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Microbiological and Biotechnological Studies Applied to Bioremediation of Volatile Organic Compounds and Air Pollutants: Biochemical Mechanisms and Novel Environmental Solutions

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Abstract

Air pollution, especially volatile organic compound (VOC) pollutants from industrial activities, transportation, and fossil fuel combustion, is recognized as one of the major threats to human health and the environment. Bioremediation, as an environmentally friendly approach, has been increasingly considered in reducing the air pollution burden through the use of specialized microorganisms capable of biodegrading these pollutants. This review article, focusing on microbiological studies, analyzes the biochemical mechanisms and metabolic pathways of bacterial, fungal, and yeast microbes with potential in the degradation of VOCs and other complex air pollutants. The complex mechanisms of electron transfer, genetic regulation related to the expression of key enzymes such as oxygenases and deoxygenases, and the role of quorum sensing systems in regulating the biological activities of microorganisms are reviewed. In addition, novel biotechnologies, including the design and development of airborne bioreactors, optimization of the use of bioactive nanoparticles with catalytic properties, and innovative quorum sensing sensors in monitoring and upgrading bioremediation processes are introduced. In another part of this review, combinatorial trends and molecular strategies for improving the efficiency and sustainability of bioremediation processes under variable environmental conditions are discussed. Also, the existing problems in the field of scalability of biotechnologies and environmental challenges caused by the emission of pollutants are discussed, and proposed solutions for sustainable development are presented. Finally, this review, emphasizing the importance of integrating microbiological approaches and modern biotechnologies, opens new horizons in the field of air pollution management and environmental health protection, and as a scientific reference, provides significant assistance to researchers and environmental biotechnology specialists.

Key words: Bioremediation, Air Pollution, Metabolic Pathways, Degrading Microorganisms, Catalytic Enzymes, Quorum Sensing,

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Graphical Abstract

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Introduction

Anthropogenic activities, particularly industrialization, urbanization, and reliance on fossil fuels, have led to the pervasive accumulation of volatile organic compounds (VOCs) and hazardous air pollutants (HAPs) in the atmosphere (Odubo & Kosoe, 2024). VOCs, characterized by high vapor pressure and low water solubility, encompass a diverse range of chemicals, including aliphatic and aromatic hydrocarbons (e.g., BTEX—benzene, toluene, ethylbenzene, xylene), chlorinated compounds (e.g., trichloroethylene, vinyl chloride), oxygenates (e.g., formaldehyde, acetone), and sulfur-containing species (ZAHRA & KWON, 2025). Their release contributes directly to tropospheric ozone formation, photochemical smog, and poses significant risks to human health, including carcinogenic, mutagenic, and teratogenic effects (Madronich et al., 2015). Traditional abatement technologies, such as thermal incineration, catalytic oxidation, and adsorption, are effective but are often burdened by high operational costs, substantial energy input, and the potential for generating secondary pollutants (e.g., NOx, dioxins).In this context, bioremediation has emerged as a sustainable, cost-effective, and environmentally benign alternative (Mathew et al., 2025). Leveraging the catabolic versatility of microorganisms and their enzymes, biological systems transform pollutants into innocuous end products like carbon dioxide, water, and biomass (Alabbosh, 2025). This review provides a detailed synthesis of contemporary microbiological foundations and cutting-edge biotechnological applications in air pollution control. It delves into the biochemical pathways governing degradation, critically assesses engineered bioreactor systems, and explores novel frontiers in biohybrid and synthetic biology solutions, thereby charting a course for next-generation environmental remediation.

Biochemical Mechanisms of Microbial Degradation

The efficacy of bioremediation hinges on the diverse and sophisticated metabolic pathways possessed by bacteria, fungi, and algae. These pathways are catalyzed by specific enzyme systems, often encoded on mobile genetic elements like plasmids or transposons, facilitating microbial adaptation(Lap et al., 2024).

Aerobic Degradation Pathways

Aerobic metabolism is the most prevalent and efficient route for VOC degradation, primarily involving oxygenases that incorporate molecular oxygen.

Aromatic Hydrocarbons (BTEX)

Initial attack is typically mediated by dioxygenases, which add both atoms of O_2 to the aromatic ring, forming cis-dihydrodiols (e.g., toluene dioxygenase). These are subsequently dehydrogenated to catechol derivatives(Neilson & Allard, 1997). The ring is then cleaved via either the ortho (intradiol) pathway using catechol 1,2-dioxygenase, leading to succinyl-CoA and acetyl-CoA, or the meta (extradiol) pathway using catechol 2,3-dioxygenase, yielding pyruvate and acetaldehyde(Islam, 2024).

