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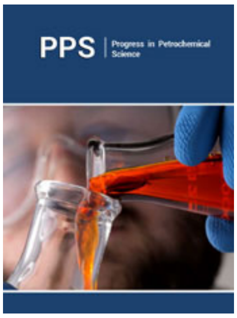
Review Article

From Indoors to the Atmosphere: The Climate Change Consequences of Volatile Organic Carbon Air Pollution

ISSN: 2637-8035



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Submission: July 09, 2025
Published: August 18, 2025

Volume 7 - Issue 3

How to cite this article: Amna Ali and Rima J Isaifan. From Indoors to the Atmosphere: The Climate Change Consequences of Volatile Organic Carbon Air Pollution. Progress Petrochem Sci. 7(3). PPS. 000662. 2025.
DOI: 10.31031/PPS.2025.07.000662

Abstract

Volatile Organic Compounds (VOCs) are a diverse group of carbon-based chemicals that readily evaporate at ambient temperatures and are released from a wide range of indoor sources, including building materials, adhesives, paints, cleaning agents, furnishings and consumer products. There are case studies mentioned about IAQ showing different items causing indoor pollution. In modern, airtight buildings, especially those designed for energy efficiency, VOCs can accumulate to levels that significantly compromise Indoor Air Quality (IAQ). Prolonged exposure to VOCs indoors has been linked to a range of health effects, from eye irritation and headaches to more serious outcomes such as respiratory illness, neurological symptoms and cancer. Despite their ubiquity and toxicity, VOCs remain underregulated and poorly monitored in both building codes and environmental health policies. While much research focuses on the outdoor atmospheric role of VOCs, their indoor emissions are often neglected in climate models and economic assessments, leading to a systemic underestimation of their broader environmental burden. VOCs emitted indoors can migrate outdoors, contributing to ground-level ozone and Secondary Organic Aerosol (SOA) formation, pollutants that influence both urban air quality and climate change. Yet, few policy frameworks fully account for these linkages or reflect the hidden costs of poor IAQ in terms of healthcare expenditures, lost productivity and environmental degradation. This review explores the dual impact of indoor VOCs as both a public health hazard and a climate-relevant pollutant. It critically examines how indoor VOC emissions are (or are not) represented in existing climate and economic models and highlights significant gaps in current measurement techniques, regulatory standards and modeling practices. Ultimately, the study calls for an interdisciplinary, IAQ-focused approach to VOC regulation that integrates emissions data into climate policy, building design and sustainable urban planning.

Keywords: Indoor Air Quality (IAQ); Volatile Organic Compounds (VOCs); Climate change; Sick Building Syndrome (SBS); Indoor environmental health; Secondary Organic Aerosols (SOAs); HVAC systems; Public health policy

Table of Abbreviations: VOCs: Volatile Organic Compounds; IAQ: Indoor Air Quality; SBS: Sick Building Syndrome; BRI: Building-Related Illness; HVAC: Heating, Ventilation and Air Conditioning; SOAs: Secondary Organic Aerosols; EPFRs: Environmentally Persistent Free Radicals; PM: Particulate Matter

Introduction

Volatile Organic Compounds (VOCs) are a diverse group of carbon-based substances that readily evaporate at room temperature and are emitted from numerous indoor sources such as building materials, cleaning agents, paints, furnishings and human activities. Although VOCs are widely studied in relation to indoor air pollution and public health, their broader environmental significance, particularly their role in atmospheric chemistry and climate dynamics, remains underrepresented in both scientific and policy frameworks. Once released indoors, VOCs not only affect human health through their contribution to Sick Building Syndrome (SBS) and other chronic exposures, but also escape into the ambient atmosphere, where they undergo photochemical reactions that form ground-level ozone and Secondary Organic Aerosols (SOAs). These products exacerbate urban smog, contribute to climate forcing and challenge efforts to mitigate air pollution. Despite this dual impact, VOCs are frequently marginalized in climate and economic models, often due to insufficient data integration, regulatory ambiguity and the complexity of chemical behavior across environments. This review critically examines the intersection of VOC emissions, indoor air quality, atmospheric chemistry and economic valuation.

Drawing on recent interdisciplinary literature, it evaluates how existing climate and economic models conceptualize VOCs and identifies key limitations in current policy approaches. The paper argues that a more robust representation of VOCs is essential to accurately quantify their environmental burden and inform public health strategies, sustainable building design and climate policy. By synthesizing scientific findings with policy and modeling perspectives, this review highlights the urgent need for integrated frameworks that reflect the true cost and consequences of VOC emissions.

Methodology

This literature review was conducted using the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) 2020 framework to ensure a systematic, transparent and reproducible approach to study selection and analysis. The aim was to synthesize contemporary research on the role of Volatile Organic Compounds (VOCs) in both Indoor Air Quality (IAQ) and broader climate systems, with particular attention to how these compounds are integrated into climate and economic modeling frameworks. A systematic search was performed across four major academic databases, Scopus, Web of Science, PubMed and Google Scholar, to capture a comprehensive range of peer-reviewed studies and institutional reports. The search was limited to articles published between 2018 and 2024 to ensure that the findings reflected recent developments in VOC research. Keywords and Boolean operators were strategically applied to include combinations such as “Volatile Organic Compounds” OR “VOCs,” “Indoor Air Quality” OR “IAQ,” “Climate Modeling” OR “Economic Modeling,” “Secondary Organic Aerosols” OR “SOAs,” and “Ozone Formation” OR “Photochemical Smog.” MeSH terms were incorporated in the PubMed search to enhance specificity.

Search strategy

A total of 111 articles were identified through database searches. After removing 20 duplicates or non-comprehensive sources, 91 articles were screened by title and abstract. Of these, 80 full-text articles were assessed for eligibility and 51 were ultimately included in the final synthesis, as illustrated in the PRISMA flow diagram (Figure 1).

