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Biological Mitigation of Malodorous Emissions in Sewage: A Comprehensive Review

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Abstract- ***Malodorous gases generated from sewage systems represent a significant environmental and public health challenge due to their offensive nature, toxicity, and persistence. Conventional odor control methods such as adsorption and chemical scrubbing are widely applied but are often associated with high operational costs, secondary pollution, and limited sustainability. Bioremediation has emerged as a promising alternative, utilizing microbial metabolism to degrade, transform, or mineralize odor-causing compounds into less harmful products. This review critically examines the sources and impacts of malodorous gases, conventional control technologies and their limitations, and advances in bioremediation strategies. Particular emphasis is placed on microbial diversity, degradation mechanisms, influencing environmental factors, and emerging molecular approaches such as omics technologies, bioaugmentation, and biostimulation. The integration of advanced biotechnological tools with microbial systems offers significant potential for sustainable odor management in sewage treatment systems.***

Keywords: Bioremediation, Malodorous Gases, Sewage, Microorganisms, Biofiltration, Bioaugmentation, Odor Control

I. INTRODUCTION

Malodorous gases are unpleasant emissions arising from sewage systems, landfills, industrial processes, and agricultural activities. Common odor-causing compounds include hydrogen sulfide (H_2S), ammonia (NH_3), volatile organic compounds (VOCs), and mercaptans. These compounds are widely reported in wastewater and waste management systems and are major contributors to environmental odor pollution (Du et al., 2024; Felföldi, 2024).

Beyond their offensive nature, these gases pose significant environmental and health risks. Odor perception is inherently subjective; however, increasing evidence shows that prolonged exposure leads to measurable physiological and psychological impacts on affected populations (Virginia et al., 2024; deSouza et al., 2024).

Traditional odor control methods, including physical adsorption and chemical neutralization, have been widely applied. However, these approaches are often limited by high operational costs, energy demand, and the generation of secondary pollutants (Li et al., 2025; Lee et al., 2023).

Bioremediation has emerged as a sustainable alternative, utilizing the metabolic capabilities of microorganisms to degrade odorous compounds into less harmful substances. Microbial systems are adaptable, cost-effective, and environmentally friendly, making them suitable for long-term odor management (Mekonnen et al., 2024; Muter, 2023).

II. HEALTH EFFECTS OF MALODOROUS GASES

2.1 Psychological Effects

Exposure to malodorous gases has significant psychological implications. Studies show that persistent odor exposure leads to stress, irritability, anxiety, and depression, particularly in communities located near waste treatment facilities (Virginia et al., 2024).

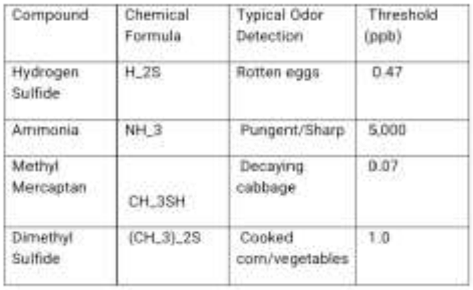
Odor pollution is also linked to reduced quality of life, social discomfort, and emotional distress. Individuals exposed to continuous unpleasant odors often experience sleep disturbances and decreased outdoor activity, highlighting the broader social and psychological burden (deSouza et al., 2024).

2.2 Physiological Effects

Inhalation of malodorous gases can result in various physiological health issues. Respiratory conditions such as asthma, bronchitis, and airway irritation are commonly associated with exposure to gases like ammonia and hydrogen sulfide (Du et al., 2024).

Other symptoms include headaches, nausea, dizziness, and eye irritation. Long-term exposure, especially to toxic VOCs, has been associated with more severe health risks, including cardiovascular diseases and potential carcinogenic effects (Virginia et al., 2024).

Table 1: Common Malodorous Compounds and Their Characteristics



Compound	Chemical Formula	Typical Odor Detection	Threshold (ppb)
Hydrogen Sulfide	H_2S	Rotten eggs	0.47
Ammonia	NH_3	Pungent/Sharp	5,000
Methyl Mercaptan	CH_3SH	Decaying cabbage	0.07
Dimethyl Sulfide	(CH_3)_2S	Cooked corn/vegetables	1.0

III. CONVENTIONAL ODOR CONTROL METHODS

Conventional odor control technologies are broadly categorized into physical and chemical methods.