Methane and Alkanes

Methanotrophic bacteria employ methane monooxygenase (MMO), a remarkable enzyme with broad substrate specificity. MMO oxidizes methane to methanol, which is further oxidized to formaldehyde, formate, and finally CO_2. Similarly, alkane monooxygenases (AlkB) hydroxylate medium-chain alkanes(Crombie, 2011).

Chlorinated Aliphatics

Co-metabolic degradation is common. For instance, soluble methane monooxygenase (sMMO) from Methylosinus trichosporium OB3b can fortuitously oxidize trichloroethylene (TCE) to TCE epoxide, which spontaneously decomposes to benign products(Zhang, 2008).

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Anaerobic and Alternative Pathways

Under oxygen-limited conditions (e.g., in soil, groundwater, or specific bioreactor zones), alternative electron acceptors drive degradation(Castro et al., 2022).

Reductive Dechlorination

Key for perchloroethylene (PCE) and TCE. Organisms like Dehalococcoides spp. use these compounds as terminal electron acceptors, sequentially replacing chlorine atoms with hydrogen, ultimately yielding ethene. This process is central to bioremediation of chlorinated solvent plumes(Field & Sierra, 2001).

Nitrate, Sulfate, and Iron Reduction

Some bacteria can degrade benzene, toluene, and xylanes under denitrifying or sulfate-reducing conditions, though rates are generally slower than aerobic processes(Beller et al., 1992).

Fungal and Enzymatic Contributions

Fungi, particularly white-rot fungi (e.g., Phanerochaete chrysosporium), employ extracellular, non-specific ligninolytic enzymes—lignin peroxidase (LiP), manganese peroxidase (MnP), and laccase. These enzymes generate powerful oxidative radicals (e.g., hydroxyl radicals) that can non-specifically attack a vast array of recalcitrant pollutants, including polycyclic aromatic hydrocarbons (PAHs) and chlorinated aromatics, making them valuable for complex mixtures (Jha, 2019).

Biotechnological Reactor Systems: Design and Application

The translation of microbial activity into controlled, large-scale processes is achieved through engineered bioreactors. Selection depends on pollutant solubility, concentration, and gas flow rate(Karamad et al., 2025).

Biofilters

The simplest and most widely used technology. A contaminated air stream is passed through a moist, porous packing material (compost, peat, wood chips, synthetic media) that supports a biofilm of degrading microorganisms. Pollutants are absorbed into the biofilm and metabolized (Wani et al., 1997). Key research focuses on media development to prevent compaction, channeling, and acidification, and on optimizing moisture content and nutrient supply. Effective for treating odorous compounds and VOCs at low to moderate concentrations (< 5 g/m^3) (Özcan, 2006).

Biotrickling Filters

An advanced variant where an aqueous nutrient solution is continuously or intermittently trickled over an inert packing material (ceramic, plastic rings, polyurethane foam). This allows better control of pH, temperature, and nutrient levels, and is effective for treating water-soluble pollutants (e.g., H_2S, formaldehyde) and higher VOC loads. Recent designs incorporate structured packings to enhance mass transfer and reduce pressure drop (Munjanja et al., 2023).

Bioscrubbers

A two-stage system: an absorption column where pollutants are scrubbed into a liquid phase, followed by a separate activated sludge bioreactor where the loaded liquid is treated. This separation allows independent optimization of absorption and biodegradation. Highly effective for treating gases with high solubility and variable loads(Anjumol et al., 2025).

Membrane Bioreactors (MBRs) for Gas Treatment

An emerging technology where a gas-permeable membrane (often hydrophobic microporous or dense silicone) separates the gaseous and liquid phases. Pollutants diffuse through the membrane and are degraded in the biofilm attached on the liquid side. MBRs offer a large surface area, independent control of gas and liquid flows, and are excellent for treating poorly soluble compounds (e.g., propene, dichloromethane) and preventing biomass washout(Roberts, 2005).

Novel Environmental Solutions and Cutting-Edge Biotechnology

Engineered Microbial Consortia and Synthetic Ecology

Moving beyond single-strain inoculants, the design of synthetic microbial consortia combines complementary metabolic pathways. For example, a consortium might pair a strain that performs initial oxidation of a chlorinated solvent with another that degrades the resulting intermediates. Quorum sensing mechanisms can be engineered to synchronize community behavior, enhancing robustness and resilience to shock loads(Duncker et al., 2021).