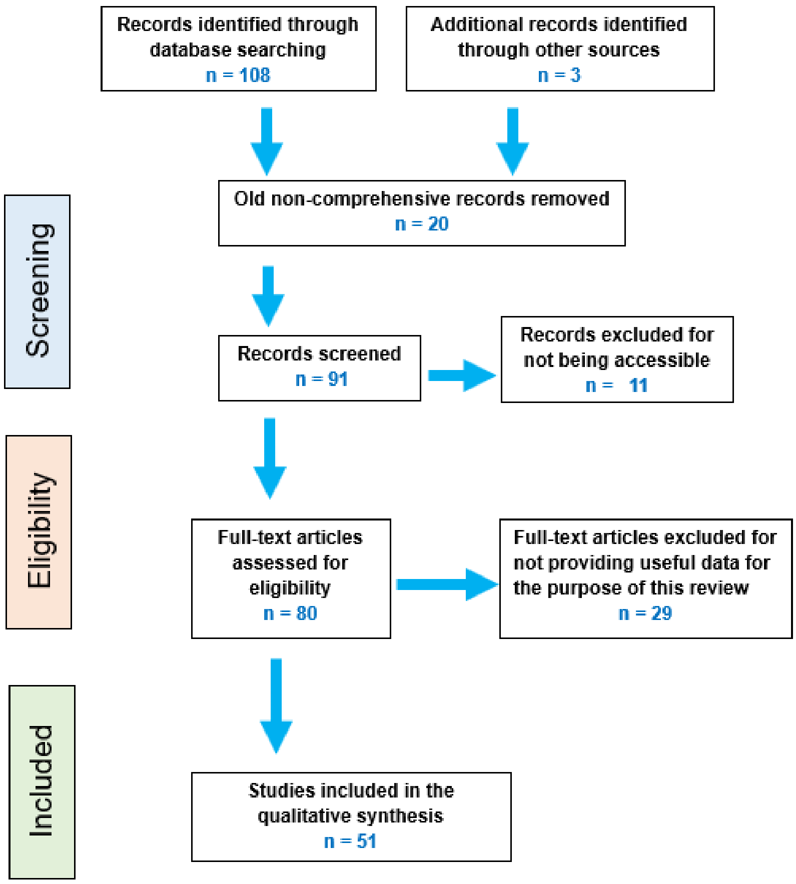

Figure 1: PRISMA of the literature selection process.

Inclusion and exclusion criteria

Data were extracted using a standardized template, capturing key information on VOC sources, categorization (e.g., building materials, human activities), environmental and health impacts and modeling integration. Attention was also given to reported gaps and limitations within each study. A narrative synthesis approach was employed to compare thematic patterns and assess both consistencies and contradictions across findings. Quantitative results such as emission levels, health burden estimates and economic projections were cross-referenced when applicable. To ensure the credibility and rigor of the included studies, methodological quality was appraised using the NIH quality assessment tool for observational studies and an adapted version of the good modeling practice guidelines for modeling research. Studies were classified as high, moderate or low quality based on clarity, reproducibility and relevance to the central research questions. This methodologically structured approach allowed for a comprehensive and critically reflective synthesis of the literature, directly supporting the interdisciplinary scope of this review. Database searches were conducted via Scopus, Web of Science and PubMed, with Google Scholar used for literature.

IAQ Effects

Efforts to improve residential energy efficiency through better insulation and airtight construction have unintentionally led to higher indoor levels of pollutants like VOCs and formaldehyde, commonly released from building materials and household items. Though these substances are linked to symptoms such as fatigue and respiratory issues, their direct connection to sick building syndrome remains unclear due to vague definitions and a lack of clear exposure limits. Many studies also ignore how factors like heat and humidity, especially in hot regions like Qatar, can increase emissions or how poor ventilation may trap and spread these pollutants. Despite acknowledging the influence of both indoor and outdoor sources, most air quality models lack dynamic, real-time integration of these variables. This highlights the need for cross-disciplinary strategies that unite environmental design, health research and material science to ensure both energy efficiency and human well-being [1]. Current energy-saving designs often overlook their unintended impact on indoor air quality. Without accounting for local climates or ventilation effectiveness, such designs risk compromising occupant health. To truly create sustainable buildings, energy efficiency must be balanced with smarter, health-centered design supported by interdisciplinary research and responsive modeling.

Driven by urban growth, climate concerns and housing demands, sustainable construction methods like modular and prefabricated buildings are gaining popularity for their speed, cost-effectiveness and reduced environmental impact. Policies in regions like the EU and China support low-carbon materials such as timber. However, this shift often overlooks indoor air quality issues. Prefabricated wood-based materials can emit toxic VOCs like benzene, toluene and formaldehyde, linked to health risks including asthma, cancer and sick building syndrome. Heat can worsen emissions and exposure may occur not just through inhalation but also via skin and eyes. Yet, most green building standards focus on emissions and energy use, neglecting the health effects of indoor pollutants [2]. While green construction rightly emphasizes carbon reduction [3,4], it risks ignoring the health consequences of indoor pollutants from prefabricated materials. Without integrating indoor air quality into sustainability metrics, these designs may trade one environmental issue for another, prioritizing energy over people. A more holistic approach is urgently needed to align climate goals with occupant health.

A simple and robust method for the comprehensive analysis of VOCs in liquid household products

Fragranced products like air fresheners, soaps and cosmetics are major indoor sources of VOCs, yet they often contain undisclosed ingredients and lack strict regulation. Unlike food or pharmaceutical industries, fragrance manufacturers are rarely required to list their chemical components, though some regions like California have begun to implement VOC limits. This lack of transparency not only leaves consumers uninformed but also hinders scientific research on health and environmental impacts. Some fragrance compounds can even trigger indoor ozone formation, but proprietary formulas make analysis difficult. This secrecy poses health risks, especially for sensitive individuals such as those with asthma, a concern largely ignored in existing research. To address this, both stronger policies and advanced testing methods are needed to evaluate emissions from these complex chemical mixtures [5]. VOCs, including benzene-based and halogenated compounds, are among the most dangerous indoor air pollutants due to their toxic and cancer-causing effects. Indoors, their levels often exceed outdoor concentrations fivefold, posing serious health risks. Although links to respiratory and neurological diseases are well documented, research remains incomplete, especially regarding hidden sources like scented products, electronics and chemical reactions on indoor surfaces.

