

Microbial Transformation of Indoor VOCs and Its Implications for Human Exposure and Environmental Health

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Abstract

Indoor air quality is shaped by a complex interplay among chemical emissions, building materials, ventilation, occupant activity, and the resident microbiome. Volatile organic compounds emitted from construction materials, finishes, furnishings, and cleaning products represent a persistent exposure burden in modern buildings. While previous research has emphasized source control, ventilation, and abiotic chemistry, the role of indoor microbial communities in transforming these compounds remains comparatively underexamined. This paper develops a systems-oriented analysis of microbial VOC transformation in indoor environments and evaluates its implications for human exposure and environmental health. The analysis integrates perspectives from indoor chemistry, microbial ecology, building science, public health, and environmental governance. It argues that microbial transformation should not be understood as a uniform removal mechanism but rather as a distributed biological infrastructure with highly variable efficiency, metabolic selectivity, and byproduct formation. The built environment functions as a coupled chemical and microbial system in which architectural design, moisture management, material selection, and ventilation interact to shape transformation pathways. Structural trade-offs arise between dilution, filtration, source control, and biologically mediated processing. These trade-offs have direct consequences for exposure equity, building-related health outcomes, antimicrobial resistance, and long-term sustainability. Governance frameworks remain fragmented and rarely incorporate microbial transformation into indoor air quality policy. The paper concludes by outlining principles for a more integrated governance model that treats indoor air as a socio-technical and ecological system, emphasizing robustness, fairness, and adaptive management.

Keywords

indoor air quality, volatile organic compounds, built environment microbiome, microbial transformation, human exposure, environmental health, building governance.

1. Introduction

Indoor volatile organic compounds represent a major category of environmental exposure. Longitudinal assessments of indoor pollutant concentrations have documented a substantial shift in the chemical composition of indoor air over recent decades, with emissions from building materials, synthetic furnishings, electronics, and consumer products becoming increasingly dominant relative to traditional combustion sources [1]. Many of these compounds are released continuously from surfaces, adhesives, paints, floorings, and composite wood products, creating a chronic baseline exposure that is further modulated by episodic activities such as cleaning, cooking, and the use of air fresheners [2]. Because people in industrialized and urbanized societies spend the overwhelming majority of their lives within enclosed spaces, the National Human Activity Pattern Survey has established that indoor microenvironments dominate inhalation exposure for many pollutants [3]. The resulting mixture is not a simple inventory of primary emissions because indoor chemistry also generates secondary pollutants through reactions among ozone, nitrogen oxides, and unsaturated organic compounds. This dynamic condition positions indoor air quality as a systems problem involving source attributes, building operations, occupant behavior, and chemical transformations.

In parallel, the built environment has been reconceptualized as an ecosystem that harbors diverse microbial communities [4]. Surfaces, dust, heating and cooling systems, plumbing, and indoor air itself contain bacteria and fungi whose composition is governed by moisture, temperature, occupancy, ventilation, and material substrates [5]. These microbial communities are not passive contaminants but active participants in biogeochemical processes. They can degrade organic matter, produce volatile metabolites, consume oxygen, and interact with surfaces in ways that alter building performance and occupant exposure. However, the intersection between indoor chemical pollutants and microbial metabolic activity has received less systematic attention than either domain in isolation. Understanding this intersection requires moving beyond static exposure models and considering indoor air as a coupled chemical and microbial system with feedbacks, spatial heterogeneity, and temporal dynamics.

The microbial transformation of indoor VOCs introduces a biologically mediated term into indoor pollutant fate. Such transformation can reduce concentrations of certain harmful compounds, but it can also generate partially oxidized intermediates, secondary organic aerosols, or microbial volatile organic compounds that may themselves affect health and perceived air quality [6]. Some very volatile organic compounds have only recently been recognized as an overlooked class of indoor pollutants [7]. Recent assessments of residential VOC emissions from building materials further indicate that material selection and housing characteristics produce long-term exposure burdens and ambient hazards that cannot be addressed solely through ventilation standards [8]. These observations imply that microbial transformation should be evaluated as part of a broader infrastructure of exposure control, with attention to its structural limitations, uneven distribution, and governance implications. The present paper develops this argument through a systems-level synthesis of microbiological, chemical, architectural, and policy perspectives.

