screening and Consortium Construction of Deodorizing Microorganisms

5.1. Screening of Deodorizing Microorganisms

5.1.1. Screening of NH_3 -Removing Strains

For NH_3 control, research has shifted from separately screening nitrifying and denitrifying bacteria to the selection of HN-AD strains. Compared with conventional nitrification–denitrification, HN-AD provides advantages in oxygen efficiency and reactor simplification, making it particularly suitable for odor treatment systems characterized by fluctuating ammonia loads. Currently identified model strains are mainly distributed among the genera *Pseudomonas*, *Bacillus*, and *Acinetobacter*, with some studies also involving fungi [68]. As shown in Table 3, reported HN-AD strains generally achieve nitrogen removal efficiencies of 85–99% under initial ammonium nitrogen concentrations of 50–500 mg/L. HN-AD strains overcome the strict dissolved oxygen limitations of conventional nitrogen removal processes and enable simultaneous nitrogen removal within a single reactor. Related studies have advanced to the molecular level, focusing on the expression and activity of AMO, HAO, and periplasmic nitrate reductase (NAP) [69]. Studies have shown that optimizing the C/N ratio (typically 8–12) can significantly upregulate the expression of *amoA* and *napA* genes, thereby enhancing metabolic rates under high ammonia loading conditions [70].

Table 3. Representative ammonia-removing microorganisms and their deodorization performance.

Strain	Domain	Source	Degradation Condition	Functional Type	Key Enzymes/ Genes	References
<i>Acinetobacter</i> sp. Y1	Bacteria	Activated sludge	99% NH_4^+ -N removal (100 mg/L, 20 h)	HN-AD	HAO, Nar, Nir	[71]
<i>Pseudomonas aeruginosa</i> SNDPR-01	Bacteria	Activated sludge	99% NH_4^+ -N removal (100 mg/L, 24 h)	HN-AD	AMO, HAO, NAP, Nir, nitrous oxide reductase (<i>nosZ</i>)	[69]
<i>Bacillus subtilis</i> B24	Bacteria	Seawater	92% NH_4^+ -N removal (simulated wastewater, 15 mg/L, 5 d)	HN-AD	HAO, NAR, NIR, AMO	[72]
<i>Stutzerimonas frequens</i> TF18	Bacteria	Seawater	98.98% NH_4^+ -N removal (20 mg/L, 48 h)	Autotrophic nitrification–denitrification	Nir, NAP, NAR	[73]
<i>Achromobacter</i> sp. HNDS-1	Bacteria	Soil	93.31% NH_4^+ -N removal (150 mg/L, 72 h)	HN-AD	AMO	[74]
<i>Pichia kudriavzevii</i> HJ2	Fungi	Marine environment	73.56% NH_4^+ -N removal (600 mg/L, 36 h)	Ammonia assimilation	Glutamate dehydrogenase (GDH) and aspartate aminotransferase (GOT)	[68]
<i>Lactobacillus paracasei</i> B1	Bacteria	Landfill leachate	78.93% NH_4^+ -N removal	Ammonia assimilation and indirect acidification effect	—	[75]

5.1.2. Screening of H₂S-Removing Strains

The dominant microbial groups for H₂S removal include acidophilic *Acidithiobacillus* spp. and neutrophilic *Thiobacillus* spp. (Table 4). Because H₂S oxidation leads to environmental acidification, recent studies have focused on screening acid-tolerant strains. These microorganisms can maintain H₂S removal efficiencies above 95% even under extreme conditions (pH 2.0–4.0), and their metabolism primarily involves the Sox multienzyme complex (SoxXYZAB), which is responsible for the complete oxidation of sulfur species with different oxidation states [54]. Screening strains with high expression of key genes such as *sqr*, *dsrA*, and *soxB* can effectively prevent excessive accumulation of elemental sulfur on biofilm surfaces, thereby avoiding packing material clogging [76].

Table 4. Representative sulfur-oxidizing microorganisms and their H₂S removal performance.

