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MICROBIAL VOLATILE ORGANIC COMPOUNDS FROM DUST-ASSOCIATED FUNGI AND BACTERIA: APPROACH TO MITIGATING HYPERSENSITIVITY PNEUMONITIS AND ASPERGILLOSIS IN DEVELOPING COUNTRIES

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ABSTRACT

The problem of indoor air quality in developing countries is one of the most serious public health issues and is mainly related to the microbial volatile organic compounds (MVOCs) emission from the bacteria and fungi present in dust. The present review highlights MVOCs participation in the induction of hypersensitivity pneumonitis and aspergillosis, which are two respiratory diseases that affect the population of resource-poor settings to a greater extent. The paper discusses the complex relationships among environmental factors, microbial communities in home dust, and the immune system that they trigger. The review provides an overview of the current situation with respect to the MVOC profiles of various indoor fungi like *Aspergillus*, *Penicillium*, and *Stachybotrys* species, plus the bacterial contributions to the indoor volatilome. We also underline the challenges in detecting the pollutants and exposure assessment, as well as the socioeconomic factors that increase the risk in developing countries. However, on the other hand, we suggest the practically applicable and cost-effective solutions for less privileged environments, like better ventilation designs, moisture control interventions, and community health education programs. The review ends with suggestions for research priorities and policy initiatives that could greatly relieve the burden of MVOC-related respiratory diseases among the vulnerable population segments.

KEYWORDS: aspergillosis, bacteria, dust-associated, fungi, indoor, air quality, Microbial Volatile Organic Compounds (MVOC), hypersensitivity pneumonitis.

INTRODUCTION

The global burden of respiratory diseases caused by indoor air pollution is still a very important problem and it mainly affects developing countries (Barberan *et al.*, 2015). In these countries bad housing, climate, and lack of resources come together and create places where microbes can grow easily. One of the many indoor air pollutants, microbial volatile organic compounds are often overlooked but still represent a significant source of respiratory health complications (Konuma *et al.*, 2015; Barberan *et al.*, 2015). These compounds eliciting the most severe immune response in susceptible individuals are the byproducts of the fungi and bacteria living in the household dust and building materials as secondary metabolites. Two of the respiratory diseases caused by microorganisms that are found indoors are hypersensitivity and aspergillosis. Hypersensitivity pneumonitis being an inflammatory lung disease is caused by the repeated inhalation of the organic antigens and has the potential to go from acute reversible symptoms to chronic irreversible fibrosis (Fadiji *et al.*, 2024; Iversen *et al.*, 2024). On the other hand, the condition called aspergillosis has a whole range of different manifestations starting from the least invasive and most common allergic bronchopulmonary aspergillosis through the more severe and less common invasive disease in immunocompromised patients (Agarwal *et al.*, 2020). Even though both diseases have their common indoor microbial source and the same environmental conditions, the problem of recognition and access to treatment in developing countries is still very significant. Poor populations living in overcrowded and poorly maintained housing in tropical and subtropical areas with little or no healthcare available are mainly those that are affected by respiratory diseases caused by MVOCs (Sehgal *et al*., 2019; Agarwal *et al*., 2020). It is necessary to know the sources, the nature, and the health impacts of these compounds in order to come up with effective and economically feasible targeted interventions.

Microbial Volatile Organic Compounds: Chemical Nature and Biological Origins

Microbial Volatile Organic Compounds are a collective term for a wide range of low-molecular-weight organic compounds that are being emitted as a result of microbial metabolism (Misztal *et al*., 2018). Among these compounds, there are alcohols, aldehydes, ketones, terpenes, sulfur compounds, and nitrogen-containing compounds, all of which have different chemical and biological characteristics (Back *et al*., 2010; Konuma *et al*., 2015; Misztal *et al*., 2018). The formation of MVOCs indicates the active role of microorganisms in the ecosystem and provides various ecological functions namely, communication, competition, and resource acquisition among the microbial population. The MVOC patterns are specific to the fungal species that dominate the indoor air. *Aspergillus* species, particularly *Aspergillus fumigatus* and *Aspergillus niger* (Sugui *et al*., 2014; van de Veerdonk *et al*., 2017), are the fungi that give the characteristic modern indoor air odor by producing a mixture of compounds composed of 1-octen-3-ol, which is often termed to have a mushroom-like smell, along with various sesquiterpenes and furanic compounds (Schleibinger *et al*., 2005; WHO, 2009; Adedoyin and Ogunsona, 2025a). *Penicillium* species are contributing their own volatiles characterized by geosmin and several methyl ketones. *Stachybotrys chartarum*, the so-called "black mold," is also known for its production of trichothecene mycotoxins and a mixture of volatile compounds that can irritate the respiratory mucosa directly (WHO, 2009; Mendell *et al*., 2011). Bacteria's role in indoor air quality is less recognized but is equally important. Gram-negative bacteria are responsible for emitting distinct sulfur-containing volatiles, while soil bacteria give off compounds with earthy smells such as geosmin and 2-methylisoborneol (Barberan *et al*., 2015). House dust comprises bacteria mainly in damp areas that can liberate volatile amines, indoles, and other nitrogen-containing compounds known to exhibit strong biological activities. MVOC concentrations and compositions in indoor air differ depending on factors such as substrate, moisture, temperature, microbial competition, and the lifespan of microbe colonies (Misztal *et al*., 2018; Kim *et al*., 2022). In developing nations, these factors often work against each other, thus high humidity, high temperatures, and organic-rich substrates along with poor ventilation have combined to set up an extremely favorable environment for the massive MVOC production (Table 1).

Table 1: Common Microbial Volatile Organic Compounds (MVOCs) from Indoor Dust-Associated Fungi and Bacteria.

Microbial Source	Representative Species	Key MVOCs Produced	Chemical Class	Characteristic Odor	Known Health Effects	Reference
***Aspergillus* spp.**	*A. fumigatus, A. niger, A. versicolor*	1-Octen-3-ol, 3-Octanone, 3-Methylfuran, β-trans-Bergamotene	Alcohols, Ketones, Furans, Sesquiterpenes	Mushroom-like, earthy	Respiratory irritation, immune activation, potential genotoxicity	WHO, 2009; Barberan *et al*., 2015; USEPA, 2017; Agarwal *et al*., 2020; Haines *et al*., 2021; Janssens *et al*., 2024
***Penicillium* spp.**	*P. chrysogenum, P. brevicompactum, P. expansum*	3-Methylbutanol, 2-Methylisoborneol, Geosmin, 1-Pentanol	Alcohols, Terpenes	Musty, earthy	Sensory irritation, headache, nausea at high concentrations	WHO, 2009; Barberan *et al*., 2015; USEPA, 2017; Agarwal *et al*., 2020; Haines *et al*., 2021; Janssens *et al*., 2024
Stachybotrys	*S. chartarum*	Trichothecenes (volatilized), Dolabellane derivatives, Various sesquiterpenes	Mycotoxins, Terpenes	Musty, pungent	Direct mucosal irritation, immunosuppression, potential neurotoxicity	WHO, 2009; Barberan *et al*., 2015; USEPA, 2017; Agarwal *et al*., 2020; Haines *et al*., 2021; Janssens *et al*., 2024