2. The Built Environment as a Coupled Chemical and Microbial System

Buildings operate as engineered environments that also sustain biological communities. The physical configuration of a building, including its envelope, internal partitions, ventilation system, and moisture dynamics, creates niches where microbial populations can establish and persist. Studies in newly opened hospitals have shown that microbial colonization follows predictable ecological succession, beginning with human-associated taxa and gradually incorporating environmental taxa shaped by room function and disinfection regimes [9]. Similar principles apply in residential and commercial buildings, where ventilation rates and occupancy patterns influence the airborne microbial assemblage [10]. Outdoor air serves as a continuous inoculum, but indoor conditions filter and transform the microbial pool, leading to communities that are distinct from those found outside. Material surfaces, humidity, and cleaning practices further differentiate microbial habitats across rooms and buildings.

The chemical environment of indoor spaces is coupled to microbial ecology through several mechanisms. Microorganisms can use organic carbon sources emitted from materials, including plasticizers, solvents, and degradation products. Antimicrobial chemicals introduced through cleaning products or material additives may suppress some taxa while selecting for others, with consequences for metabolic function and antibiotic resistance gene carriage [11]. This selection pressure is particularly important because buildings are not merely passive containers but active selective environments. The presence of disinfectants, preservatives, and low-moisture conditions can favor oligotrophic or stress-tolerant taxa whose impact on VOC transformation is highly specific. Consequently, the indoor microbiome should be understood as an ecological system shaped by a combination of architectural design, chemical inputs, and operational practices.

The conceptual shift from viewing indoor microbes as contaminants to viewing them as components of a beneficial built environment has important implications. The beneficial microbe hypothesis proposes that some microbial exposures may support immune training and reduce allergic disease, but it also implies that interventions aimed at sterilization can inadvertently remove protective functions [12]. In the context of VOC transformation, this perspective suggests that microbial communities may perform ecosystem services such as organic pollutant degradation, but these services are context dependent and cannot be assumed to occur uniformly. Building design choices that reduce moisture and organic carbon availability may limit both harmful microbial growth and beneficial transformation capacity. Therefore, a systems approach must explicitly evaluate trade-offs among microbial exposure, chemical exposure, energy use, and material durability.

3. Microbial Metabolic Pathways and Transformation Networks for Indoor VOCs

Indoor microorganisms possess a range of metabolic capabilities relevant to VOC transformation. Bacteria and fungi can metabolize alcohols, aldehydes, ketones, aromatic compounds, and short-chain hydrocarbons under aerobic and sometimes anaerobic conditions. The transformation of VOCs depends on enzyme availability, cofactors, moisture, temperature, and substrate concentration. Some compounds are used as carbon and energy sources, while others are transformed incidentally through co-metabolism when microbes grow on other substrates. Because indoor VOC concentrations are often low relative to industrial or soil environments, the kinetics of transformation may be limited by substrate bioavailability, surface area, and microbial biomass. Moisture is a critical mediator because many metabolic processes require aqueous films on surfaces, and dry indoor conditions can severely restrict microbial activity even when microbes are present [13].

Material properties strongly influence the potential for microbial transformation. Synthetic floorings, adhesives, and coatings can emit compounds that partition into dust and surface films. The diffusion of plasticizers and other additives from vinyl flooring illustrates how material chemistry creates a slow-release source that maintains indoor concentrations over long periods [14]. In damp or humid environments, these organic films can host microbial communities capable of degrading the emitted compounds. However, the same process can produce metabolic intermediates that differ in sensory and toxicological properties. Perceived indoor air quality is often driven not only by primary emissions but also by oxidation products and microbial metabolites [15]. Thus, microbial transformation is not equivalent to simple removal; it can shift the chemical signature of indoor air without necessarily eliminating all adverse effects.