Physical methods, such as activated carbon adsorption and ventilation systems, are commonly used to capture and dilute odorous compounds. However, these methods often transfer pollutants rather than eliminate them (Li et al., 2025).

Chemical methods, including chemical scrubbers and masking agents, neutralize or conceal odors. Despite their effectiveness, they may lead to secondary pollution and involve high chemical and maintenance costs (Lee et al., 2023).

Overall, conventional methods are limited in sustainability and long-term efficiency, necessitating alternative approaches.

IV. BIOREMEDIATION TECHNIQUES

Bioremediation strategies are classified into in-situ and ex-situ approaches depending on the treatment location see figure1.

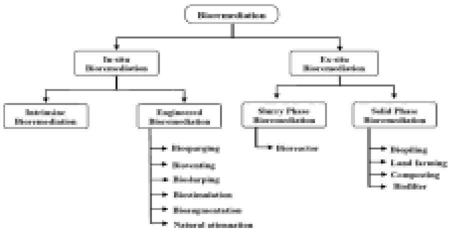


Figure 1: Bioremediation approaches for environmental clean-up. (Azubuike et al., 2016)

4.1 Ex-situ Bioremediation

Ex-situ techniques involve the excavation and treatment of contaminated materials under controlled conditions. These include biopiles, windrows, land farming, and slurry-phase bioreactors.

Biopiling: contaminated soil is piled up and aerated. Nutrients and moisture are added to encourage microbes to breakdown pollutants.

Land farming: polluted soil is spread in a thin layer on land and regularly turned, to expose the soil to air and sunlight, thereby helping microbes to degrade pollutants (Silva-Castro et al., 2012).

Composting: Contaminated soil is mixed with organic materials (manure or plant waste) to speed up microbial cleanup.

Biofilter: This is the passing of odorous air or water through a bed of organic material (compost or soil) containing microbes that can trap and destroy (remove) bad smells and pollutants Bioreactors, in particular, offer optimized environmental conditions such as temperature, aeration, and nutrient supply, which enhance microbial degradation rates and treatment efficiency (Kaur et al., 2025; Mekonnen et al., 2024).

However, ex-situ methods are often costly and may disrupt the natural environment due to excavation and transportation requirements.

4.2 In-situ Bioremediation

In-situ techniques treat contaminants directly at the pollution site. Common approaches include natural attenuation, bioventing, biosparging, bioslurping, and phytoremediation.

Natural attenuation: it simply means letting nature treat the pollution on its own. Microbes, sunlight, dilution, and natural chemical reactions slowly reduce pollution over time.

Bioventing is used to clean contaminated soil by slowly supplying air to the soil.
Biosparging cleans polluted groundwater by pumping air or oxygen into the soil below the water table.
Bioslurping removes liquid pollutants (petroleum) from soil and groundwater at the same time.
Phytoremediation is an environmental technique that uses plants to remove, stabilize, or break down pollutants from soil, water, or air.

These methods are cost-effective and environmentally less disruptive but may require longer treatment durations and careful monitoring to ensure effectiveness (Xie et al., 2024).

V. MICROORGANISMS IN BIOREMEDIATION

Microorganisms play a central role in bioremediation due to their metabolic versatility and adaptability.
Bacterial genera such as Pseudomonas, Bacillus, Acinetobacter, Rhodococcus, and Arthrobacter are widely reported for their ability to degrade organic pollutants and odorous gases (Mekonnen et al., 2024).

Fungi contribute through the production of extracellular enzymes capable of breaking down complex organic compounds, while algae assist via bioaccumulation and adsorption processes.

Microbial consortia have been shown to outperform single strains due to synergistic interactions that enhance degradation pathways and system resilience (Muter, 2023).

VI. FACTORS AFFECTING BIOREMEDIATION

The efficiency of bioremediation is influenced by biological, environmental, and pollutant-related factors.
Biological Factors: these factors include, Microbial diversity, Enzyme activity, Genetic adaptability, and Population dynamics (Muter, 2023) Environmental Factors: temperature, pH (optimal range 6.5–8.5), oxygen availability, moisture content, and nutrient levels (Mekonnen et al., 2024).

Pollutant Characteristics include: chemical structure, concentration and toxicity, and bioavailability (Kaur et al., 2025).