***Fusarium* spp.**	*F. oxysporum, F. solani*	1-Octen-3-ol, Geosmin, Trichodiene	Alcohols, Terpenes	Earthy, moldy	Allergic sensitization, respiratory irritation	WHO, 2009; Barberan *et al*., 2015; USEPA, 2017; Agarwal *et al*., 2020; Haines *et al*., 2021; Janssens *et al*., 2024
***Cladosporium* spp.**	*C. cladosporioides, C. sphaerospermum*	2-Methylfuran, 3-Methylfuran, 1,3-Octadiene	Furans, Alkenes	Slightly sweet, musty	Generally low toxicity, allergenic spores	WHO, 2009; Barberan *et al*., 2015; USEPA, 2017; Agarwal *et al*., 2020; Haines *et al*., 2021; Janssens *et al*., 2024
***Alternaria* spp.**	*A. alternata*	Alternariol (volatile), Tenuazonic acid derivatives	Mycotoxins, Organic acids	Earthy, hay-like	Allergenic, potential carcinogenic metabolites	Misztal *et al*., 2018; Gohli *et al*., 2019; Gangneux *et al*., 2020; Lee *et al*., 2021; Kim *et al*., 2022
Gram-negative bacteria	*Pseudomonas, E. coli, Klebsiella*	Dimethyl disulfide, Dimethyl trisulfide, Indole, Skatole	Sulfur compounds, Nitrogen heterocycles	Putrid, fecal	Nausea, respiratory irritation, neurotoxicity at high levels	Misztal *et al*., 2018; Gohli *et al*., 2019; Gangneux *et al*., 2020; Lee *et al*., 2021; Kim *et al*., 2022
Gram-positive bacteria	*Bacillus spp., Staphylococcus spp.*	3-Methyl-1-butanol, 2-Methylbutanal, Acetoin	Alcohols, Aldehydes, Ketones	Sweet, buttery	Generally low acute toxicity, hronic effects unclear	Misztal *et al*., 2018; Gohli *et al*., 2019; Gangneux *et al*., 2020; Lee *et al*., 2021; Kim *et al*., 2022
Actinomycetes	*Streptomyces spp.*	Geosmin, 2-Methylisoborneol, Various terpenes	Terpenes, Alcohols	Strongly earthy, soil-like	Hypersensitivity pneumonitis trigger, allergic alveolitis	Misztal *et al*., 2018; Gohli *et al*., 2019; Gangneux *et al*., 2020; Lee *et al*., 2021; Kim *et al*., 2022
Mixed biofilms	Multi-species communities	Complex mixtures including alcohols, ketones, aldehydes, terpenes	Multiple classes	Variable, often musty	Synergistic and antagonistic effects, poorly characterized	Lee *et al*., 2021

Dust as a Reservoir and Amplifier of Microbial Contamination

Household dust is not just an easy collection of inert particles; it is a dynamic ecosystem that supports a variety of microbial communities (Moreno-Ancillo *et al*., 1997; Barberan *et al*., 2015). The chemical composition of dust changes quite a lot depending on geographical location, type of housing, the behavior of people living there, and environmental conditions but it has the same function everywhere to provide nutrients, moisture retention, and protected microhabitats for microbial growth (Iversen *et al*., 2024). In developing countries, dust composition is a mirror of the unique environmental inputs. Higher soil infiltration due to unpaved roads and incomplete building envelopes allows outdoor microbial communities to invade indoor spaces. Agricultural practices close to residential areas add fungal spores and bacteria that are capable of decomposing organic matter. Traditional construction materials, such as thatch, mud, and untreated wood, may be a habitat for indigenous microbes that continuously inoculate the dust inside the house. The distribution of dust particle sizes determines the extent to which both the microbes capitalize on the dust and people get to be exposed to the dust (Natasi *et al*., 2020; Heo *et al*., 2021; Haines *et al*., 2021). The smaller particles that are less than 10 micrometers in diameter are referred to as fine particles. Fine particles stay airborne for a longer period of time and, when inhaled, will reach deeper parts of the respiratory tract. Besides being carriers of live microorganisms, these fine particles can also diffuse their chemical products among the occupants of the space like MVOCs through the adsorption of the grease-like molecules on the particle surfaces (Fernandes *et al*., 2016; Natasi *et al*., 2020; Heo *et al*., 2021; Haines *et al*., 2020; Haines *et al*., 2021).

Resuspension of settled dust is a common occurrence due to household activities, and this leads to repeated exposure events, especially in houses with earthen floors or where cleaning resources are inadequate (Fernandes *et al*., 2016). The moisture in the dust microhabitats is the main factor that controls microbial activity and the production of MVOCs. The dust particles, even in dry environments, can still attract moisture and form places where fungi and bacteria can stay alive. Moisture in the air during the rainy season promotes the growth of these microbes and the subsequent release of MVOCs, leading to a peak in respiratory symptoms that usually coincide with the rainy season (WHO, 2009; Jayaprakash *et al*., 2017).

Hypersensitivity Pneumonitis: Immunological Mechanisms and MVOC Connections

Hypersensitivity pneumonitis is an intricate immunological response that comes to be when an inhaled organic antigen is constantly repeating. It has been traditionally viewed as being involved only with proteinaceous antigens, but new research indicates that, in fact, MVOCs have a part in both the direct and indirect paths of the disease's development (Iversen *et al*., 2024). The disease comes in the form of acute, subacute, and chronic, which all have different clinical manifestations but still share the same immunopathological characteristics. The acute form occurs within hours of heavy antigen exposure and its main symptoms are fever, chills, cough, and dyspnea. These symptoms sometimes go away with stopping the exposure but come back when re-exposed, thus a pattern is created which should prompt an environmental investigation (Moreno-Ancillo *et al*., 1997; Iversen *et al*., 2024). Still, in developing countries, where exposure might be constant and access to healthcare limited, this acute phase often goes unnoticed and the patient may thus progress to subacute or chronic disease.