Current detection tools lack the sensitivity to capture short-term, low-level emissions and inconsistent VOC classifications hinder regulatory efforts. This points to the urgent need for real-time, precise monitoring systems and standardized guidelines to better assess and manage health risks [6]. Monoterpenes, common in scented products due to their strong aromas, are among the most volatile indoor pollutants and often reach high concentrations during product use. Studies using EEG link compounds like limonene and terpinolene to mood-enhancing effects, such as relaxation and pleasure. Their volatility also makes them easier to detect using methods like TD-GC-MS, unlike less volatile fragrance compounds like terpene oxides or sesquiterpenes. However, other monoterpenoids, despite being classified as volatile, have low vapor pressures that hinder measurement. As a result, monoterpenes are often used as stand-ins for overall fragrance exposure, even though they may come from unrelated sources. This approach overlooks many low-concentration yet perceptually significant compounds, leading to an incomplete and potentially misleading picture of indoor fragrance-related VOC exposure [7].

Indoor air pollution and exposure in GCC countries

Indoor air pollution is a major health concern in GCC countries due to harsh weather, industrialization and cultural practices like incense burning and waterpipe smoking. With people spending over 90% of their time indoors, exposure to pollutants such as VOCs, PM2.5, PM10, radon and bioaerosols is alarmingly high. Key sources include poor ventilation, use of chemical-heavy cleaning agents and infiltration of outdoor dust and emissions. Studies in the UAE, KSA and Qatar report pollutant levels often exceeding WHO limits, especially in homes, schools and hospitals. The health risks linked to these exposures include respiratory diseases, cardiovascular issues and cancer. To reduce exposure, the article highlights the need for better ventilation systems, stricter IAQ guidelines, awareness programs and sustainable building materials. Importantly, region-specific air quality standards and consistent monitoring are necessary to address the unique environmental and cultural factors influencing indoor pollution in the GCC [8].

VOC Concentration in Buildings

People spend most of their time inside, making indoor air quality a vital factor in public health. Decorative materials such as paints, coatings, flooring and furniture are key sources of indoor VOC emissions. Long-term exposure to high indoor VOC concentrations has been associated with various health issues, including dizziness, sneezing, skin and respiratory irritation and an increased risk of cancer. Although significant advancements have been made in identifying VOC emissions from individual building materials, there is still a considerable gap in understanding the complex interactions among multiple emission origins. The variety of decorative materials and the variability in emission profiles make it difficult to accurately model indoor air chemistry. Specifically, there is limited knowledge regarding the mechanisms of mutual inhibition or promotion among pollutants from different sources. Understanding these interactions is crucial for devising targeted strategies to prevent and mitigate indoor pollution. Previous studies have laid the groundwork by analyzing emission rates, chemical compositions and environmental influences in controlled single-source conditions. However, the shift from single-to multisource emission models has revealed methodological challenges and data inconsistencies [9-13] (Figure 2).

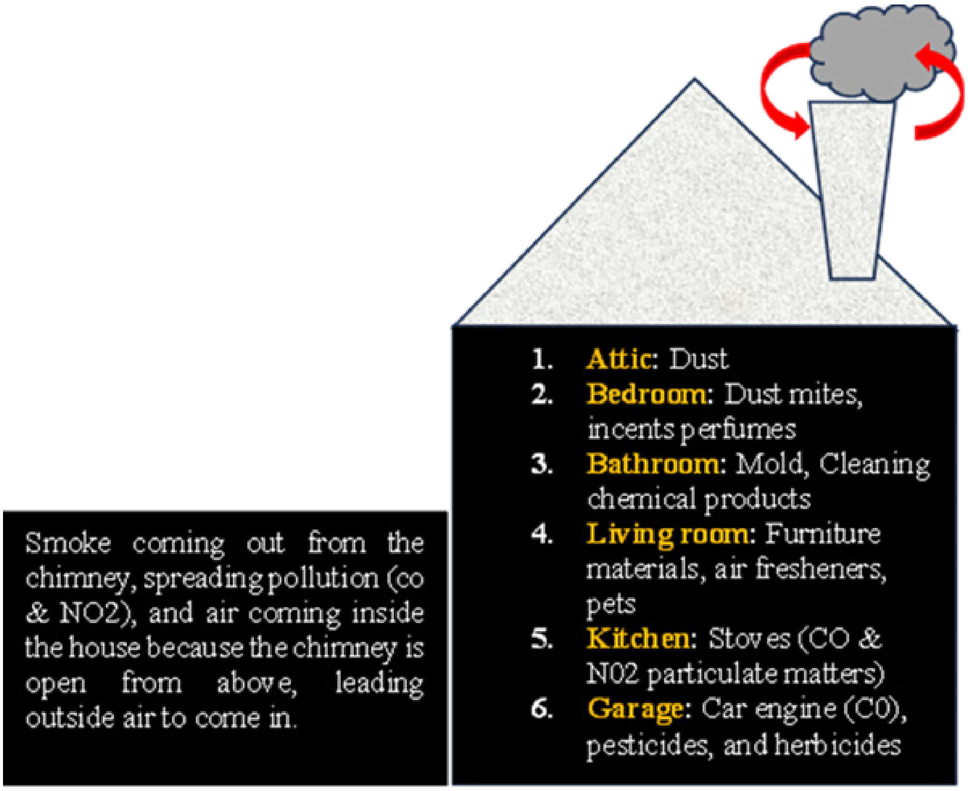

Figure 2: VOC concentration in indoor building quality.

Recent studies have attempted to improve the accuracy of VOC emission models by using multiple sources and mathematical principles like superposition. While some methods showed potential, they often failed to fully capture the complex, non-linear interactions among different materials, especially when materials differ in texture, surface area or reactivity. More advanced mass transfer models have improved accuracy, but they often rely on simplified assumptions, such as treating all materials and pollutants as uniform, limiting their use in real-world indoor spaces. A major oversight remains the adsorption and delayed release (desorption) of VOCs, particularly from porous items like fabrics and leather. These materials can both absorb and later release pollutants, making indoor VOC levels harder to predict. Secondary emissions from such surfaces may increase human exposure over time, especially when combined with new sources. Current models don't fully account for these dynamics, due in part to difficulties in real-time monitoring and the lack of standardized indoor testing environments. Additionally, varying environmental factors like humidity and temperature complicate predictions, and the absence of detailed emission databases for building materials restricts regulation and policy efforts. This calls for a more integrated approach combining science, technology, and public health [14-19].

While modeling VOC behavior has advanced, it still lags behind the complex reality of indoor environments. Over-simplified assumptions and missing data on material-specific emissions weaken predictive power. Without standardized methods and interdisciplinary collaboration, policies remain reactive rather than preventive, leaving occupants vulnerable to prolonged VOC exposure.