Optimal interaction of these factors is essential for efficient pollutant degradation.

VII. MECHANISMS OF BIOREMEDIATION OF MALODOROUS GASES

Microbial degradation of malodorous gases involves enzymatic transformations that convert harmful compounds into less toxic forms.

7.1 Biochemical Pathways

Major enzymes involved include oxidoreductases, hydrolases, lyases, and transferases. These enzymes catalyze reactions such as oxidation, hydrolysis, and bond cleavage.

For example, sulfur-oxidizing bacteria convert hydrogen sulfide (H_2S) into sulfate, thereby significantly reducing odor intensity (Yang et al., 2025).

7.2 Mechanisms of Bioremediation

Sulfur-oxidizing bacteria convert hydrogen sulfide into sulfate, reducing odor intensity (Yang et al., 2025).

The microbial breakdown of odors generally follows this sequence:

Recognition: Microbes detect the presence of the substrate.
Attachment: Formation of biofilms on the medium.
Enzymatic Attack: Secretion of extracellular enzymes to break down complex molecules.

Assimilation: Absorption of the broken-down nutrients into the cell.

Mineralization: Conversion into inert end-products (e.g., SO24, N2, CO_2 and H_2O)

These processes ensure complete detoxification rather than mere pollutant transfer (Mekonnen et al., 2024).

VIII. APPLICATIONS OF BIOREMEDIATION

Bioremediation is widely applied in environmental management systems.
Major application areas include:
Sewage and wastewater treatment
Industrial emission control
Contaminated soils and sediments
Biological air treatment systems are particularly effective for odor removal.

Biological Air Treatment Systems

Biological air treatment systems are eco-friendly technologies that employ microorganisms to remove gaseous pollutants, particularly odorous compounds such as hydrogen sulfide (H_2S), ammonia (NH_3), and volatile organic compounds (VOCs). These systems are increasingly preferred over physicochemical methods due to their low operational cost, minimal secondary pollution, and sustainability (Regidor-Alfageme et al., 2024; Sheoran et al., 2022).

The treatment process generally involves mass transfer of pollutants from the gas phase into a biofilm or liquid phase, followed by microbial biodegradation into harmless end-products such as CO_2, H_2O, sulfate, or nitrate (Liu et al., 2023). The three most widely applied systems are biofilters, bioscrubbers, and biotrickling filters.

1. Biofilters

Biofilters are the most commonly used biological air treatment systems, especially for odor control in wastewater treatment plants.

In biofilters, contaminated air passes through a moist packed bed (e.g., compost, peat, or wood chips), which supports microbial growth. Pollutants are first adsorbed into the biofilm and then metabolized by microorganisms (Pachaiappan et al., 2022).

The biofilm contains diverse microbial communities, such as:
Pseudomonas spp. (VOC degradation)
Thiobacillus spp. (H_2S oxidation)
These organisms utilize pollutants as sources of carbon and/or energy.

Performance and Recent Advances

Biofilters can achieve removal efficiencies above 90% for many odorous gases under optimal conditions (Sheoran et al., 2022). Recent research has focused on:

Improved packing materials
Engineered microbial consortia
Enhanced moisture and airflow control
These innovations have significantly increased system stability and efficiency (Regidor-Alfageme et al., 2024).

Merits of biofilter include:
Simple and cost-effective
Environmentally sustainable
Low energy requirements
Limitations
Media clogging over time
Sensitivity to drying conditions
Lower efficiency for hydrophobic VOCs

2. Bioscrubbers

Bioscrubbers integrate physical absorption and biological degradation in separate units.
The system operates in two stages:
Absorption stage: Polluted air is contacted with a liquid, allowing contaminants to dissolve.
Biodegradation stage: The contaminated liquid is transferred to a bioreactor, where microorganisms degrade the pollutants (Vitko et al., 2022).

This separation allows precise control of environmental parameters such as pH, temperature, and nutrient levels.

Performance and Applications

Bioscrubbers are particularly effective for highly soluble pollutants, such as ammonia and some VOCs. They also perform well under fluctuating pollutant loads, making them suitable for industrial applications (Regidor-Alfageme et al., 2024).