Residential surveys of VOC concentrations reveal wide variability across dwellings, reflecting differences in building age, ventilation, material loading, and occupant practices [16]. This variability also extends to the microbial communities that occupy these spaces. Urban greenness and the surrounding environment can influence indoor and outdoor microbiome composition, suggesting that the metabolic potential for VOC transformation may be unevenly distributed across urban neighborhoods [17,18]. Buildings in greener areas may receive different microbial inocula, potentially affecting the functional capacity of indoor communities. Conversely, buildings with tightly sealed envelopes may develop communities with limited diversity and reduced functional redundancy. The spatial and socioeconomic distribution of microbial transformation capacity is therefore an environmental justice concern that has not been adequately quantified.

4. Structural Trade-offs in Indoor VOC Transformation Systems

Indoor air quality management involves multiple competing objectives. Source control, dilution ventilation, air cleaning, and microbial transformation are not independent strategies; they interact in ways that create structural trade-offs. Ventilation dilutes VOCs but also imports outdoor pollutants and changes moisture and temperature conditions. Air cleaning can remove particulate matter and some gas-phase contaminants, but filters and sorbents require maintenance and embodied energy. Source control reduces primary emissions but may be difficult for existing building stocks. Microbial transformation offers a passive, potentially low-energy pathway for organic pollutant attenuation, but it depends on conditions that may also promote dampness, biodeterioration, or unwanted microbial exposure [19].

The relationship between microbial activity and building durability is a central trade-off. Many VOC-degrading microorganisms require moisture, but excess moisture is a leading cause of material degradation, mold growth, and adverse health outcomes. Thus, building designs that favor sustained microbial VOC transformation may conflict with moisture control guidelines. Conversely, dry environments may preserve material integrity and reduce microbial hazards but limit the biological transformation of organic pollutants. The challenge is not to maximize microbial activity but to manage it as a functional component of the indoor system. This requires a more sophisticated theoretical framework for indoor microbiology that connects ecological dynamics, building physics, and health outcomes [20].

Antimicrobial interventions add another layer of complexity. The widespread use of disinfectants and antimicrobial materials has coincided with concerns about antibiotic resistance and the disruption of beneficial microbial functions [Antimicrobial interventions add another layer of complexity. The widespread use of disinfectants and antimicrobial materials has coincided with concerns about antibiotic resistance and the disruption of

beneficial microbial functions [11]. Such interventions often target pathogenic or nuisance microbes, but their broad-spectrum activity may eliminate taxa capable of degrading specific VOCs. The resulting indoor ecosystem may become less functionally redundant and more susceptible to shifts under environmental stress. Conversely, some biocides can leave residual carbon sources that support resistant taxa, altering the balance between chemical degradation and harmful metabolite production. This dynamic underscores the importance of considering microbial transformation within an ecological rather than purely engineering framework. The structural trade-off is not simply between biological and mechanical control but among multiple forms of resilience: chemical resilience through source control and dilution, biological resilience through community diversity and metabolic redundancy, and operational resilience through maintenance and occupant engagement [21].

Moisture governance is crucial. High humidity can increase microbial activity and VOC degradation potential, but it is also associated with dust mite allergens, mold proliferation, and material damage [22]. The optimal moisture range for human comfort and building durability may not overlap with the range that maximizes microbial VOC transformation. Thus, designers and building operators must decide how to allocate control effort across different risk domains. In most existing buildings, moisture management is driven by condensation prevention and health guidelines rather than by any explicit consideration of pollutant biotransformation. A more integrated approach would evaluate microbial activity as one of several services provided by the indoor ecosystem, with explicit thresholds for acceptable risk. This requires new metrics for microbial function, not merely abundance or diversity.