Systems Biology and Metabolic Engineering

Omics technologies (genomics, transcriptomics, proteomics, metabolomics) provide a holistic view of microbial responses to pollutants. This knowledge fuels rational metabolic engineering. By overexpressing rate-limiting enzymes (e.g., toluene monooxygenase), deleting pathways to toxic intermediates, or introducing novel pathways from other organisms, researchers can create "superbugs" with enhanced degradation kinetics and expanded substrate ranges(Dvořák, 2014).

Immobilized Enzyme Systems and Biohybrid Materials

To overcome limitations of whole cells (e.g., slow growth, sensitivity to toxicity), purified enzymes can be immobilized on solid supports (nanoparticles, polymers, membranes). Laccase and peroxygenase immobilized on magnetic nanoparticles or electrospun fibers show promise for continuous flow gas treatment.Biohybrid materials combine biological components with advanced materials, such as metal-organic framework (MOF)-encapsulated enzymes for increased stability, or conductive biofilms that facilitate direct electron transfer in microbial electrochemical cells for pollutant oxidation(Zdarta et al., 2018).

Integration with Phytoremediation and Constructed Wetlands

A green, macro-scale solution involves using plants and their associated rhizosphere microbes. Plants like poplars and willows can take up and transpire VOCs (phytovolatilization), while root exudates stimulate microbial degradation in the rhizosphere (rhizodegradation). Constructed biofilters using specific plants and engineered soil beds are being developed for treating landfill gases and industrial emissions(Nguyen et al., 2025).

Nanobiotechnology

Nanomaterials act as catalysts or scaffolds to enhance biological processes. Nanoparticle-enhanced biofilters use TiO_2 or ZnO nanoparticles for photocatalytic pre-treatment of recalcitrant VOCs, breaking them into more biodegradable intermediates. Carbon nanotubes and graphene oxide can be used as high-surface-area supports for microbial biofilm attachment, significantly improving biomass density and mass transfer(Shahcheraghi et al., 2022).

Challenges and Future Perspectives

Despite significant progress, challenges remain:

Treatment of Complex, Variable Streams

Real industrial emissions are mixtures of VOCs, inorganic gases, and particulates at fluctuating concentrations and flow rates, which can inhibit microbial communities.

Low Concentration and Hydrophobic VOCs

Achieving high removal efficiency for poorly soluble compounds (e.g., alkanes) at sub-ppm levels requires advanced reactor designs with enhanced mass transfer.

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Process Monitoring and Control

Real-time, in-situ monitoring of microbial activity and community composition using biosensors and molecular tools (qPCR, next-generation sequencing) is needed for intelligent process control.

Scale-up and Economic Viability

Bridging the gap between lab-scale success and cost-effective, reliable industrial implementation. Future research must focus on multidisciplinary integration. The convergence of synthetic biology (for creating novel biocatalysts), materials science (for advanced bioreactor media and membranes), and digital automation (AI for process optimization) holds the key to developing the next generation of smart, adaptive, and highly efficient bioremediation systems. Furthermore, integrating air bioremediation with waste gas-to-resource concepts, such as converting CH_4 or CO_2 into bioplastics or biofuels using engineered microbes, aligns perfectly with the principles of a circular bioeconomy.

Conclusion

Bioremediation of VOCs and air pollutants has evolved from a concept reliant on natural attenuation to a sophisticated biotechnology frontier. A deep understanding of biochemical mechanisms provides the foundation, while innovations in bioreactor design, microbial consortia engineering, enzyme technology, and hybrid systems offer powerful tools for implementation. While technical and economic hurdles persist, the trajectory of research points toward more efficient, robust, and sustainable biological solutions. By harnessing and enhancing the innate capabilities of microorganisms, we can develop effective strategies to mitigate air pollution, protect human health, and contribute to environmental sustainability.

References

Alabbosh, K. F. (2025). Leveraging the Potential of Environmental Microorganisms: An Extensive Examination of Their Capacity in Tackling Global and Local Environmental and Ecological Challenges. Polish Journal of Environmental Studies, 34(1).

Anjumol, K. P., Kundu, P., Mishra, I. M., & Anju, A. (2025). Current Progress and Perspectives of Various Biological Technologies for Treatment of Gaseous Pollutants: A State-of-the-Art Review. Journal of The Institution of Engineers (India): Series E, 1-31.

Beller, H. R., Grbić-Galić, D., & Reinhard, M. (1992). Microbial degradation of toluene under sulfate-reducing conditions and the influence of iron on the process. Applied and Environmental Microbiology, 58(3), 786-793.

Castro, A. R., Martins, G., Salvador, A. F., & Cavaleiro, A. J. (2022). Iron Compounds in anaerobic degradation of petroleum hydrocarbons: A review. Microorganisms, 10(11), 2142.