Merits
High efficiency for soluble gases
Greater operational control

Stable performance under variable conditions
Demerits
Higher operational and maintenance costs
Requires wastewater handling
Less effective for poorly soluble compounds

3. Biotrickling Filters
Biotrickling filters (BTFs) are advanced systems combining features of biofilters and bioscrubbers. In BTFs, contaminated air flows through a packed column while a nutrient-rich liquid continuously trickles over the packing material. This ensures:

Adequate moisture, nutrient supply, and efficient mass transfer
Microorganisms form biofilms on the packing material and degrade pollutants absorbed from the gas phase (Liu et al., 2023).

Performance and Recent Developments
Biotrickling filters exhibit high removal efficiencies (up to 95–97%) for VOCs and sulfur compounds (Feng et al., 2024). Their performance is enhanced by:
Continuous nutrient delivery
Controlled pH conditions
Reduced clogging compared to biofilters
Recent studies also highlight their robustness for high pollutant loading rates and long-term operation (Sheoran et al., 2022).
Merits
High efficiency and stability
Suitable for moderate to high pollutant loads
Better process control
Demerits
More complex system design
Requires liquid circulation and monitoring
Higher capital cost

4. Applications in Wastewater Treatment Facilities
Biological air treatment systems are extensively used in wastewater treatment plants for odor control, particularly in units such as:
Sludge digestion tanks
Aeration basins
Pumping stations
These systems effectively convert odorous compounds into non-odorous products, thereby improving air quality and reducing environmental and health risks (de Falco et al., 2025).

Compared to chemical treatment methods, biological systems are more sustainable and produce fewer harmful by-products, making them ideal for long-term environmental management (Regidor-Alfageme et al., 2024).

Table 2: Comparative Overview of Biological Air Treatment Systems

System	Key Strength	Limitation	Best Application
Biofilter	Low cost, simple	Clogging, moisture sensitivity	Low–moderate pollutant loads
Bioscrubber	High control	High cost, wastewater generation	Soluble pollutants
Biotrickling Filter	High efficiency	Complex operation	High pollutant loads

IX. DISCUSSION

The application of bioremediation for controlling malodorous gases in sewage systems represents a paradigm shift from conventional physicochemical methods toward sustainable environmental biotechnology. One of the most significant advantages of bioremediation is its ability to achieve complete mineralization of pollutants rather than merely transferring them between environmental compartments.

Microbial communities play a crucial role in determining the efficiency of odor removal. Recent studies highlight the importance of microbial consortia over pure cultures due to their metabolic diversity and synergistic interactions. These consortia enable the simultaneous degradation of multiple odor-causing compounds, including complex mixtures of VOCs and reduced sulfur compounds.

Environmental parameters such as pH, temperature, and oxygen availability critically influence microbial activity. For instance, sulfur-oxidizing bacteria involved in H2S degradation perform optimally under aerobic conditions, while anaerobic microbes contribute to methane and ammonia transformations. Therefore, maintaining optimal environmental conditions is essential for maximizing treatment efficiency.

The integration of advanced molecular tools, including metagenomics and transcriptomics, has significantly improved our understanding of microbial ecology in bioremediation systems. These technologies enable the identification of functional genes and metabolic pathways involved in odor degradation, facilitating the design of more efficient microbial consortia.

Furthermore, strategies such as bioaugmentation and biostimulation have enhanced the performance of bioremediation systems. Bioaugmentation introduces specialized microorganisms capable of degrading specific pollutants, while biostimulation enhances the activity of indigenous microbes through nutrient supplementation (Rittmann & McCarty, 2012).

Despite these advancements, several challenges remain. These include limited bioavailability of pollutants, inhibitory effects of toxic compounds, and difficulties in scaling up laboratory findings to field applications. Additionally, regulatory concerns regarding the use of genetically engineered microorganisms may hinder widespread adoption.

Future research should focus on the development of hybrid systems combining biological and physicochemical methods, optimization of reactor designs, and application of synthetic biology to engineer robust microbial strains could further enhance process control and efficiency.

X. CONCLUSION

Bioremediation offers a sustainable, eco-friendly, and cost-effective approach for managing malodorous gases in sewage systems. Its success depends on microbial activity, environmental conditions, and pollutant characteristics. Advances in molecular biology and environmental biotechnology are expected to further enhance its efficiency and scalability. Continued interdisciplinary research will be essential for overcoming current limitations and achieving widespread application.

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