Strain	Domain	Source	Performance	Functional Type	Key Enzymes/ Genes	References
<i>Geobacillus thermodenitrificans</i> DSM465	Bacteria	Beet juice extraction system	27.5% H ₂ S emission reduction (35 d composting); +34.4% sulfate in compost (vs. control)	Sulfide oxidation, sulfite oxidation	SQR, PDO	[77]
<i>Acidithiobacillus thiooxidans</i> (KCTC8928P)	Bacteria	Soil	99–100% H ₂ S removal (300 ppm inlet, 5 d post-inoculation)	Sulfide oxidation	—	[78]
<i>Thiobacillus denitrificans</i> DSM 807	Bacteria	Seawater and sediments	99% H ₂ S removal (8 mg/d loading, 7 d)	Sulfide oxidation	—	[79]
<i>Thiomonas</i>	Bacteria	Sludge	95.01% max H ₂ S removal increase (70 min residence time, 30 °C, vs. control)	Sulfide oxidation	Fcc	[80]

5.1.3. Screening of VOC-Degrading Strains

VOCs are highly diverse and are often associated with high toxicity. Efficient degrading strains typically possess diverse and highly active core enzyme systems, as well as strong stress resistance and tolerance mechanisms (Table 5). For hydrophilic VOCs (e.g., methanol, ethanol, and acetone), the dominant screened genera are methylotrophic bacteria such as *Rhodococcus*. For more hydrophobic VOCs, fungi (e.g., *Candida* and *Fusarium*) are more effective due to their hyphal structures and hydrophobic proteins in the cell wall, which enhance adsorption and degradation of such pollutants. Compared with bacteria, fungi possess a larger specific surface area and stronger resistance to desiccation and acidic conditions. Their extracellular enzymes (e.g., lignin peroxidase and laccase) exhibit strong nonspecific oxidative capabilities, enabling the degradation of structurally complex aromatic compounds. In addition, fungal mycelia can enhance the mass transfer efficiency of hydrophobic VOCs in biofiltration systems [81]. Studies have shown that, for hydrophobic gases such as toluene and xylene, fungal biofilters typically achieve 20–40% higher removal loading rate than bacterial systems. However, fungal emissions may cause secondary pollution due to odor release [82]. In addition, many strains have evolved tolerance to harsh environmental conditions such as high salinity, extreme pH, or high temperature, enabling them to survive and function under the severe conditions of real contaminated sites [83,84].

Table 5. Representative VOCs-degrading microorganisms and their VOCs removal performance.

Strain	Domain	Source	Performance	Key Enzymes/Genes	References
<i>Rhodococcus qingshengii</i> strain SCJ-1	Bacteria	Activated sludge	78.5% n-hexane removal (200 mg/L, 48 h, pH 7, 30 °C)	AlkB, ADH	[85]
<i>Brevibacillus</i> CAT37	Bacteria	Wastewater	~37% methanethiol removal	—	[86]
<i>Candida subhashii</i>	Fungi	Peat	24–44% mixed VOCs removal (EBRT = 30 s; n-hexane, TCE, toluene, α -pinene) trichloroethylene, toluene, and α -pinene)	—	[82]
<i>Fusarium solani</i>	Fungi	Purchased from culture collection center	~99% dimethyl disulfide removal (30 h)	Dimethylsulfoniopropionate (DMSP) lyase	[41]
<i>Alcaligenes</i> SY1	Bacteria	Activated sludge	61.02% dimethyl disulfide removal (1:2 consortium, 3 d)	Dimethyl disulfide reductase (DDR), trimethylamine monooxygenase (Tmm), dimethyl sulfone monooxygenase (DMSMO)	[87]
<i>Acinetobacter lwoffii</i> strain pJ15; <i>Pseudomonas mendocina</i> strain C41	Bacteria	Canteen food waste from Shanxi University			

5.2. Construction of Deodorizing Microbial Consortia

In recent years, in response to the complex coexistence of NH_3 , H_2S , and VOCs under real operating conditions, microbial deodorization technology has shifted from the screening of single-function strains toward the construction and engineering application of multifunctional microbial consortia. In this process, early composite microbial systems represented by Effective Microorganisms (EM) were the first to achieve industrial application. These systems integrate lactic acid bacteria, yeasts, and photosynthetic bacteria to inhibit organic matter decay and reduce the formation of odor precursors [88,89].

On this basis, currently commercialized microbial deodorization products exhibit clear characteristics of multi-consortia synergy and functional complementarity. Their core compositions typically include *Lactobacillus*, *Bacillus*, yeasts and actinomycetes (Table 6), while some products further incorporate sulfur-oxidizing bacteria (SOB) or functional enzyme preparations to enhance targeted conversion of NH_3 and H_2S [90]. For example, certain commercial formulations achieve NH_3 removal efficiencies above 90% and H_2S removal efficiencies of 85–95% in landfill and wastewater treatment applications, demonstrating relatively stable engineering applicability. However, such commercial microbial agents are often marketed as “consortia” or “probiotic consortia”, while their specific strain composition is rarely disclosed. This lack of transparency hampers comparative evaluation among commercial products.