Hypersensitivity pneumonitis is a complex disease wherein an immunological cascade is activated involving both cellular and humoral immunity. The cellular event draws in CD4+ T lymphocytes, and among them, Th1 and Th17 are the main ones that signal inflammatory reactions in the lung tissue. Granuloma formation, albeit poorly defined, is a feature that separates hypersensitivity pneumonitis from the rest of the interstitial lung diseases. The procedure of bronchoalveolar lavage shows a predominance of lymphocytes, and in some of the cases, especially the chronic ones, the CD4/CD8 ratio is inverted (Moreno-Ancillo *et al*., 2004; Iversen *et al*., 2024). It is clear that MVOCs are one of the causative factors contributing to this illness in many ways. For instance, some of the volatile compounds can link with the proteins of the body thereby forming new antigens that are perceived by the immune system leading to immune reaction. Others can directly modulate the immune system by either increasing the production of inflammatory cytokines or changing the function of the dendritic cells (Costabel *et al*., 2020; Gomes *et al*., 2021). Certain MVOCs cause loosening of the epithelium thus making it easier for the antigens to penetrate deeper and this in turn activates the immune system more. The deposition of some volatiles in the body can lead to oxidative stress which combined with tissue damage will further contribute to inflammation. The chronic form of hypersensitivity pneumonitis is, however, the one that clinically poses the greatest challenge. The limit of lung function due to fibrosis becomes progressively smaller, and the lung become totally non-functional. This is a typical manifestation of lungs in radiological terms as reticular opacities, ground-glass attenuation, and finally honeycombing as seen on high-resolution computed tomography (Costabel *et al*., 2020). The gradual maturation of chronic hypersensitivity pneumonitis has a gradual increase in dyspnea and cough which sometimes leads to late diagnosis when non-reversible damage has already taken a substantial amount (Nogueira *et al*., 2019; Costabel *et al*., 2020; Gomes *et al*., 2021).

The situation is complicated in less developed nations as several factors increase the occurrence and seriousness of hypersensitivity pneumonitis. The different occupations which expose workers to organic dusts in agriculture, mainly in rice, sugarcane, and cotton cultivation, in addition to housing exposures are all factors that cause cumulative antigen loads (Nogueira *et al*., 2019). Using biomass for cooking adds not only particulate matter but also combustion products that might lead to MVOC-induced inflammation. Possibly, malnutrition and simultaneous infections may change immune responses in a way that one's body becomes either more vulnerable or less to the disease or its symptoms g*et al*tered (Nogueira *et al*., 2019; Costabel *et al*., 2020; Gomes *et al*., 2021).

Aspergillosis: From Sensitization to Invasion

Aspergillosis includes a variety of conditions that denote different interactions between host and pathogen. The allergic bronchopulmonary aspergillosis, a hypersensitivity disorder occurring in asthmatic and cystic fibrosis patients, is one of the conditions on the other end (Kosmidis and Denning, 2015; Agarwal *et al*., 2020). Invasive aspergillosis is in immunocompromised patients, where the infection is life-threatening. The middle condition chronic pulmonary aspergillosis, usually affecting persons with lung cavities or abnormalities in structure, is often considered as a mix of hypersensitivity and infections since the patient's immune system is neither fully working nor completely disabled. The roles of MVOCs in the whole situation are underestimated. Allergic bronchopulmonary aspergillosis is caused by the immune system getting out of control due to the presence of *Aspergillus* in the airways. The syndrome includes IgE-mediated hypersensitivity along with IgG protection, presenting thus a mixed immunological picture. Symptoms are further described by the presence of central bronchiectasis, mucus plugging, and eosinophilia in peripheral blood (Rohm *et al*., 2014; Agarwal *et al*., 2020). If the disorder is not treated, the person will end up with progressive bronchiectasis and pulmonary fibrosis. The MVOCs produced in the airways by the *Aspergillus* species also co-operate with the fungus in direct immunological recognition of fungal antigens causing inflammation and tissue damage (Rohm *et al*., 2014; Oguma *et al*., 2018; Agarwal *et al*., 2020).

Aldehydes can change proteins by carbonylation and thus might produce neoantigens. The smells of terpene volatiles are anti-inflammatory and that is their mechanism of stimulating the release of cytokines by epithelial cells. Certain MVOCs of *Aspergillus* have an antimicrobial effect, so there is a possibility that they will interfere with the respiratory microbiome causing dysbiosis and inflammation associated with it will be continued (Agarwal *et al*., 2016; Bhankhur *et al*., 2019). The chronic pulmonary aspergillosis takes place in the persons suffering from lung diseases, namely, post-tuberculous cavities, chronic obstructive pulmonary disease, and cases with previous pneumothorax. The growing tuberculosis epidemic in developing countries is the reason why such a big part of the population is at risk. The fungi that grow on the lesions of the lungs cause the formation of the so-called fungal ball or chronic cavitary infection, which is characterized by progressive symptoms like cough with blood, loss of appetite, and increasing difficulty in breathing (Vitte *et al*., 2017). One reason for the unpleasantness of these cavities might be the production of MVOCs in the lungs, which, besides causing local tissue death, might also aggravate the patient's systemic symptoms through their absorption as volatiles (Schleibinger *et al*., 2005; Katalian *et al*., 2020; Agarwal *et al*., 2020).

Invasive aspergillosis is mainly a problem for the severely immunocompromised persons in developed countries, however, it is also drawing attention as a challenge in less developed areas. Patients with HIV/AIDS who have gone through a stage of advanced immunosuppression, those undergoing cancer treatments with chemotherapy, and transplant recipients are all in danger. The shortage of antifungal medications for prophylaxis, coupled with slow diagnosis due to poor diagnostic facilities, results in high mortality rates (Katalian *et al*., 2020; Agarwal *et al*., 2020). Even though MVOCs are not very direct in their roles in cases of invasive illness as compared to allergic forms, the environmental conditions that lead to colonization and invasion are one and the same as they originate in the dust and associated fungi reservoirs (Griffiths *et al*., 2021).

In disadvantaged regions the occurrence of aspergillosis still poses a huge problem. The tests done to identify the antibodies specific for *Aspergillus* could be either nonexistent or too expensive. Galactomannan testing is a process that helps in the diagnosis of invasive diseases but it needs specialized equipment and skilled personnel. Besides, radiological examination which is very important may be limited to just basic chest X-ray because of the inability to access CT scan facilities. All these limitations in diagnosis lead to the conditions not being recognized properly and treatment being delayed which eventually results in bad outcomes (Katalian *et al*., 2020; Agarwal *et al*., 2020).