University campuses air quality

University campuses, home to large student populations, are key areas for assessing indoor air quality, yet research on VOC exposure in such spaces is still limited. Rising enrollment, especially in China, increases the urgency of understanding related health risks. Studies have revealed VOC concentrations in libraries and dormitories that exceed national and international safety limits, indicating significant exposure risks. To explore this further, a recent study collected air samples from various campus locations-including classrooms, dormitories, canteens and libraries-over several months using standard canister methods at breathing height. Despite smaller sample sizes in some areas, the findings emphasize the urgent need for improved air quality monitoring and management in educational settings [20].

Household dust as a source of phthalate exposure in Qatar's indoor environments

Phthalates, extensively utilized as plasticizers in various products such as Polyvinyl Chloride (PVC) flooring, electronic devices and personal care products, are classified as Semi-Volatile Organic Compounds (SVOCs) that readily migrate into indoor air and particulate matter. They are associated with significant health concerns, including the disruption of endocrine function and respiratory problems, with potential routes of entry into the human body being inhalation, dermal absorption or ingestion. Research indicates that indoor spaces typically exhibit elevated phthalate concentrations compared to outdoor air, particularly in regions with hot climates, such as Qatar, where individuals predominantly spend their time indoors. This investigation provides the inaugural data on phthalate concentrations in dust samples collected from domestic, healthcare and laboratory environments in Qatar. Particle assessments from 11 residences, 3 laboratories and 1 medical facility in Qatar (2014-2015) were scrutinized for phthalate content. DEHP emerged as the predominant compound in residential settings, with concentrations varying from 14 to 4059µg/g (median: 395µg/g). In the medical facility, DINP was predominant (94%), while DEHP and DIDP were comparatively insignificant. Laboratories exhibited a different predominance: DEHP was dominant in laboratory 1 (82%), whereas DINP was preeminent in laboratory 2 (71%). Denser phthalates such as DEHP displayed a tendency to amass in particles, whereas lighter counterparts like DMP and DEP manifested due to adsorption. The outcomes are consistent with regional data and substantiate the pervasive indoor existence of DEHP and DINP [21].

The cause of IAQ by humans

Indoor Air Quality (IAQ) is shaped not only by materials and pollutants within buildings but also significantly by the biological presence and behaviors of people [22,23]. As humans spend over 90% of their time indoors, studies have shown that common activities like cooking, cleaning and even breathing and sweating introduce a range of Volatile Organic Compounds (VOCs) and particulates into the air. The HOMEChem project, one of the largest indoor air chemistry studies, demonstrated that cooking can briefly elevate PM2.5 levels beyond those found in the most polluted cities, while cleaning with bleach can produce harmful chlorine-based gases. These findings underline how everyday routines generate complex chemical transformations in indoor environments, often at concentrations far greater than outdoor levels. Beyond activities, the human body itself is a significant source of indoor pollution. Emissions from skin and breath, such as ammonia, isoprene and VOCs from personal care products, contribute substantially to indoor air composition. Controlled chamber studies (like ICHEAR) have shown that human presence alters air chemistry by increasing particle formation and influencing surface reactions. For instance, human-emitted ammonia can neutralize surface acidity caused by CO_2, altering how toxins like smoking residues behave.

These results challenge traditional assumptions about surface chemistry indoors and highlight how even small changes in room temperature or skin exposure can drastically affect emissions. This research is particularly important in the context of zero-energy buildings, which minimize ventilation to conserve energy, potentially trapping pollutants emitted by occupants. As recirculated air becomes the norm in both residential and commercial settings, understanding human contributions to IAQ becomes critical for public health. Future regulations may need to consider not only building materials and outdoor air exchange but also biological emissions from occupants. This body of evidence suggests that policy changes such as ventilation standards, consumer product labeling and interior design using pollutant-absorbing materials are essential to ensure healthy indoor environments [24].

The impact of cooking on IAQ, VOC and PM

There are various cooking methods, oil types and temperatures that significantly affect indoor air pollution, particularly levels of Particulate Matter (PM) and Volatile Organic Compounds (VOCs). Controlled experiments in a sealed kitchen showed that oil-based cooking emits more pollutants than water-based methods, with air fryers producing the least PM. Higher temperatures generally increased pollutant levels, while more oil sometimes reduced PM but increased VOCs. Harmful VOCs detected included aldehydes, ketones and aromatic compounds. Additionally, Environmentally

Persistent Free Radicals (EPFRs), linked to oxidative stress, were found to form during cooking. These findings underscore the health risks of common cooking practices and the need for better ventilation and cleaner cooking alternatives. There are specific cooking conditions that influence indoor air pollution, particularly the emission of Particulate Matter (PM) and Volatile Organic Compounds (VOCs). By controlling variables such as ingredient weight and ventilation, researchers focused on how cooking method, oil quantity and initial temperature shape emissions. The results confirmed that oil-based cooking, due to the Maillard reaction, produces significantly more PM and VOCs than water-based methods. Notably, air fryers released the lowest PM levels, while higher cooking temperatures generally increased pollutant concentrations. Interestingly, larger oil volumes reduced PM levels but increased VOC concentrations.

The VOCs released during frying were classified into several chemical groups, including aldehydes, ketones, furans, aromatic hydrocarbons, alkenes, pyrazines and alkanes. These chemical compounds highlight the complex and potentially hazardous nature of emissions during common cooking practices. PM emission rates and personal exposure assessments enabled a comparative analysis of health risks associated with each method, providing insight into which practices pose greater respiratory or toxicological threats in indoor settings. In addition to PM and VOC measurements, the study assessed Environmentally Persistent Free Radicals (EPFRs), pollutants known for their long-term health risks. EPFR levels were directly linked to cooking activity and heat exposure, though ozone did not significantly alter their concentration. These findings reinforce the need for greater awareness of how everyday cooking behaviors can affect indoor air quality and support calls for ventilation improvements and healthier cooking technologies [25].

VOC emissions in the paint industry

The paint industry significantly contributes to Volatile Organic Compound (VOC) emissions, presenting considerable challenges for both environmental health and human well-being. This systematic review synthesizes findings from 51 studies to evaluate effective emission reduction strategies. Three main approaches emerge from literature: Embracing green chemistry principles, implementing cleaner production techniques and adhering to stringent environmental regulations. Green chemistry approaches prioritize the replacement of traditional fossil-based and toxic materials with bio-based resins, environmentally benign solvents and renewable feedstocks. Notably, polyurethane and alkyd resins receive considerable attention due to their adaptability within low-VOC coating formulations, reflecting a research consensus on their potential to balance performance with sustainability. However, variations in resin effectiveness and availability highlight ongoing challenges in material innovation. Cleaner production methods aim to minimize VOC emissions throughout manufacturing and application stages by adopting technologies such as waterborne, powder and high-solids coatings.