From an engineering perspective, current commercial microbial deodorization agents still exhibit three common limitations: (i) large variations in functional microbial composition among products, with no unified screening standards or performance evaluation systems, resulting in strong dependence of treatment efficiency on application scenarios and operational conditions; (ii) poor long-term colonization ability and functional stability due to competition with indigenous microbial communities and environmental stresses under open or high-load conditions; and (iii) optimization primarily targeting single odor indicators (e.g., NH_3 or H_2S), with insufficient capability for synergistic degradation of multi-component VOCs and control of intermediate metabolites.

To address these issues, future research and industrial development should focus on several directions. First, standardized functional microbial community databases should be established based on metagenomics and metabolic network analysis to enable rational design of microbial consortia. Second, synthetic microbial consortia and directed domestication strategies should be developed to enhance ecological competitiveness and functional stability in complex environments. In addition, an integrated “inoculum-carrier material-reactor system” design concept should be promoted to improve overall deodorization efficiency through microenvironment regulation and enhanced mass transfer. Finally, a

unified evaluation system and engineering application standards for commercial microbial agents should be established to improve comparability and engineering compatibility across products.

Table 6. Performance of typical commercial microbial deodorization consortia.

Product Name	Microbial Formulation/Community	Application Scenarios	Reported Performance	Company	References
EM consortium	Typically contains lactic acid bacteria, yeasts, and photosynthetic bacteria	Composting, livestock housing, landfill leachate	Exhibits deodorization effects and reduces COD, BOD, and suspended solids (SS) in wastewater	EM Research Organization Inc. (Okinawa, Japan)	[89]
Bio-Enzymatic OdorEliminator	<i>Lactobacillus</i> , Yeast, <i>Bacillus</i>	Landfills, farms, wastewater treatment	Metabolizes odor precursors and biodegrades NH ₃ , benzene, and total VOCs (TVOCs)	Airsafer Environmental Technology Co., Ltd. (Suzhou, China)	[91]
Evogen Odour Neutraliser Powder	<i>Bacillus</i> consortium, specific strains not disclosed	Agricultural facilities, landfills, municipal wastewater, composting	Achieves >84% NH ₃ removal in environments with high levels of putrefactive bacteria	Genesis Biosciences Ltd. (Cardiff, UK)	[92]
Microbial Deodorant	Probiotics, lactic acid bacteria, actinomycetes, and other microorganisms	Wastewater plants, landfills, livestock operations	96% NH ₃ removal and 90% H ₂ S removal	Bluwat Chemicals Co., Ltd. (Yixing, China)	[93]
Odor control microbial blend	<i>Bacillus subtilis</i> , <i>Bacillus amyloliquefaciens</i> , etc.	Waste transfer stations, wastewater treatment, livestock farming	70–90% reduction in NH ₃ /H ₂ S emissions	BioWorld USA Inc. (Visalia, CA, USA)	[94]
Microbe-Lift IND	Purple sulfur bacteria and other aerobic, anaerobic, and facultative anaerobic microorganisms (not fully specified)	Solid waste, animal manure, wastewater systems, landfills, transfer stations	96% NH ₃ removal and 85% H ₂ S removal	INAVET Nutrition Technologies Inc. (Quezon City, Philippines)	[95]
OMNIFERM SLURRY	<i>Lactobacillus</i> , <i>Saccharomyces cerevisiae</i> , and <i>Bacillus</i>	Feed additives, source odor control in livestock manure, composting process regulation	30–70% reduction in NH ₃ and inhibition of putrefactive microbial growth	Lallemand Inc. (Montréal, QC, Canada)	[96]

With the further development of microbiome engineering and environmental biotechnology, commercial deodorizing microbial agents are expected to gradually shift from empirically developed products to rationally designed biological formulations, enabling precise regulation and long-term stable control of complex odor pollution systems.

5.3. Metabolic Engineering Strategies for Enhancing Microbial Deodorization

Metabolic engineering in microbial deodorization remains at a transitional stage, progressing from target identification and enzyme function validation toward the development and application of engineered strains and microbial consortia. Current molecular engineering studies have primarily focused on the overexpression of individual functional enzymes and heterologous validation of key metabolic modules, whereas comprehensive pathway reconstruction strategies that simultaneously integrate multi-component odor degradation, environmental robustness, genetic stability, and biosafety considerations remain relatively limited.