Environmental Factors Amplifying Risk in Developing Countries

The high incidence of MVOC-related respiratory diseases in developing countries is largely due to the combined effect of the environmental, socioeconomic, and behavioral factors that are in convergence (Fernandes *et al*., 2016; Jayaprakash *et al*., 2017). It is very important to know these determinants since they can help in the formulation of the intervention strategies that are effective. Housing quality is probably the most important factor. Building materials in many developing areas are such that houses have dirt floors, roofs made of natural fibers and walls that allow for moisture penetration and microbial colonization. Poor weatherproofing allows for the infiltration of rain leading to the formation of areas of dampness which in turn become the breeding ground for fungi and bacteria (Haines *et al*., 2021; Adedoyin and Ogunsona, 2025a). The lack of moisture barriers between the soil and the living areas makes it easy for moisture to be wicked up continually and for microorganisms to enter from the ground-dwelling community. Poor ventilation increases microbial contamination and the accumulation of MVOCs indoors. Some traditional housing designs in certain areas, which have evolved for climate adaptation, might allow for natural ventilation thanks to such features as high ceilings, careful window placement, and the use of permeable wall materials (WHO, 2009; Fernandes *et al*., 2016). However, modern cheap housing usually does not have these features, thus leading to the creation of poorly ventilated boxes that trap moisture and volatiles. The situation of overcrowding which is typical in urban informal settlements and rural areas at the same time, decreases the air exchange rates and increases the moisture level by respiration and cooking thus making the air quality worse. The climate differs from one region to another but in general, it supports the growth of microbes in the tropical and subtropical developing countries. Living conditions that are very humid, warm, and with rainfall create a suitable environment for the growth of fungi and bacteria (WHO, 2009; Fernandes *et al*., 2016; Jayaprakash *et al*., 2017). The rise in respiratory symptoms during the rainy season in different regions matches the rise in the concentration of fungal spores and the production of MVOCs during and after the rains. Very often, the damage to the interior caused by flooding, leaks in the roof, and plumbing failures is not repaired because of the lack of financial resources. In the developed world, water-damaged materials are quickly removed and replaced while in the resource-constrained places, the damaged materials may be left indefinitely in place as a source of continuous microbial growth. Climate change has increased the frequency of natural disasters which lead to large-scale water damage that repairs can't handle. The use of biomass fuels indoors for cooking and heating, which is a practice common among billions of people around the globe, produces additional respiratory problems that might interact with the MVOC emissions. Gaseous pollutants and particulate matter caused by incomplete combustion could, in several ways, intensify the inflammation caused by MVOCs (WHO, 2009; Lorentzen *et al*., 2016; Fernandes *et al*., 2016; Jayaprakash *et al*., 2017; Adedoyin and Ogunsona, 2025a). The relationship between the use of biomass fuels and various respiratory diseases is very well documented, however, the interaction with MVOC exposure is an area that needs more research (Table 2).

Table 2: Risk Factors and Mitigation Strategies for MVOC-Related Respiratory Diseases in Developing Countries.

Risk Factor Category	Specific Risk Factors	Population Most Affected	Low-Cost Mitigation Strategies	Intermediate Interventions	Long-Term Solutions	Estimated Relative Effectiveness	References
Structural Moisture	Roof leaks, inadequate weatherproofing, rising damp, lack of moisture barriers	Rural households, informal settlements, flood-prone areas	Immediate action to repair leaks, plastic sheeting below beds, and improve drainage around the foundation.	Roof repair/replacement, lime-based waterproof plasters, vapor barriers under floors	Durable roofing materials, concrete floors with integrated moisture barriers, proper foundation design	High (80-90% reduction in moisture)	WHO, 2009; Fernandes *et al.*, 2016; Jayaprakash *et al.*, 2017
Poor Ventilation	Sealed or minimal windows, low ceilings, overcrowding, no cross-ventilation	Urban slums, energy-efficient but poorly designed housing	Opening existing windows during dry periods; reduce occupant density, adjacent-door positioning for air movement.	Installing additional windows/vents, roof ventilation, high-level openings, insect screening	Mechanical ventilation systems, architectural redesign with passive ventilation principles	Moderate-High (50-70% reduction in MVOC concentrations)	WHO, 2009; Fernandes *et al.*, 2016; Jayaprakash *et al.*, 2017; Adedoyin and Ogunsona, 2025a
Organic Substrates	Earthen floors, natural fiber materials, indoor grain/crop storage, inadequate waste disposal	Agricultural communities, traditional housing, food-insecure households	Regular wet cleaning, removal of unnecessary organic materials, separate crop storage structures	Sealed storage containers, improved waste management systems, treatment of natural materials	Non-organic building materials, mechanized agriculture reducing indoor processing, improved food security	Moderate (40-60% reduction in microbial growth)	WHO, 2009; Lorentzen *et al.*, 2016; Fernandes *et al.*, 2016; Jayaprakash *et al.*, 2017; Adedoyin and Ogunsona, 2025a
Climate Factors	High humidity, warm temperatures, seasonal flooding, monsoon periods	Tropical and subtropical regions, coastal areas, river valleys	Strategic ventilation timing (opening windows during dry periods), solar exposure of damp materials, elevated storage	Dehumidification strategies (desiccants, solar dehumidifiers), climate-adaptive building design	Active humidity control, climate-controlled living spaces, resilient infrastructure against extreme weather	Low-Moderate (20-40% achievable in resource-limited settings)	WHO, 2009; Lorentzen *et al.*, 2016; Fernandes *et al.*, 2016; Jayaprakash *et al.*, 2017; Adedoyin and Ogunsona, 2025a, 2025b
Indoor Combustion	Biomass fuel use for cooking/heating, inadequate ventilation of combustion products	Rural populations, urban poor, regions with limited electricity access	Moving cooking outdoors when possible, maximizing ventilation during cooking	Improved cookstoves with chimneys/flues, transition to cleaner fuels (LPG, biogas)	Electrification, solar cooking, complete transition to clean cooking fuels	Moderate (reduces PM and moisture but limited direct MVOC impact; 30-50% improvement in IAQ)	WHO, 2009; Lorentzen *et al.*, 2016; Fernandes *et al.*, 2016; Jayaprakash *et al.*, 2017; Adedoyin and Ogunsona, 2025a, 2025b
Socioeconomic	Poverty limiting	Low-income	Community education	Microfinance for	Economic development,	Foundation for all	WHO, 2009;

Barriers	repairs, lack of health awareness, inadequate access to materials, competing priorities	households universally	programs, peer-to-peer knowledge sharing, prioritization of high-impact low-cost changes	housing improvements, community bulk purchasing of materials, subsidies for vulnerable households	affordable housing programs, universal health coverage including environmental health	other interventions (enables implementation)	Lorentzen *et al*., 2016; Fernandes *et al*., 2016; Jayaprakash *et al*., 2017; Adedoyin and Ogunsona, 2025a, 2025b
Water Damage Events	Flooding, plumbing failures, storm damage, delayed drying/remediation	Disaster-prone areas, aging infrastructure, homes without insurance or savings	Immediate water removal, maximizing natural drying (sun, wind), disposal of heavily damaged porous materials	Rapid response teams, community drying equipment (fans, dehumidifiers), emergency repair supplies	Disaster-resistant construction, flood protection infrastructure, insurance/relief mechanisms enabling rapid repair	High if implemented quickly (preventing >70% of post-water-damage microbial growth)	Fernandes *et al*., 2016; Jayaprakash *et al*., 2017; Haines *et al*., 2021; Adedoyin and Ogunsona, 2025a, 2025b
Occupational Overlap	Agricultural activities in living spaces, grain threshing indoors, livestock proximity, cottage industries	Rural farming families, home-based workers, mixed-use dwellings	Physical separation of work/living areas, personal protective equipment (masks) during high-exposure tasks	Dedicated agricultural processing spaces, improved ventilation in work areas, work practice modifications	Mechanization reducing manual processing, complete separation of residential and agricultural/industrial spaces	Moderate-High (50-75% exposure reduction with full separation)	Fernandes *et al*., 2016; Jayaprakash *et al*., 2017; Haines *et al*., 2021; Adedoyin and Ogunsona, 2025a, 2025b
Healthcare Access	Delayed diagnosis, lack of specialist care, inadequate diagnostic facilities, poor follow-up	Rural populations, marginalized communities, areas with healthcare workforce shortages	Training primary care workers in clinical diagnosis, exposure history assessment, basic spirometry	Telemedicine consultations, mobile diagnostic units, regional referral centers	Universal health coverage, distributed specialist expertise, advanced diagnostic availability	Doesn't prevent disease but critical for reducing morbidity/mortality (50-80% improvement in outcomes)	WHO, 2009; Mendell *et al*., 2020; Adedoyin and Ogunsona, 2025a
Behavioral Factors	Infrequent cleaning, keeping windows closed, drying clothes indoors, inadequate maintenance awareness	Variable across populations, influenced by cultural practices and education	Health education campaigns, community health worker home visits, peer demonstration programs	School-based environmental health curriculum, mass media campaigns, integration into maternal-child health programs	Cultural shift toward preventive environmental health practices, sustained multi-generational education	Moderate (30-50% when combined with enabling environmental improvements)	WHO, 2009; Mendell *et al*., 2020; Adedoyin and Ogunsona, 2025a