These alternatives reduce solvent evaporation during drying, leading to substantial emission cuts. Life Cycle Assessments (LCA) within several studies further indicate that these sustainable formulations offer ancillary benefits, including enhanced energy efficiency and lowered costs, suggesting a holistic advantage beyond emission reductions. Case studies in the automotive and furniture sectors, employing hybrid coating systems, underscore practical feasibility but also reveal industry-specific constraints that may limit broader adoption. Regulatory frameworks, particularly in North America and Europe, exert significant pressure on manufacturers to transition toward VOC-free or low-VOC paints. Nevertheless, evidence indicates that some “zero VOC” labeled products still release harmful compounds, pointing to gaps in regulatory definitions and enforcement. This discrepancy suggests that compliance alone is insufficient without concurrent innovation in raw material selection and process improvements. The literature converges on the necessity of integrating material innovation, cleaner manufacturing practices and robust regulatory oversight to achieve meaningful reductions in VOC emissions. The interplay of these factors reflects a complex landscape where technical, economic and policy dimensions must be aligned to improve both indoor and outdoor air quality sustainably [26].

Health Impacts

Building-associated illness

In recent decades, an increasing accumulation of research has associated a diverse array of symptoms and ailments with substandard indoor air quality in both residential and commercial structures. Even though exposures to inorganic, organic, physical and biological pollutants indoors often occur at minimal concentrations, they are widespread, persistent and impact vast populations, particularly within urban settings. The ongoing nature of these exposures has rendered the health consequences of indoor air pollution a topic of continuous concern for public health and regulatory bodies. The World Health Organization categorizes illnesses related to building environments into two main groups: Sick Building Syndrome (SBS) and Building-Related Illness (BRI). SBS encompasses a range of nonspecific symptoms, like headaches, fatigue, eye irritation and respiratory issues, which generally improve upon leaving the building and cannot be tied to a specific disease. Conversely, BRI includes clearly diagnosable diseases caused by identifiable indoor environmental agents, such as Legionnaires’ disease or hypersensitivity pneumonitis. While this dichotomy has served as a foundational model, it has also been criticized for oversimplifying the complex interactions between exposure and response, failing to consider multi-factorial and synergistic interactions among pollutants.

For example, this classification does not sufficiently address emerging conditions linked to prolonged exposure to low concentrations of Volatile Organic Compounds (VOCs), Semi-Volatile Organic Compounds (SVOCs) or microbial agents that might not cause acute illness but contribute to ongoing inflammation, neurotoxic effects or endocrine disturbances. This terminological and conceptual inadequacy suggests a need to revisit and expand current classification systems to more accurately represent contemporary understandings of indoor environmental health. Furthermore, uncertainties in diagnostic criteria, especially for SBS, complicate epidemiological monitoring and policy interventions. Many individuals experiencing persistent symptoms go without formal diagnoses, their conditions neglected by current occupational and housing regulations. From a policy standpoint, these shortcomings emphasize the need for more comprehensive health surveillance systems, integrated building inspections and environmental assessment protocols. From a research perspective, the challenge involves bridging the gap between medical symptomatology and environmental exposure science, necessitating interdisciplinary cooperation across public health, building engineering, environmental chemistry and clinical medicine [11].

The SBS/BRI framework is outdated and fails to capture the subtle, chronic health effects of modern indoor pollutants. Without updated classifications and diagnostic tools, many individuals fall through regulatory and medical cracks. A shift toward a more nuanced, systems-based approach is essential for advancing both policy and health equity in indoor environments.

Impact of poor IAQ on human health

Suboptimal indoor air quality detrimentally influences the inhabitants of structures by compromising their physical health, well-being and efficiency. The health consequences are contingent upon the concentration of pollutants, the duration of exposure and individual characteristics such as age and susceptibility. Linked health issues encompass respiratory ailments, unfavorable birth outcomes, neurological impairments and numerous forms of cancer. The utilization of kerosene and charcoal contributes to toxic exposure, thermal injuries and substantial domestic air contamination, culminating in an estimated 3.2 million premature mortalities annually [27]. Despite its clear link to mortality and chronic illness, indoor air pollution remains severely underprioritized in global health policy. The reliance on harmful fuels in many households underscores a failure in energy equity, making clean indoor air a matter of both public health and social justice (Figure 3).

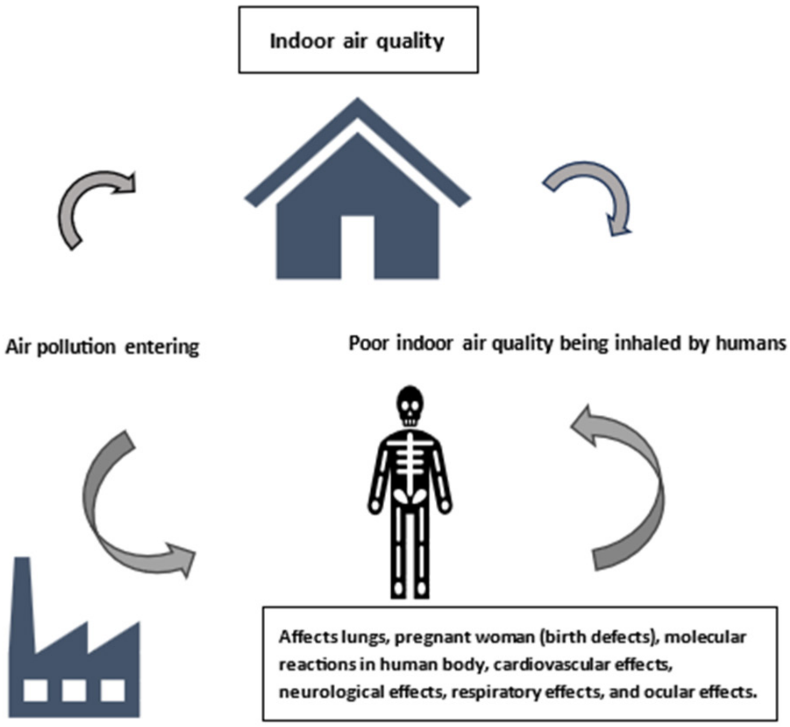

Figure 3: VOC air quality effect on humans, based on data from [26].