For the transformation of nitrogen-containing odor compounds, AMO represents the most direct potential engineering target. However, the complete AMO complex is a structurally and assembly-wise complex membrane-bound copper-containing monooxygenase, and overexpression of *amoA* alone is generally insufficient to reconstruct functional ammonia oxidation activity. Previous studies have introduced the heterotrophic nitrification

gene cluster from *Paracoccus denitrificans* into *Pseudomonas putida*, resulting in functional heterologous expression of AMO activity. These studies further demonstrated that continuous ammonia oxidation requires the coordinated expression of AMO and hydroxylamine oxidation-related functional modules within the introduced genetic region [97]. This study indicates that rational metabolic engineering of NH_3 conversion should target the reconstruction of the entire functional pathway comprising catalytic subunits, accessory components, and downstream hydroxylamine detoxification modules, rather than simply enhancing the expression of *amoA* alone. Recent structural studies have further revealed the complexity of AMO complex composition, membrane assembly, and electron transfer processes. The heterologous expression of the complete CuMMO system remains substantially constrained by challenges associated with protein folding, copper homeostasis, and the cytotoxicity of hydroxylamine (NH_2OH) [98,99]. Therefore, future metabolic engineering strategies for NH_3 removal should simultaneously consider the coordinated regulation of *amoCAB* expression, metal cofactor supply, downstream hydroxylamine oxidation, and by-product control, rather than simply equating increased functional gene abundance with enhanced ammonia oxidation performance.

Compared with ammonia oxidation systems, sulfur oxidation pathways have demonstrated more established examples of metabolic engineering applications. Jung et al. [100] cloned and constitutively overexpressed two sulfide:quinone oxidoreductase genes, *AFE_0267* and *AFE_1792*, in *Acidithiobacillus ferrooxidans*. Both recombinant enzymes exhibited SQR activity, and *AFE_1792* retained functional activity under aerobic conditions. The engineered strains not only showed improved growth on sulfur substrates and enhanced sulfur oxidation capacity but also exhibited reduced cellular toxicity caused by H_2S exposure. Although this study was conducted in a bioleaching system rather than an odor-control bioreactor, it demonstrated that enhancing the expression of the initial H_2S oxidation enzyme can effectively redirect sulfur metabolic flux, representing one of the most relevant molecular engineering examples for microbial deodorization applications to date. For heterologous expression, Han et al. [101] introduced three homologous *sqr* genes from *Sulfurimonas denitrificans* individually into the *Rhodobacter capsulatus* Δsqr mutant strain, and all three recombinant proteins restored detectable SQR activity. These results demonstrate that sulfide oxidation enzyme modules possess the potential for cross-host transfer. However, the introduction of complete *Sox* gene clusters into industrial chassis microorganisms for H_2S gas treatment has not yet been achieved. Further efforts are required to address key challenges, including membrane localization, compatibility with host quinone pools, electron acceptor availability, and the regulation of sulfur product distribution between S^0 and SO_4^{2-} .

For benzene derivatives and other VOCs, the primary strategy involves the introduction of heterologous degradation modules, chromosomal integration of functional gene clusters, and coordinated reconstruction of multiple metabolic pathways to expand the substrate spectrum of chassis microorganisms and enhance the continuous mineralization capacity toward complex organic pollutants. Su et al. [84] employed iterative natural transformation technology to integrate five synthetic gene clusters, comprising a total of 43 kb of exogenous genetic elements, into the chromosome of the fast-growing marine chassis microorganism *Vibrio natriegens*. The engineered strain VCOD-15 exhibited the capability to simultaneously degrade toluene, phenol, naphthalene, biphenyl, and dibenzofuran, achieving over 90% pollutant removal efficiency in high-salinity industrial wastewater. These findings demonstrate that the coordinated assembly of multiple gene clusters can effectively establish interconnected metabolic pathways encompassing the initial oxidation, aromatic ring cleavage, and downstream central metabolism of aromatic compounds. Although the validation scenario of this study involved industrial wastewater rather than

odor-containing gas treatment, gaseous pollutants such as toluene undergo gas–liquid mass transfer before entering biofilms, after which their intracellular transformation relies on the same oxidative enzymes, ring-cleavage enzymes, and central metabolic networks. Therefore, immobilization of such broad-spectrum engineered strains in biological deodorization reactors may enhance the simultaneous degradation capacity of multiple VOC components after their transfer into the liquid phase of biofilms. However, pollutant removal efficiency in liquid systems cannot be directly extrapolated to gas-phase removal performance. Further investigations are required to specifically evaluate the impacts of gas–liquid mass transfer limitations, biofilm colonization stability, metabolic gene expression under low-concentration gaseous substrates, and the accumulation or release of intermediate metabolites in gas-phase bioremediation systems.