Microbial sources are added by the agricultural activities taking place in or close to living areas. Indoor storage of grains, hay, and other agricultural products results in fungal growth and the production of high-concentration MVOCs (Konuma *et al*., 2015; Shorter *et al*., 2018). Activities such as grain threshing or coffee fermentation produce enormous aerosols that not only contain microorganisms but also their volatile products. The merging of living and agricultural areas, which is typical in rural developing regions, results in continuous high-level exposures, a scenario that is rare in developed countries (Shorter *et al*., 2018; Adedoyin and Ogunsona, 2025a).

Detection and Measurement Challenges

The characterization of MVOC exposures in developing countries is difficult due to significant methodological challenges. The gold standard for MVOC analysis is gas chromatography-mass spectrometry, requiring advanced instrumentation, skilled personnel, and uninterrupted electrical power resources that are generally lacking in the areas of greatest concern. Alternative methods are needed that are both analytically rigorous and practically feasible (Mendell and Adams, 2019; Nastasi *et al*., 2020). Active air sampling with sorbent tubes followed by thermal desorption and analysis produces quantitative data for MVOCs but necessitates portable sampling pumps and laboratory facilities for the analysis. Passive sampling with the use of diffusive samplers provides easier deployment but the resulting time-averaged concentrations may overlook peak exposures (Mendell and Adams, 2019; Adedoyin and Ogunsona, 2025a). The two methods have to cope with the problems of hot and humid environments that can lead to the decline of sample integrity during storage and transport. Specific volatile direct-reading sensors are capable of providing real-time monitoring but they commonly focus on single compounds or classes instead of covering the entire MVOC profile. Photo-ionization detectors can give an overall measurement of volatile organic compounds but they will not be able to identify whether the source is microbial or not (Dannemiller *et al*., 2017; Lucattini *et al*., 2018; Kormos *et al*., 2019; Nastasi *et al*., 2020; Adedoyin and Ogunsona, 2025a).

The use of sensor arrays to create MVOC fingerprints is an emerging electronic nose technology that has the potential to be applied in screening but still needs to be validated in terms of specific environments and outcomes first. Biological monitoring methods, which involve measuring MVOC metabolites or adducts in blood, urine, or exhaled breath, could avoid the challenges of environmental sampling. Nevertheless, the short half-lives of most MVOCs and their metabolites, coupled with a limited understanding of metabolism and elimination kinetics, are the bottleneck of current applications. Exhaled breath analysis is non-invasive and possibly field-deployable, but it requires sophisticated analytical techniques and interpretive frameworks that are still under development. Moisture damage and visible microbial growth detection by inspection provide a very basic but practical way of assessing exposure in places with limited resources. Created protocols for identifying risk factors water damage history, visible fungal growth, musty odors, humidity levels can clarify interventions even without sophisticated analytical confirmation. Educating community health workers on these assessment techniques could make possible widespread screening (Mendell and Adams, 2019; Nastasi *et al*., 2020; Adedoyin and Ogunsona, 2025, 2025b).

The reading of MVOC measurements comes with additional difficulties. Exposure-response relationships for individual compounds are still not well characterized, especially for the complex mixtures that are very common in real environments. It is likely that threshold concentrations for health effects differ between populations depending on genetic susceptibility, immune status, and concurrent exposures. The absence of defined occupational or residential exposure limits for the majority of MVOCs makes risk assessment and regulatory action more difficult (Mendell and Adams, 2019; Nastasi *et al*., 2020; Adedoyin and Ogunsona, 2025, 2025b).

Health Impact Assessment and Epidemiological Considerations

The assignment of the workplace contribution of MVOC exposures to the respiratory disease burden in developing countries will demand thorough epidemiological inquiry. Nevertheless, numerous factors will complicate the situation such as outcome misclassification, difficulty in assessing exposure, and confounding by correlated risk factors (Adedoyin and Ogunsona, 2025b). Hypersensitivity pneumonitis is probably a condition that is not being diagnosed in developing areas, to a great extent, The condition needs clinical suspicion, particular diagnostic testing which includes when necessary CT scan and sometimes bronchoscopy with biopsy, and careful environmental investigational of which are often not available resources (Nogueira *et al*., 2019). Many cases could easily be misdiagnosed as tuberculosis, community-acquired pneumonia, or other respiratory conditions especially when acute presentations are most common. The chronic form, which has a slow and subtle onset, might be attributed to smoking, occupational exposures, or idiopathic pulmonary fibrosis (Costabel *et al*., 2020; Gomes *et al*., 2021; Iversen *et al*., 2024). The same is true in the case of the diagnosis of aspergillosis which also faces huge barriers. The entire disease spectrum, ranging from allergic to invasive and requiring different diagnostic approaches, some quite sophisticated, makes it difficult to diagnose. In high tuberculosis prevalence areas, post-tuberculous cavities may not only be mistaken for treatment-resistant tuberculosis but also overlooked when chronic pulmonary aspergillosis develops. Specific immunological and radiological evaluations may be needed for allergic bronchopulmonary aspergillosis in asthmatic patients since it might not be distinguished from poorly controlled asthma without such evaluations (Iversen *et al*., 2024; Janssens *et al*., 2024).