Acute respiratory infection

Sick Building Syndrome (SBS) pertains to a collection of symptoms associated with specific indoor environments, primarily impacting the respiratory system due to exposure to Indoor Air Pollutants (IAP). Acute respiratory infections are prevalent, with Upper Respiratory Tract Infections (URIs) being mild and Lower Respiratory Tract Infections (ALRIs) more severe, particularly in children. Exposure to IAP elevates the risk of childhood ALRI by 78%, notably in households utilizing solid fuels. It also weakens respiratory defenses and contributes to the onset of chronic bronchitis in women who cook. Susceptible populations, including infants, the elderly and individuals with chronic health conditions, are at increased risk. Factors contributing to SBS include inadequate ventilation, building dampness, elevated indoor temperatures, gender, atopy and psychosocial stressors [11]. SBS is often treated as a building maintenance issue rather than a public health concern, minimizing its seriousness. This narrow view obscures how deeply indoor air quality intersects with gender inequality, child welfare and environmental justice, especially in low-income or fuel-reliant households.

VOC sensor technologies for indoor health risk reduction

One of the most promising strategies to reduce indoor air pollution and VOC exposure is the implementation of real-time VOC sensor technologies for early detection and health monitoring. These sensors, particularly those based on chemiresistive, optical and electrochemical principles, enable continuous and noninvasive assessment of air quality in indoor environments by detecting harmful VOC concentrations from breath, sweat and other biofluids. When integrated with wearable or IoT-connected devices, they allow personalized exposure tracking and can trigger timely interventions such as ventilation control or air purifier activation. Advances in nanomaterials, such as metal oxides and carbon-based composites, have significantly improved the sensitivity, selectivity and stability of these sensors, making them suitable for detecting VOCs and other gaseous pollutants at sub-ppm levels [28-31]. By offering rapid, portable and affordable diagnostics, these smart VOC sensors empower individuals to manage their indoor environment proactively, thus reducing health risks associated with prolonged VOC exposure [32].

Practical strategies to protect workers from VOC exposure

To reduce the health risks posed by VOC emissions during asphalt pavement construction, several key strategies can be implemented. Lowering the asphalt temperature, especially by using Warm Mix Asphalt (WMA), can significantly cut down VOC release. Minimizing disturbances during paving such as mixing and dumping asphalt helps limit fume generation. Water spraying, if applied carefully, can suppress VOC fumes, while redirecting fume flow using blowers or aligning paving direction with the wind can reduce worker exposure. Personal protective equipment like masks, gloves and long clothing are crucial, as VOCs can harm through both inhalation and skin contact. Additionally, rotating job roles and encouraging upright working postures may prevent long-term exposure to high VOC concentrations. These targeted interventions, combined with better worker training and policy enforcement, form a practical framework to protect construction workers from serious health effects linked to VOCs [33].

Green materials for health risk reduction in buildings

Reducing health risks in buildings begins with replacing Conventional Building Materials (CBMs), which are major sources of indoor Volatile Organic Compounds (VOCs), With Green Building Materials (GBMs). CBMs often emit hazardous chemicals like benzene, toluene and formaldehyde, which can cause respiratory irritation, neurological damage and even cancer with long-term exposure. In contrast, GBMs made from non-toxic, natural and biodegradable materials like biopolymers and natural fibers release fewer pollutants and improve Indoor Air Quality (IAQ). Life cycle assessments using tools like SimaPro have shown that biocomposites not only reduce VOC emissions but also significantly lower the overall human health impact when compared to petroleum-based materials. These green alternatives are especially effective because they require less energy, generate fewer emissions across their lifecycle and meet IAQ standards, making them safer for both the environment and human health [34]. While GBMs offer clear benefits, adoption remains slow due to cost, limited awareness and resistance from the construction industry. Without stronger policy incentives or public demand, healthier materials may remain niche rather than standard.

Air Purification Technologies for IAQ Improvement

Improving indoor air quality generally encompasses three principal approaches: Regulating source emissions, increasing ventilation and advancing air purification technologies. Recent investigations have concentrated on creating novel filtration techniques, with carbon-based filter media emerging as efficacious solutions for eliminating gaseous contaminants. Various HVAC systems deployed in residences, educational facilities, office spaces and commercial establishments have demonstrated their ability to filter ozone, aerosols, volatile organic compounds and particulate matter. These systems exist in forms such as flat sheet filters, carbon-laden cartridges and bag filters. Nevertheless, a significant limitation persists: Their adsorption efficiency markedly diminishes at pollutant concentrations below 1 part per million, curtailing their efficacy in environments with low exposure [11].

The influence of 10% indoor plant coverage on the diminishment of VOC concentrations

In the past few years, there has been increasing focus on the significance of indoor plants in enhancing Indoor Air Quality (IAQ), specifically through the mitigation of Volatile Organic Compounds (VOCs) like formaldehyde (CH_2O). Building upon NASA's early trials in the 1980s that investigated plant-based air cleaning for space habitats, current research has explored how the volume and type of plants influence VOC reduction in standard indoor settings. The adequate light an important factor affecting plant metabolic processes and VOC absorption [35,36] all plant pots were situated near windows. The study utilized three plant species: *Aglaonema commutatum*, *Pachira aquatica* and *Ficus benjamina*, chosen for their previously demonstrated efficacy in air purification studies [35-37]. *Aglaonema*, with its broad leaves, required fewer pots, while Pachira and *Ficus* featured taller, denser foliage due to their more numerous leaves. To standardize the experiment, the number of pots for each species was adjusted to ensure equal total plant volume [38]. The findings revealed that covering 10% of the room volume with specific indoor plants substantially decreased VOC concentrations, with variations noted based on species and leaf configuration. Plants with broad leaves showed swift pollutant absorption, whereas those with many smaller leaves provided prolonged filtration over time.

Exposure to sunlight further amplified these effects by enhancing plant transpiration and photosynthetic processes. This research substantiates the application of careful plant selection and strategic positioning to improve indoor air quality. It affirms that even relatively modest amounts of greenery when appropriately selected and placed can deliver concrete advantages in reducing pollutants within confined areas.