6. Microbial Deodorization Technologies and Their Applications

Microbial deodorization technologies have primarily evolved into in situ treatment technologies focused on source control and ex situ bioreactor technologies oriented toward end-of-pipe treatment, depending on the treatment stage and spatial dimension of pollutant management.

6.1. In Situ Treatment Technologies

In situ treatment technologies are designed to achieve the on-site conversion of odorous compounds through direct intervention in the biological metabolic processes of pollution sources, offering relatively low infrastructure costs and high operational convenience [102].

6.1.1. Feed Additives

In this approach, probiotic consortia, such as lactic acid bacteria and *Bacillus* spp., are strategically incorporated into livestock and poultry feed to reshape the intestinal microecosystem and suppress the proliferation of pathogenic putrefactive microorganisms, thereby significantly reducing the generation of odor precursors at the physiological and metabolic levels [103,104]. The major advantage of this technology lies in shifting odor control to the source while simultaneously improving animal production performance. However, its deodorization efficiency may be substantially influenced by physiological heterogeneity among animals, and dispersed odors released into the atmosphere cannot be effectively captured. Therefore, this technology is particularly suitable for intensive livestock operations with highly enclosed environments and concurrent demands for animal health improvement. In a commercial broiler farm, the inclusion of *Bacillus subtilis* in the diet was found to reduce the NH₃ emission flux from the cecum by approximately 30% [104]. From an economic perspective, although microbial additives increase feed costs by approximately 2–5%, the additional benefits derived from improved feed conversion efficiency and reduced disease incidence can largely offset the treatment costs, demonstrating considerable application potential.

6.1.2. Direct Inoculation and Spraying of Microbial Agents

This technology relies on the targeted application of highly efficient microbial degraders to manure piles or landfill surfaces, where their strong metabolic activity is utilized to accelerate the mineralization of odorous compounds. It has been widely applied for the rapid treatment of odor emissions from organic solid waste composting facilities, landfill sites, and temporary odor outbreak hotspots [105]. A major advantage of this approach is its high specificity, as functional microbial consortia can be tailored according to the characteristics of target pollutants under different application scenarios. However, its practical application is constrained by limited environmental robustness, and challenges

remain in maintaining microbial activity and competitive colonization within complex field environments. Zhang et al. [106] reported that the inoculation of thermophilic functional bacteria during the initial stage of thermophilic composting not only significantly accelerated compost maturation but also reduced the cumulative emissions of NH_3 and H_2S by 25.06% and 25.05%, respectively. By enhancing nitrogen retention within the composting material, this technology not only improves the surrounding atmospheric environment but also increases the fertilizer value of the final product, thereby providing substantial environmental and societal benefits.

6.2. Ex Situ Treatment Technologies

Ex situ treatment technologies involve the systematic collection of odorous gases and their transfer to dedicated bioreactors, where pollutant degradation is enhanced by highly concentrated microbial communities. These technologies are particularly suitable for the treatment of continuous industrial exhaust streams with high gas flow rates (Figure 4).