Cross-sectional studies that look into the relationship between home characteristics and respiratory symptoms have given us the first evidence of the connection between environmental conditions and health outcomes. Many of these studies, covering different areas of the world, have already established links between visible mold, moisture signs, and respiratory symptoms such as wheeze, cough, and dyspnea (WHO, 2009; ME, 2019; Mendell *et al*., 2011; Iversen *et al*., 2024; Janssens *et al*., 2024). Nevertheless, these studies usually miss MVOC measurements and hence cannot claim causation. Longitudinal cohort studies, which would track individuals over time with repeated health assessments and exposure characterization, would yield stronger causal inference but they are practically impossible to conduct in resource-limited settings. People constantly moving from one place to another, especially in urban informal settlements, makes follow-up quite impossible. The complex nature of respiratory diseases requires very large sample sizes to detect certain MVOC effects surrounded by many competing risk factors. On the other hand, intervention studies such as those that implement mitigation strategies and evaluate health outcomes not only allow for causal inference but also directly show the effectiveness of the intervention (Iversen *et al*., 2024; Janssens *et al*., 2024). However, such studies are not without difficulties, like getting meaningful exposure reductions with resource-constrained interventions, maintaining blinding, and ensuring adequate follow-up duration to observe health improvements.

When epidemiological results are interpreted, it is necessary to take the population's differences in susceptibility into account. The immune response to microorganisms is determined by genetic factors, and some HLA types are linked with the risk of hypersensitivity pneumonitis. The immune system is influenced by the individual's nutritional status and, in turn, the disease may be expressed differently. Simultaneous exposure to tobacco smoke, biomass fuel emissions, occupational dusts, and germs might interact with MVOC exposures in a complicated manner. Socioeconomic status not only correlates with the quality of housing but also impacts the accessibility of healthcare, which in turn, may influence the recognition of the disease and thus the reported prevalence (WHO, 2009; ME, 2019; Mendell *et al*., 2011; Iversen *et al*., 2024; Janssens *et al*., 2024; Adedoyin and Ogunsona, 2025b).

Mitigation Strategies: Principles and Priorities

The issue of MVOC-related respiratory diseases in underdeveloped countries can only be taken care of by the means of interventions at different levels that will altogether include environmental modification, behavioral change, and health-system strengthening. The strategies should be technically efficacious, economically viable, culturally appropriate, and resource-friendly in terms of sustainability (Adedoyin and Ogunsona, 2025a, 2025b).

Source Control

Let's say our first step is going to be preventing microbial growth which by the way is the most basic and hence the greatest approach. Moisture control comes to the front as the primary intervention since the existence of water is a must for the growth of bacteria and fungi. The control strategies are as follows.

Employing moisture-resistant materials combined with appropriate weatherproofing while taking up good construction practices can keep water away from the house. The traditional moisture barriers might be costly but the use of locally sourced materials for alternative methods is worth considering. Such methods include adopting buried earth blocks that are made robust by using stabilizers, applying lime-based plaster and natural waterproofing agents coming from plant materials which, in fact, may be the way of providing the low-priced solutions. Roofing plans and upkeep avoid the most prevalent reason for water penetration in residences of the developing regions. Training programs focusing on basic roof repair and the given significance of immediate leak detection and repair could result in huge benefits. Roof repair projects in the community, which might be connected to financial aid programs, potentially will help to eliminate economic obstacles (Haines *et al*., 2020; Haines *et al*., 2021; Adedoyin and Ogunsona, 2025a, 2025b).

Simple interventions like placing plastic sheeting under earthen floors can be considered as a kind of moisture barrier to reduce moisture intrusion from the soil. On the other hand, concrete floors with buried moisture barriers are more complicated; still, their high price often makes it impossible to adopt them. Hence, the gradual improvement maybe starting at sleeping areas where exposure time is longest may be an ideal solution. Leak prevention and condensation control through plumbing repair will lead to less indoor humidity. In places where piped water is absent, storage and use of water behavioral interventions can be designed and applied to reduce spillage and condensation. Technologies like better cookstoves with flues are simple to use and they help removing both the smoke and the water vapor created during cooking (Knudsen *et al*., 2017; Haines *et al*., 2020; Haines *et al*., 2021; Adedoyin and Ogunsona, 2025a, 2025b).

Ventilation Enhancement

The air exchange rates are increased, the MVOC concentration is diluted and indoor humidity is reduced (Adedoyin and Ogunsona, 2025a). The natural ventilation strategies should be preserved and promoted that are in accordance with traditional design wisdom and that modern construction might have lost.

The placement of windows and vents can be very strategically done so that the prevailing winds can be harnessed for cross-ventilation. The orientation of the building in relation to the wind patterns will determine how natural ventilation potential can be maximized. Having operable windows on several walls will be the way for the residents to manage the airflow just according to the prevailing conditions (Adedoyin and Ogunsona, 2025a, 2025b).

The humidity and heat created during the day will be reduced with the help of high ceilings and attic ventilation. The thermal stack effect pulls the air up and thus creating natural circulation. Roof ventilators or ridge vents aid in this without the use of mechanical power or consuming electrical energy. Screened openings have been a solution for tropical regions' sealing of windows due to insects, for they provide ventilation and at the same time shut off the insects. The government should provide community education programs as a means of disseminating information on screening materials and installation techniques that are economically feasible. The installation of physical modifications along with behavioral interventions that encouraged the establishment of ventilation practices i.e. opening windows during appropriate times, avoiding overcrowding, controlling moisture-generating activities could complement each other. Notably, however, this is only up to a point where competing factors that include security risks, noise, outdoor air pollution, and thermal comfort would come into play.

Cleaning and Maintenance

Engaging in regular dust removal activities not only wipes out the sources of microbial growth but also reduces the amounts of volatile organic compounds (VOCs) in the environment. Cleaning practices should still take care not to increase the exposure level in the room being cleaned due to dust resuspension during the process.

Among the different cleaning methods, wet cleaning by means of damp cloths or mops is recommended since it causes the least amount of dust to go back into the air compared to dry sweeping. The availability of water may sometimes be a limitation in this method being used in some areas, hence the need to pay special attention to the water sources and conservation techniques. The vacuum cleaning method, when done with HEPA filtration, is the most effective way to eliminate dust without allowing a large resuspension of dust. The cost of vacuum cleaners is a major barrier to use in many poor areas; however, sharing among communities or renting may be a solution to a more accessible option. Moreover, simple machines that are easily made locally could bring the cost down and at the same time create jobs for locals (Knudsen *et al*., 2017; Haines *et al*., 2020; Haines *et al*., 2021; Adedoyin and Ogunsona, 2025a, 2025b).

If resources are scarce, the cleaning of areas with visible fungal growth will be prioritized. Affordable antimicrobial agents like vinegar and borax can be used to disinfect the localized contamination. The complete removal and disposal of heavily contaminated materials may be the best solution, but it is probably not economically feasible and therefore treatment will have to be based on the exposure of other areas being less than that of the one treated. Dust mite and microbial antigen exposure in sleeping environments is reduced through regular bedding laundering. Solar drying uses UV radiation for its antimicrobial effects. Culturally appropriate education on bedding hygiene, adapted to local washing practices and water availability, helps to instill the desired behavior (Knudsen *et al*., 2017; Haines *et al*., 2020; Haines *et al*., 2021; Adedoyin and Ogunsona, 2025a, 2025b, 2025c).