Living walls and phytoremediation for indoor VOC mitigation

Indoor air frequently harbors hazardous Volatile Organic Compounds (VOCs), with formaldehyde being particularly prevalent due to its emission from materials like composite wood. n-Hexane, another VOC, is less explored but can adversely impact the central nervous system. Phytoremediation, which involves utilizing plants to eliminate air contaminants, serves as an energy-efficient alternative to mechanical purification systems. Its efficiency hinges on variables such as plant species, light, temperature, VOC type and whether the configuration is passive (e.g., potted plants) or active (e.g., filter-based systems). Of these variables, the choice of plant species is significant in determining the effectiveness of VOC removal. In scenarios where space is constrained, living walls present a compact and efficient solution. These vertical plant arrangements can notably diminish VOC concentrations while concurrently enhancing indoor aesthetics and providing psychological advantages. In a particular study, a chamber equipped with a small felt-based living wall demonstrated accelerated VOC reduction (including formaldehyde and n-hexane) compared to an empty chamber. Thus, living walls constitute a practical and aesthetically pleasing approach to augmenting indoor air quality through nature-based technologies [39].

Graphene nanomaterials for VOC removal

Graphene-based nanostructures exhibit remarkable potential for the elimination of chlorinated Volatile Organic Compounds (VOCs), such as methylene chloride and carbon tetrachloride. Notably, when graphene oxide is integrated with Metal-Organic Frameworks (MOFs) like MIL-101(Cr), it demonstrates a noteworthy carbon tetrachloride adsorption capacity of 2368mg/g. This superior efficiency is credited to the composite's extensive surface area, enhanced dispersion interactions and the formation of defects and novel pores, which collectively augment adsorption performance. Although experimental analyses indicate promising outcomes, practical applications frequently experience diminished efficacy due to decreased pollutant concentrations and environmental variability. To overcome these obstacles, it is essential to reduce experimental bias and authenticate the materials under genuine indoor conditions. Despite these impediments, graphene nanostructures continue to represent a promising area in the advancement of VOC remediation technologies [40].

Hybrid oxidation-biological systems for VOC control

To effectively reduce indoor air pollution caused by Volatile Organic Compounds (VOCs), integrating Advanced Oxidation Processes (AOPs) with biological treatment systems presents a promising solution. AOPs, including photocatalysis, catalytic ozonation and non-thermal plasma, are highly effective at breaking down complex and recalcitrant VOCs into more biodegradable intermediates. However, their high energy demands and potential for secondary by-product formation pose limitations when used alone. To overcome these drawbacks, coupling AOPs with biological methods, such as biofiltration or biotrickling filters leverages the strengths of both approaches. AOPs serve as a pre-treatment stage, transforming toxic VOCs into simpler compounds that are more easily mineralized by microorganisms in bioreactors. This hybrid strategy not only enhances VOC removal efficiency but also minimizes harmful residues, reduces operational costs and supports environmentally sustainable air purification. By addressing the limitations of standalone technologies, this integrated method offers a comprehensive and adaptable framework for improving indoor air quality in residential and industrial settings [41].

Characterization of wood odors, their impact on indoor air quality and their removal

Wood is often considered a natural and pleasant material, commonly used indoors for furniture and decoration. However, wood can release Volatile Organic Compounds (VOCs) that affect indoor air quality. These VOCs sometimes carry unpleasant odors, which are more than just annoying smells. They can cause discomfort, stress and even health problems for sensitive people. A study examined the odors coming from two types of wood: Rubberwood (RW) and Cathy Poplar (CP). Scientists used advanced techniques called Gas Chromatography-Mass Spectrometry (GC-MS) and gas Chromatography-Olfactometry (GC-O) to identify the specific odor-causing compounds in these woods. They found about 40 different odorants, mostly unpleasant smells caused by chemicals like carboxylic acids, aldehydes and aromatic compounds. To try to reduce these odors, the researchers treated the wood with an ethanol-benzene extraction process. This method lowered the number and strength of many odorants. However, some stubborn smells, such as sour, stinky and burnt notes, still remained. These persistent odors likely come from chemical changes in the wood caused by heat and oxidation, which are harder to remove.

Interestingly, the study found that not all VOCs detected by chemical analysis actually produce odors. This means that simply measuring the number of VOCs in the air is not enough to understand how wood affects indoor air quality. Using both chemical and sensory (smell) methods together gives a more accurate picture. The study concludes that more research is needed to understand how temperature changes affect odor release from wood and to develop better ways to control these odors indoors. This is especially important as wood products become more popular in homes and buildings [42].

Economic Impact of VOC's

The impact of IAQ economic considerations on health

The health impact of air pollution has a significant economic impact [43]. Asthma imposes the most substantial costs, with yearly expenses for treatment and management amounting to billions of dollars. Considerable economic repercussions are also linked to Chronic Obstructive Pulmonary Disease (COPD) and cardiovascular conditions. Although chronic allergies and headaches contribute to a lesser extent, they still constitute a significant segment of the overall fiscal strain [44]. The multifaceted nature of Indoor Air Quality (IAQ) challenges, encompassing biological, physical and economic aspects, highlights the necessity for comprehensive management approaches. Sophisticated ventilation systems with features for energy efficiency and air purification present viable solutions. Collaborative efforts among biologists, physicists and economists are crucial for creating IAQ strategies that harmonize public health advantages with economic viability. Future scholarly endeavors should concentrate on ventilation technologies that not only improve air circulation but also effectively remove indoor contaminants. Policymakers are encouraged to advocate for investments in IAQ advancements by emphasizing their enduring health and economic advantages. Interdisciplinary innovation remains vital for developing sustainable, scientifically-founded IAQ policies and technologies [44].