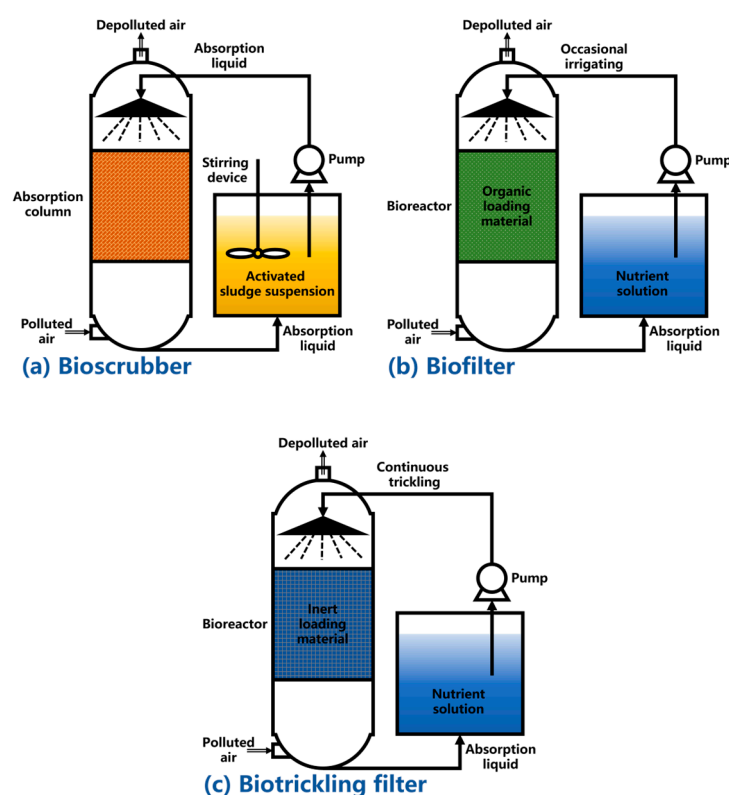


Figure 4. Schematic diagram of deodorization bioreactor.

6.2.1. Bioscrubber

In bioscrubbing systems, odorous gases are first absorbed into a liquid phase within a scrubbing column and are subsequently degraded in a separate bioreactor by suspended activated sludge. The main advantages of this system include precise controllability of operational parameters (e.g., pH and nutrient concentration) and high process stability. However, relatively low removal efficiencies for hydrophobic organic compounds have been reported. In addition, long start-up periods and a relatively high risk of secondary pollution associated with wastewater treatment have been identified. This technology is mainly applied to high-concentration industrial waste gases with complex compositions, particularly those containing sulfur or ammonia compounds. Castagnoli et al. [107] evaluated the performance and cost of conventional chemical scrubbing and bioscrubbing for treating sulfur-containing exhaust gases from a sulfur-based pigment factory. It was

found that bioscrubbing achieved better treatment performance than chemical scrubbing. Moreover, bioscrubbing reduced $\text{SO}_4^{2-}/\text{SO}_3^{2-}$ concentrations in the scrubber effluent by 98.88% and enabled biological sulfur recovery. Although the initial capital investment of this system is relatively high, its high degree of automation and large treatment capacity make it indispensable in large-scale industrial emission control applications.

6.2.2. Biofilter

This technology employs moist active filter media (e.g., wood chips and biochar) as carriers, through which odorous gases pass across a microbially colonized packed bed, where pollutants are directly degraded by immobilized biofilms. A key advantage of this technology is its simplified operational and maintenance procedures, as no frequent chemical dosing is required, resulting in highly competitive operating costs. However, limitations include a large footprint, as well as acidification, compaction, and clogging of the packing material during long-term operation [108]. Billones et al. [109] developed a biofilter using a composite packing material of durian husk and chicken manure for NH_3 treatment, achieving an average removal efficiency of 91.53%. By using low-cost waste materials as packing media, this technology maintains high deodorization efficiency while significantly reducing construction costs.

6.2.3. Biotrickling Filter

Biotrickling filters are similar to biofilters, but a nutrient solution is continuously trickled over the packing material, resulting in the formation of a flowing biofilm, which facilitates pH control and nutrient supplementation. The main advantages of this system include a compact configuration and high space utilization efficiency. Biomass accumulation can be effectively controlled by adjusting the composition of the irrigation liquid. Therefore, this technology is particularly suitable for urban wastewater treatment plants and industrial workshops with limited land availability and strict deodorization requirements. However, high-precision management of circulation pumps and spraying systems is required, and continuous treatment of waste liquid remains a key challenge. Huan et al. [110] applied a biotrickling filter packed with bamboo charcoal for NH_3 treatment. A maximum removal loading rate exceeding $150 \text{ g}/(\text{m}^3 \cdot \text{h})$ and a removal efficiency of up to 96.52% were achieved. Zhang et al. [111] introduced a photocatalysis-coupled microbial fuel cell (MFC) system. At an aniline concentration of $790 \text{ mg}/\text{m}^3$, a removal capacity of $18.97 \text{ g}/(\text{m}^3 \cdot \text{h})$ was achieved. Meanwhile, electricity generation was also realized, with a maximum power density of $172.9 \text{ mW}/\text{m}^3$.