Material Selection and Building Improvement

Long-term housing improvements with moisture-resistant and microbial-resistant materials are regarded as the sustainable solutions. The economic aspect of these interventions is greater, but the rewards are also greater.

Wall materials resistant to moisture and bacteria include fired brick, concrete blocks, and stabilized earth blocks. They may be cheaper than traditional materials in some regions, but mainly the costs of repairs and maintenance and the need for long life might justify the investment. Phased improvements, perhaps through savings groups or microfinance, make these approaches more accessible. Antifungal additives or naturally antimicrobial coatings like lime wash can be used for painting that will help protect the surface. Lime-based paints provide alkaline pH that discourages fungi while remaining affordable and locally producible. Proper surface preparation and reapplication schedules ensure effectiveness. When the flooring is improved from the earthen to the concrete or other sealed surfaces, the major moisture source and dust reservoir will be eliminated. The substantial cost represents a barrier, but prioritizing sleeping areas or spaces where vulnerable individuals spend most time provides pragmatic compromise. Roofing materials that are resistant to water and that also decay biologically have replaced the thatch or any other organic material that is prone to microbial growth. Metal roofing, which is still more expensive upfront, but durability will eventually make it the more economical choice, has become very accessible due to the global supply chains. Proper installation with sufficient overhang not only keeps the walls dry but also prevents rain from getting in (Knudsen *et al*., 2017; Haines *et al*., 2020; Haines *et al*., 2021; Adedoyin and Ogunsona, 2025a, 2025b, 2025c).

Environmental Monitoring and Remediation Programs

Community-based programs that give the people in the neighborhood the power to survey and control the risks of housing are tactics that can be scaled up.

The training of community health workers in home environmental assessment will make local capacity. The simple protocols taking care of moisture problems, indicating the need for better ventilation, and spotting visible contamination will help in getting the problems prioritized for intervention. The coupling of the assessment with the resources available for the remediation ensures that the recommendations turn into actions instead of causing frustrations. Participatory improvement programs are such that residents are involved in the process of identifying priorities and the like. The community members frequently have the practical knowledge of the local resources and methods, which combined with the technical expertise, forms a very effective approach. The use of collaborative approaches makes the process more culturally appropriate and the results more durable (Knudsen *et al*., 2017; Haines *et al*., 2020; Haines *et al*., 2021; Adedoyin and Ogunsona, 2025a, 2025b, 2025c).

The demonstration homes are there to show the way with effective and affordable improvements that have been done and thus provide real models. The seeing of the successful implementations in the familiar contexts overcomes the refusal and shows the possibility. The residents of the demonstration homes are the peer educators, and they are the ones sharing the experiences and motivating the adoption. Interventions School-based issues related to children's exposures are dealt with, and at the same time, the knowledge about healthy housing is implanted which is going to be lasting. Children having better school environment may become the advocates for similar changes in their homes. The environmental health concepts that are included in the educational curricula are the means of creating a multi-generational impact (Knudsen *et al*., 2017; Haines *et al*., 2020; Haines *et al*., 2021; Adedoyin and Ogunsona, 2025a, 2025b, 2025c).

Medical Management and Health System Strengthening

The medical management improvement is a major contributor to the reduction of the disease burden, whereas the environmental control is still the main prevention strategy: The enhancement of diagnostic ability, through the training of personnel and the purchase of new equipment, leads to the correct identification of cases. Portable spirometry, which is less expensive than imaging, is used to identify the lung function impairment that requires further examination. In the absence of sophisticated testing, algorithms for clinical diagnosis direct the empirical management (WHO, 2009; Knudsen *et al*., 2017; Haines *et al*., 2020; Haines *et al*., 2021; Adedoyin and Ogunsona, 2025a, 2025b, 2025c).

The distribution of treatment protocols assures that patients according to their diagnoses receive the evidence-based therapy. Avoidance of hypersensitivity pneumonitis is the primary goal of management along with corticosteroid therapy when indicated. Treatment protocols for aspergillosis are made according to the medications available and the local resistance pattern, thus giving the patients the best chance of successful outcome.

The linkages between rural primary care and specialized centers in urban areas through Referral networks allow for proper handling of difficult cases. Telemedicine consultations help to deal with situations where expertise is not readily available due to geographical limitations. Secondary hospitals are being equipped with specialists through training programs so that the knowledge is spread more widely. Patients have the right to be informed about the environmental factors and the way to avoid exposure so that they can control their health better. Giving the patients information about the connection between the condition of their homes and respiratory symptoms is a good way to encourage them to change their behavior and to improve their environment. Written materials that are appropriate to the literacy levels and languages of the local people are very helpful in making understanding and retention easier. Surveillance techniques monitoring the occurrence of respiratory diseases help to find the areas with the most cases and require to take actions accordingly. The syndromic surveillance for the respiratory illnesses' clusters could be the source of the environmental case if the syndromic surveillance continues to identify such clusters. The health facilities and housing conditions data linked together show the exposure-disease relationships (WHO, 2009; Knudsen *et al*., 2017; Haines *et al*., 2020; Haines *et al*., 2021; Adedoyin and Ogunsona, 2025a, 2025b, 2025c).

Research Priority Areas and Knowledge Deprivation

Regardless of the increasing acknowledgment of MVOC-related respiratory diseases, considerable knowledge gaps hinder the optimum prevention and management strategies in developing countries: A detailed MVOC characterization in different housing contexts of the developing country will not only define the range of exposures but also, through priority compounds, would establish the most important areas of research. MVOCs studies across different geographic locations, climate zones, and types of housing would uncover the factors that cause variability in exposure. Characterization by seasons would show the time patterns that are important for intervention timing. The relationships between doses of major MVOCs and respiratory health outcomes are still very little known. To define these relationships, cohort studies with exposure and health assessments done longitudinally are needed. Also, the integration of genetic susceptibility markers would expose the at-risk groups that need specified attention (Haines *et al*., 2020; Haines *et al*., 2021; Adedoyin and Ogunsona, 2025a, 2025b, 2025c).

Intervention trials for the testing of the proposed strategies to deal with the issue would provide the evidence to decide on resource allocation. Among the various methods moisture control interventions, ventilation improvements, cleaning protocols controlled trials would not only identify the most effective and cost-effective strategies but also (WHO, 2009; ME, 2019; Adedoyin and Ogunsona, 2025a, 2025b, 2025c). Real-world developing country contexts for the trials would ensure their external validity. Mechanistic investigations revealing the MVOC toxicology and immunology would pave the way for more precise interventions. In vitro models investigating the responses of epithelium to the MVOC mixtures that are pertinent to the exposure levels in developing countries would help to detect the most toxic substances. Animal experiments with chronic exposure would be utilized to assess the hazard that has been created (Haines *et al*., 2020; Haines *et al*., 2021; Adedoyin and Ogunsona, 2025a, 2025b, 2025c).