Ventilation standards also embody hidden assumptions about indoor pollutant fate. Many standards treat VOC removal as primarily a function of outdoor air exchange, ignoring surface sinks, chemical transformations, and microbial metabolism [23]. This simplification can lead to overventilation in some contexts and underventilation in others. Overventilation consumes energy and can introduce outdoor pollutants; underventilation allows accumulation of primary emissions and microbial metabolites. Because microbial transformation rates are difficult to measure in real time, they are rarely integrated into ventilation calculations. Nevertheless, a growing body of research suggests that indoor surfaces and microbial biofilms can function as passive reactors that alter the net indoor air composition. Recognizing this role may enable building systems to use lower ventilation rates while maintaining acceptable exposure, provided that moisture and pollutant loads are managed within safe limits.

The equity dimension arises when microbial transformation capacity is distributed unevenly across housing types and neighborhoods. Dwellings with older materials, high moisture loads, or limited maintenance may host microbial communities with both beneficial degradation capacities and harmful microbial exposures. Conversely, newer high-performance buildings may have reduced microbial diversity due to low air exchange and antimicrobial materials, potentially limiting their capacity to transform organic pollutants. Residents in lower-income housing are more likely to experience both elevated VOC emissions from aged or low-quality materials and moisture-related microbial growth, creating a dual exposure burden that is not captured by average indoor air quality standards [24]. Addressing this challenge requires building policies that consider not only pollutant concentrations but also the functional state of the indoor ecosystem and the capacity of occupants to maintain it.

5. Microbial Transformation, Human Health, and Exposure Assessment

Human exposure to VOCs occurs through inhalation, dermal absorption, and ingestion of settled dust. Microbial transformation can modify each of these pathways by altering gas-phase concentrations, producing less volatile products, or influencing the partitioning of compounds between air and surfaces. Some transformation products are more water soluble and may dissolve in mucus membranes, while others may be more toxic or more odorous than their parent compounds. Therefore, exposure models that assume a constant emission rate and first-order decay without microbial terms may misestimate long-term health risks. The health relevance of microbial VOC transformation extends beyond chemical concentration to include the biological activity of the microbial community itself. Inhalation of microbial fragments, spores, and endotoxins can contribute to respiratory symptoms, while some microbial metabolites may act as sensory irritants [6,15]. The distinction between chemical and biological exposures blurs in the indoor environment.

From a health perspective, the transformation of benign or moderately irritating VOCs into more hazardous compounds is a central concern. For example, unsaturated terpenes and fragrances can react with ozone to form formaldehyde, ultrafine particles, and secondary organic aerosols. Microbial oxidation can also generate formaldehyde and other carbonyls under certain conditions. Residential VOC assessments have noted that health risks from building materials are often driven by a combination of primary and secondary pollutants, with some compounds exceeding non-cancer thresholds in sensitive populations [8]. The presence of active microbial communities may mitigate or exacerbate these risks depending on substrate availability and transformation pathways. Therefore, exposure assessment must incorporate biological transformation modules that are parameterized for specific indoor environments.

There is also an immunological dimension to indoor microbial exposure. Early life exposure to diverse environmental microbes has been associated with reduced allergic sensitization, while exposure to certain indoor dampness-related fungi is associated with asthma symptoms [12]. The transformation of VOCs by indoor microbes may affect immune outcomes indirectly by altering the chemical milieu, and directly by shaping microbial diversity. If building interventions aimed at reducing VOC exposure inadvertently reduce microbial diversity, they could trade one health risk for another. Conversely, promoting microbial growth to enhance VOC degradation may increase exposure to allergens and pathogens. These trade-offs require careful risk assessment and cannot be resolved by assuming that more microbial activity is always beneficial.

Perceived air quality and sensory comfort further complicate intervention strategies. Occupants often evaluate indoor air based on odor intensity and irritation rather than measured chemical concentrations. Microbial metabolism can produce alcohols, ketones, and sulfur compounds that have low odor thresholds, leading to complaints even when objective health risks are low [15]. This means that microbial transformation can reduce the concentration of a regulated VOC while simultaneously degrading perceived air quality through the production of malodorous intermediates. In buildings where occupant satisfaction is a primary outcome, microbial transformation may need to be coupled with sensory management strategies, such as controlling humidity, reducing carbon sources, or maintaining consistent ventilation.