Typical cases are summarized in Table 7.

Table 7. Comparison of typical biological odor-control reactors.

Biological Reactors	Application Scenarios	Advantages	Disadvantages	Performance	References
Bioscrubber	Highly soluble odorous gases or industrial processes requiring strict operational control (e.g., chemical exhaust gases)	High efficiency for highly soluble compounds, precise operational control, and capability to handle high loading rates	High energy consumption, wastewater generation, and complex maintenance	99.3% H_2S removal (inlet 2200–2500 ppm; outlet 20 ppm)	[112]
Biofilter	Low-concentration odorous gases (e.g., composting, agriculture, and low-load zones of wastewater treatment plants)	Simple operation, low capital and operating costs, no chemical consumption, and suitability for high gas flow rates	Large footprint, prone to clogging, difficult control of pH and humidity, and low efficiency for hydrophobic compounds	100% toluene removal (loading $32 \text{ g}/(\text{m}^3 \cdot \text{h})$, EBRT 60 s)	[81]

Table 7. Cont.

Biological Reactors	Application Scenarios	Advantages	Disadvantages	Performance	References
Biotrickling filter	High-concentration H ₂ S or VOCs (e.g., wastewater treatment headworks and industrial exhaust gases)	High removal efficiency, easy control of pH and nutrients, compact size, and suitability for acidic gases	Requires pumps and liquid circulation, potential acid accumulation, and moderate operating costs	71% degradation and 52% mineralization of tetrachloroethylene (50 ppm, EBRT 30 s, liquid recirculation 2 m ³ /(m ² ·h))	[113]

7. Conclusions and Perspectives

Microbial deodorization technologies have become an important approach for odor control in livestock farming, organic solid waste treatment, and sewage sludge management due to their environmentally friendly, efficient, and low-cost characteristics. However, their long-term and stable application under complex real-world conditions is still constrained by multiple factors, and insufficient adaptability has been further revealed in engineering and commercialization practices. First, most currently available high-efficiency deodorizing strains are obtained through laboratory screening, and their performance is typically evaluated under single-pollutant and idealized conditions. However, real odor systems are characterized by multi-component coexistence, fluctuating concentrations, and high salinity, which can reduce microbial colonization and metabolic stability in engineering environments. Second, although various commercial composite microbial deodorization agents are available on the market, their microbial compositions and mechanisms of action lack transparency, and no unified evaluation standards exist among different products, resulting in application outcomes that are highly dependent on specific operating conditions, with insufficient stability and reproducibility. In addition, existing studies have mainly focused on the removal mechanisms of NH₃, H₂S, or individual VOCs, while the synergistic metabolism and interactions of microbial communities in multi-pollutant systems remain insufficiently understood. Meanwhile, composite microbial agents are prone to functional decline during long-term operation due to environmental stress and community succession, and bioreactors commonly suffer from engineering issues such as packing clogging, acidification-induced deactivation, and biofilm aging, all of which collectively limit large-scale application.

Therefore, future research should focus on the following aspects: (1) strengthening multi-omics-based (genomic, transcriptomic, and metabolomic) analyses of functional microbial communities, elucidating the response mechanisms of key functional genes and metabolic networks in complex odor systems, and establishing correlations among “pollutants-functional microbiota-metabolic pathways”; (2) under complex conditions such as high ammonia, high sulfur, high salinity, and mixed VOCs, screening stress-resistant functional microorganisms with broad metabolic capabilities, and constructing stable synergistic microbial consortia using synthetic biology and directed domestication approaches; (3) developing novel packing materials with adsorption, buffering, and microbial immobilization functions to enhance mass transfer efficiency and biofilm stability, thereby improving long-term reactor performance; (4) promoting the deep integration of microbial deodorization with artificial intelligence monitoring, online sensing, and digital control technologies to enable dynamic regulation of operational parameters and real-time optimization of treatment performance; (5) establishing unified standards for strain screening, reactor performance evaluation, and engineering application, providing a basis for technology selection and performance assessment across different odor-control scenarios.

With the development of multi-omics technologies, synthetic microbial community construction, and intelligent bioreactors, microbial deodorization research is expected to

shift from experience-driven approaches to rational design, and from single-pollutant treatment to coordinated control of complex odor systems, thereby providing more efficient and sustainable technical support for precise odor management and waste resource utilization.

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