Economical evaluations that estimate the disease burden as well as the cost-effectiveness of the interventions would be a supporting factor in policy formulation. The disability-adjusted life years that can be attributed to the MVOC exposures would render the problem comparable with other health-related issues. The cost-benefit analysis of the proposed interventions would indicate the direction of resource-limited decision making. Research in the area of implementation science that aims at identifying and analyzing the barriers and facilitators to intervention adoption would be instrumental in increasing the effectiveness of the program. Behavior economics strategies would possibly improve the adoption of protective behaviors. Community-engaged research is a way of ensuring that the interventions are in line with the local priorities and preferences. The impact of climate change on indoor microbial exposures is an issue that developing countries are a major concern. Predicting future scenarios of exposure based on different climate scenarios would be the basis for the formation of proactive adaptation strategies. Research on the impact of extreme weather events on housing conditions and respiratory disease would be an input to disaster preparedness (WHO, 2009; Knudsen *et al*., 2017; Haines *et al*., 2020; Haines *et al*., 2021; Adedoyin and Ogunsona, 2025a, 2025b, 2025c).

Cross-cutting themes such as gender aspects, urbanization effects, and economic development trajectories necessitate the involvement of all the research efforts during the whole process. Women and children usually suffer the most due to their time-activity patterns that lead to high exposures, hence the need for gender-sensitive interventions. Rapid urbanization changes the housing conditions but the impact on MVOC exposures is still uncertain. Economic growth may improve housing quality, however, it might also bring in new risk factors that will need to be guided by anticipatory measures (WHO, 2009; Knudsen *et al*., 2017; Haines *et al*., 2020; Haines *et al*., 2021; Adedoyin and Ogunsona, 2025a, 2025b, 2025c).

Policy Implications and Recommendations

Policy initiatives should form a basis of action for a comprehensive solution to the problem of respiratory diseases that are related to MVOC across the housing, health, environment, and education sectors. The policy frameworks should formulate standards, generate resources, and synchronize multi-sectoral actions.

Standards related to housing which include moisture control and ventilation requirements form the regulatory basis for the industry. Though there are difficulties in enforcing such standards in informal settlements and rural areas, they still provide guidance for the development of formal housing and offer aspirational targets. The adaptation of building codes to local materials and construction practices make the process feasible while still being protective (WHO, 2009; ME, 2019; Haines *et al*., 2020; Haines *et al*., 2021; Adedoyin and Ogunsona, 2025a, 2025b, 2025c).

Health policies that focus on indoor air quality, especially microbial contamination and MVOC exposures, give the issue a high priority on the already crowded policy agendas. The creation of national action plans consisting of exposure reduction and health outcome improvement goals leads to the establishment of accountability. The marriage of the housing quality assessment with primary health care not only leads to the case finding but also makes referral for intervention possible (WHO, 2009; ME, 2019; Haines *et al*., 2020; Haines *et al*., 202; Adedoyin and Ogunsona, 2025a, 2025b, 2025c).

Financial mechanisms that back housing improvement projects remove the economic barrier to risk reduction. Economic support for the moisture-resistant building materials or improvement of ventilation makes the homeowner's decision more favorable towards protection. Low-interest lending programs for housing upgrading allow for staged improvements. Cash transfers conditioned on the quality of housing linked to enhancing market demand for investment are also a form of incentive. Protection measures will be taken as more people are informed through the campaigns about the connection between housing conditions and lung health. Mass media such as radio, TV, and the growing use of mobile platforms are great for reaching large audiences. The reception of the message is improved by community-based education through reliable local leaders. A school curriculum that includes the concept of healthy housing can create knowledge that lasts for a long time. By training professionals who are healthcare workers, builders, and environmental health practitioners, the required capacity is developed. Including environmental determinants of respiratory disease in medical curricula increases diagnostic suspicion. Builders' vocational training that includes principles of moisture control and ventilation leads to better construction practices. Training of environmental health workers enables them to perform assessment and intervention at the community level. Next, research funding that gives priority to the contexts of developing countries generates evidence that is locally relevant. North-South partnerships in research should make sure that the participation of the investigator from the developing country is meaningful and that there is building of capacity. Collaborations between the South sharing experiences across similar contexts might be a way of fostering the exchange of solutions. The publication requirements of open-access ensure that the knowledge dissemination is maximized. The international cooperation through development assistance and technology transfer speeds up the progress. The funding of infrastructure improvements which include the upgrading of housing is aimed at the root causes. Technical assistance that helps in the adoption of interventions from one context to another improves effectiveness. Global monitoring frameworks that will be tracking the progress are encouragements for accountability (WHO, 2009; ME, 2019; Haines *et al*., 2020; Haines *et al*., 202; Adedoyin and Ogunsona, 2025a, 2025b, 2025c).

CONCLUSION

Microbial volatile organic compounds, which are produced by dust-associated fungi and bacteria, have been largely underrated but still present a significant contribution to the respiratory disease scenario in underdeveloped nations. Among these diseases, hypersensitivity pneumonitis and aspergillosis are the ones that can be very serious and even deathly, yet they remain largely preventable through environmental measures that monopoly moisture, ventilation, and microbe reservoirs. Inadequate housing, bad climate conditions, and poor resources combine to create high risk areas in many developing countries, however, the same situation also brings about multi-benefit interventions. The journey ahead needs to be the collaboration of environmental science, clinical medicine, social science, and community participation. Technical solutions must be based on the local context understanding, cultural practices, and resource realities. The top-down policy initiatives have to be complemented by the bottom-up community actions that make use of local knowledge and priorities. Research has to produce evidence that is actionable while also increasing the capacity of the investigator in developing countries to continue scientific research. The challenge is gigantic, but not impossible. Moisture control, ventilation improvement, and microbial contamination reduction can all be achieved through the use of inexpensive, locally tailored approaches. To spread these interventions across the board needs strong political support, sufficient funding, and continued cooperation among sectors and stakeholders. The health benefits fewer respiratory cases, better living conditions, lower health costs—are more than enough to cover the investment. The situation is such that the global community is increasingly shifting its focus onto the environmental aspects of health, which will consequently lead to a greater demand from the indoor air quality in the housing of developing countries.

Exposures to MVOCs show the intricate connection between the physical atmosphere, the microbial ecologies, and human health. Overcoming this difficulty signifies the dedication to health equity, acknowledging that the right to healthy housing is not limited to the economically advantaged. The fight against this problem will demand cooperative work, creativity, and steadfastness, nonetheless, the ability to relieve pain and even save lives is a powerful reason to take action. Combining environmental advances with health enhancement, community empowerment, and policy changes brings up a full plan that has the potential to cut down by far the number of people suffering from MVOC-related respiratory illnesses in the most affected communities.

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