6. Governance, Standards, and Policy Implications

Current governance of indoor air quality is fragmented across building codes, ventilation standards, occupational health regulations, and product emission labeling programs. These

frameworks rarely address microbial transformation as a distinct process, and they seldom require measurement of microbial function in indoor environments. Ventilation standards such as those developed by professional bodies focus on minimum outdoor air supply rates and carbon dioxide limits, while material emission standards focus on primary VOC emissions [25]. This separation leaves microbial transformation in a regulatory blind spot. It is not classified as source control because microbes are not typically treated as active sources or sinks; it is not classified as air cleaning because the transformation is diffuse and not engineered; and it is not classified as an environmental health issue because the indoor microbiome is not routinely regulated.

The absence of regulatory attention creates both risks and opportunities. On one hand, unmanaged microbial growth in damp buildings remains a major public health problem, and adding microbial transformation considerations could complicate existing moisture and mold guidance. On the other hand, ignoring the functional role of indoor microbes may lead to interventions that unintentionally increase VOC exposure or fail to exploit passive degradation capacity. A more coherent governance approach would integrate microbial transformation into indoor environmental quality frameworks, treating it as one component of a multilayered control hierarchy. Standards could define performance criteria for biologically active surfaces, encourage material selections that avoid antimicrobial additives where they are not needed, and require building commissioning to include assessments of microbial and chemical interactions in occupied spaces.

Regulatory caution is warranted because the evidence base remains uneven. Many studies of VOC biodegradation have been conducted in laboratory microcosms, industrial biofilters, or soil systems, and their extrapolation to indoor surfaces is uncertain. The indoor environment is characterized by low substrate concentrations, intermittent moisture, complex microbial communities, and continuous human exposure. These conditions differ substantially from engineered bioreactors where degradation rates are optimized. Therefore, policy should support research that links indoor microbial community function to real-time chemical measurements, while avoiding premature mandates that could have unintended consequences. Field studies in occupied homes and offices are needed to quantify transformation rates under realistic conditions and to identify building characteristics that support safe and effective microbial processing.

International building sustainability programs increasingly emphasize occupant health, material transparency, and carbon reduction. These programs provide entry points for microbial transformation considerations, but they often treat indoor air quality as a checklist of pollutant concentrations rather than a dynamic biological and chemical system. Integrating microbial function into building sustainability certification would require new indicators that are meaningful to designers, operators, and occupants. Such indicators might include moisture load, surface cleanliness, microbial diversity, metabolic potential for VOC degradation, and occupant-reported symptom prevalence. However, indicator development must be accompanied by standardized measurement protocols and interpretive guidance. Otherwise, building owners may be reluctant to report data that could be misinterpreted as evidence of contamination.

The precautionary principle supports continued emphasis on source control as the foundation of indoor VOC management. Source control is generally more reliable, less energy intensive, and less dependent on environmental conditions than microbial transformation. Nevertheless, source control cannot eliminate all indoor VOCs, especially in existing buildings with legacy

materials. In this context, microbial transformation may serve as a complementary mechanism that reduces residual exposure if managed within moisture and material limits. Policy should therefore encourage a layered approach in which source reduction, ventilation, filtration, and biological processing are evaluated together, with explicit attention to their interactions and trade-offs.

7. Toward Integrated Microbial and Chemical Management Infrastructures

The future management of indoor VOCs will require infrastructures that sense, model, and intervene in coupled chemical and microbial processes. Advances in low-cost sensors, multi-omics analysis, and building information modeling create the possibility of real-time indoor environmental monitoring that includes not only CO₂, temperature, humidity, and selected VOCs but also indicators of microbial activity and function. However, translating these data into actionable guidance remains challenging. Building operators and occupants need decision support tools that integrate chemical and biological information without overwhelming them. The design of such tools should draw on human-computer interaction principles and consider how different stakeholders interpret environmental risk.