Crombie, A. (2011). Metabolism of methane and propane and the role of the glyoxylate bypass enzymes in Methylocella silvestris BL2 University of Warwick].

Duncker, K. E., Holmes, Z. A., & You, L. (2021). Engineered microbial consortia: strategies and applications. Microbial Cell Factories, 20(1), 211.

Dvořák, P. (2014). Engineering of the synthetic metabolic pathway for biodegradation of environmental pollutant Masaryk University, Faculty of Science Brno, Czech Republic].

Field, J. A., & Sierra, R. (2001). Review of scientific literature on microbial dechlorination and chlorination of key chlorinated compounds. Department of Chemical & Environmental Engineering University of Arizona, 37p.

Biotechnological Journal of Environmental Microorganisms(BJEM) 4(13) 2025 701-708

Jha, H. (2019). Fungal diversity and enzymes involved in lignin degradation. In Mycodegradation of lignocelluloses (pp. 35-49). Springer.

Karamad, A., Mirtamizdoust, B., & Chenari, M. (2025). Biotechnological Solutions for Air Pollution Mitigation: A Comprehensive Review. J. Chem. Rev, 7(4), 748-783.

Kumari, S., & Das, S. (2023). Bacterial enzymatic degradation of recalcitrant organic pollutants: catabolic pathways and genetic regulations. Environmental Science and Pollution Research, 30(33), 79676-79705.

Lap, B., Debnath, A., Singh, G. K., Chaturvedi, P., Dey, J. K., & Saha, S. (2024). Microbial enzymes in biodegradation of organic pollutants: Mechanisms and applications. Microbes based approaches for the management of hazardous contaminants, 12-19.

Madronich, S., Shao, M., Wilson, S., Solomon, K., Longstreth, J., & Tang, X. (2015). Changes in air quality and tropospheric composition due to depletion of stratospheric ozone and interactions with changing climate: implications for human and environmental health. Photochemical & Photobiological Sciences, 14(1), 149-169.

Mathew, N., Somanathan, A., Tirpude, A., Pillai, A. M., Mondal, P., & Arfin, T. (2025). Dioxins and their impact: a review of toxicity, persistence, and novel remediation strategies. Analytical Methods.

Munjanja, B. K., Wagh, N. S., Nomngongo, P. N., Lakkakula, J., & Mketo, N. (2023). Biofiltration-Based Methods for the Removal of Volatile Organic Compounds and Heavy Metals in Industrial Effluent Treatment Plants. In Bio-Nano Filtration in Industrial Effluent Treatment (pp. 1-15). CRC Press.

Neilson, A. H., & Allard, A.-S. (1997). 10 Microbial Metabolism of PAHs and Heteroarenes. PAHs and Related Compounds: Biology, 3(Part J), 1.

Nguyen, T. Q., Nguyen, H. X., Bui, M. Q., Pham, D. H., Truong, H. M., Nguyen, T. N., Hoang, T. M., & Truong, M. N. (2025). Standardized Design Metrics and Policy Integration for Phytoremediation Systems in Water Contaminant Management. Standards, 5(4), 25.

Odubo, T. C., & Kosoe, E. A. (2024). Sources of air pollutants: impacts and solutions. In Air pollutants in the context of one health: fundamentals, sources, and impacts (pp. 75-121). Springer.

Özcan, E. B. (2006). Agricultural waste products as filter media and as cover materials in biofilters for Mediterranean countries (Vol. 88). Oldenbourg Industrieverlag.

Roberts, M. G. (2005). Removal of cyclohexane from a contaminated air stream using a dense phase membrane bioreactor.

Shahcheraghi, N., Golchin, H., Sadri, Z., Tabari, Y., Borhanifar, F., & Makani, S. (2022). Nano-biotechnology, an applicable approach for sustainable future. 3 Biotech, 12(3), 65.

Wani, A. H., Branion, R. M., & Lau, A. K. (1997). Biofiltration: A promising and cost-effective control technology for Odors, VOCs and air toxics. Journal of Environmental Science & Health Part A, 32(7), 2027-2055.

ZAHRA, B., & KWON, W.-T. (2025). A Study on Global Health Impacts of Volatile and Semi-Volatile Organic Compounds. Journal of Wellbeing Management and Applied Psychology, 8(3), 17-31.

Zdarta, J., Meyer, A. S., Jesionowski, T., & Pinelo, M. (2018). A general overview of support materials for enzyme immobilization: characteristics, properties, practical utility. Catalysts, 8(2), 92.

Zhang, Y. (2008). Co-metabolism of trichloroethylene by phenol grown aerobic granules