Digital twins of buildings could incorporate microbial and chemical transformation models to simulate the effects of ventilation changes, moisture events, material replacements, and cleaning protocols. These simulations could reveal unexpected interactions, such as a reduction in ventilation that raises humidity and increases microbial VOC degradation but also increases occupant exposure to microbial metabolites. They could also support scenario planning for climate adaptation, because outdoor temperature and humidity changes will affect indoor moisture loads and microbial activity. Yet the development of these tools depends on robust model validation across diverse building types and climates. Without validation, model outputs may create false precision and undermine trust.

Material innovation offers another pathway for integrating microbial transformation into building practice. Bio-based materials, breathable finishes, and surfaces designed to support selected microbial communities could be engineered to degrade specific VOC classes while minimizing harmful byproducts. This approach resembles the use of biofiltration in industrial air treatment but applied at the material scale. However, bio-based interventions raise questions about durability, maintenance, occupant acceptance, and risk. Materials that retain moisture or organic carbon may support beneficial organisms during some conditions and harmful organisms during others. Life-cycle assessment should include not only embodied carbon and chemical emissions but also biological performance and potential health outcomes across the building's operational life.

Robustness and resilience are particularly relevant for microbial transformation systems. A robust indoor ecosystem should maintain acceptable VOC transformation and low harmful exposure across a range of conditions, including occupancy changes, cleaning events, power outages, and seasonal moisture variations. Functional redundancy, where multiple microbial taxa can perform similar transformations, is an important determinant of robustness. Buildings that are repeatedly disinfected or that have low microbial diversity may lose this redundancy, making them more vulnerable to disturbances. Resilience may also require modular building components that can be adjusted without disrupting entire systems, such as localized moisture controls or replaceable bioactive panels.

Fairness in deploying microbial transformation technologies is essential. If bioactive surfaces or enhanced microbial management become premium features of high-end buildings, benefits

may accrue disproportionately to affluent occupants while lower-income households continue to face both higher VOC emissions and moisture-related microbial hazards. Policy frameworks should ensure that microbial and chemical management strategies are accessible across housing types, including rental housing where occupants have limited control over material selection and maintenance. Equity also requires transparent communication about the role of indoor microbes, avoiding both the stigma of contamination and the overstatement of benefits. Public engagement should acknowledge scientific uncertainty while providing practical guidance for maintaining a healthy indoor environment.

Long-term sustainability depends on aligning microbial transformation goals with energy, materials, and health policies. Indoor VOC management cannot be optimized in isolation from building energy performance. Tighter building envelopes reduce energy use but can increase pollutant accumulation if ventilation is insufficient. Microbial activity may be higher in some energy-efficient buildings due to modified humidity and temperature profiles. Therefore, integrated design processes that involve building physicists, microbiologists, chemists, and health scientists are needed from the earliest stages of building projects. This interdisciplinary integration should extend into building operation, where facility managers can use sensor data to balance energy, moisture, chemical exposure, and microbial function.

8. Conclusion

The microbial transformation of indoor VOCs represents an underexplored but significant process linking building materials, microbial ecology, chemical exposure, and human health. This paper has argued that the built environment should be understood as a coupled chemical and microbial system in which structural, operational, and biological factors jointly determine indoor air composition. Microbial transformation is not a uniform removal mechanism but a variable and context-dependent set of metabolic processes that may reduce some exposures while generating new byproducts. Its implications extend beyond chemistry to include microbial exposure, moisture management, material durability, energy use, and environmental equity. Current governance frameworks do not adequately account for these interactions, leaving a regulatory gap between building codes, ventilation standards, and indoor microbiome research. A more integrated approach would treat source control, ventilation, moisture management, and microbial function as components of a single adaptive management strategy. Achieving this integration requires new metrics, improved models, and collaborative governance that includes building science, microbiology, public health, and occupant perspectives. The future of indoor VOC management will depend less on any single technology and more on the capacity to design and operate buildings as resilient socio-ecological systems that support both environmental quality and human well-being.

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