Economic impact of waste-to-energy technologies in IAQ

Transforming municipal solid waste into energy presents both ecological and financial opportunities [45]. A study evaluating three conversion technologies, incineration, gasification and plasma gasification, based on Portuguese waste data, found incineration to be the most cost-effective. With operational expenses around €0.12 per kilowatt and revenue near €1.68 per kilowatt, incineration emerges as a mature and economically beneficial approach. However, if not adequately managed, it can release substantial amounts of Volatile Organic Compounds (VOCs) and harmful gases, posing risks to air quality. In contrast, gasification and plasma gasification offer environmental advantages due to potentially lower pollutant emissions, but they face economic challenges: Plasma's costs reach €0.54 per kilowatt and gasification's about €1.25, both exceeding Portugal's grid price of €0.15 per kilowatt. Unless subsidized or significantly optimized, these cleaner methods remain less financially competitive. Technological innovations could eventually bridge this gap, aligning environmental performance with economic viability [46]. While incineration is currently the most economically attractive waste-to-energy method, its environmental drawbacks underscore the need to invest in cleaner alternatives. With further innovation, utilization of renewable energy [47-49], gasification and plasma gasification could become both cost-effective and less polluting, making them preferable long-term solutions for sustainable energy and air quality management.

The economics of Indoor Air Quality (IAQ)

Smart ventilation optimizes ventilation by adjusting airflow based on time or location to meet air quality goals while minimizing energy use and discomfort. According to the air infiltration and ventilation center, it adapts ventilation to factors like occupancy, outdoor conditions, electricity demand, pollutant detection and other air systems. These systems also provide feedback on energy use and air quality, alerting when maintenance is needed. By responding to occupancy and environmental changes, Smart Ventilation can reduce airflow during low demand, shift ventilation to favorable times and improve overall efficiency and comfort [50]. While smart ventilation promises energy savings and better air quality by adapting to real-time conditions, its effectiveness depends on accurate sensing and user engagement. Without reliable data and proper maintenance, such systems may underperform or compromise indoor health.

IAQ EU home, economic analysis

According to 2011 EU-SILC data, 0.3% of the EU population about 1.5 million people lived in "deprived" housing, facing issues like dampness, poor lighting and lack of basic sanitation. This figure rose to 1.3% in Eastern Europe. More broadly, 0.9% across the EU and 3.7% in the newer member states lived with three of these four issues. Additionally, 5.5% of the EU population experienced severe housing deprivation, combining overcrowding with at least one major housing flaw. In countries like Latvia and Romania, rates were particularly high, reaching 17.9% and 25.9% respectively. Poverty remains a key factor in housing deprivation across the EU [51]. These expose a troubling inequality in housing standards within the EU, especially in Eastern and newer member states. Despite being part of a wealthy union, millions still lack basic living conditions. The strong link between poverty and housing deprivation highlights the failure of policy to ensure decent housing as a universal right, underscoring the need for targeted investment in social housing and infrastructure.

Discussion

Recent studies have yielded valuable insights into the intersection between climate change and Indoor Air Quality (IAQ). However, accurately predicting the compounded and occasionally contradictory impacts of climate change on indoor pollutant levels poses a significant challenge. Modeling is emerging as an indispensable instrument for tackling this complexity, as evidenced by research that integrates IAQ simulations with thermal exchange and airflow models. Yet, despite these advancements, numerous sophisticated IAQ models, especially those that incorporate intricate physical and chemical dynamics across various pollutants, are not yet fully synchronized with projected future climate scenarios. Moreover, several models omit crucial parameters or neglect to evaluate their influence on results, leading to concerns about the reliability of their predictions. This scenario necessitates cautious interpretation of modeling findings and a critical reassessment of model design criteria. For instance, evidence demonstrates that VOC emission rates from indoor materials substantially increase with temperature, suggesting that escalating global temperatures and more frequent heat waves could exacerbate indoor VOC concentrations in the ensuing decades. While many studies qualitatively describe the roles of environmental, structural and behavioral elements in shaping IAQ, there is an urgent need for more quantitative and dynamic methodologies.

Techniques such as stochastic modeling and empirical investigations like those examining window-opening behaviors may enhance our comprehension of how ventilation interacts with climatic factors. These approaches are particularly pertinent as climate change modifies temperature, humidity and seasonal airflow patterns, all of which influence indoor pollutant accumulation. Ultimately, the long-term consequences of climate change on IAQ remain uncertain due to unpredictable aspects such as advancements in building materials, evolving construction codes and shifts in building typologies. These effects are likely to differ by region, reflecting variations in architectural styles, socio-economic conditions, cultural practices and local climatic tendencies. Future research must tackle these intricacies through interdisciplinary, region-specific analyses that integrate climate science, building physics and behavioral studies.

Conclusion

A. General findings: Volatile Organic Compounds (VOCs) represent a vital yet frequently underestimated element affecting climate change, indoor air quality and public health. This review has detailed the complex roles VOCs play in atmospheric chemistry, notably in the generation of ozone and Secondary Organic Aerosols (SOAs) and their ensuing impacts on radiative forcing, cloud development and climate dynamics. Indoors, VOCs present a significant health risk, particularly in enclosed or inadequately ventilated spaces where their concentrations often surpass those outside. Despite their importance, VOCs are insufficiently incorporated into many environmental and health models, resulting in a limited comprehension of their complete societal impact.

B. Recommendations: To address these gaps, interdisciplinary collaboration proves vital. Enhanced cooperation among atmospheric scientists, indoor air specialists, public health authorities, economists and decision makers is requisite to bridge the disjunction between indoor exposure science and broader environmental simulations. Environmental regulations and climate health economic frameworks ought to explicitly integrate health impacts associated with VOCs, particularly those arising from consumer goods and Volatile Chemical Products (VCPs). Furthermore, revisions to atmospheric simulations should prioritize precise VOC characterization and incorporate contemporary emission databases, especially in metropolitan areas where VOC configurations are swiftly changing.

C. Limitations of this review: Although this review amalgamates recent advancements across a wide array of disciplines, it is constrained by the scarcity of comprehensive, interdisciplinary investigations. Numerous referenced studies concentrate exclusively on either indoor or outdoor settings, thereby hindering the capacity to derive strong conclusions regarding their interplay. Additionally, inconsistencies in measurement techniques, modeling premises and reporting norms among studies present obstacles for juxtaposition and meta-analysis.

Future directions: Research should prioritize acquiring a more sophisticated comprehension of Volatile Organic Compound (VOC) speciation and reactivity, especially within indoor environments. There exists an urgent requirement to harmonize real-time surveillance techniques, traditionally engineered for ambient air quality, with the unique temporal and spatial characteristics present indoors. Enhanced integration of data is essential to prevent erroneous extrapolations from external to internal settings. Progressing in the development of portable and economical VOC monitoring instruments, coupled with refining the precision of exposure data, will facilitate more accurate assessments of health risks. Ultimately, promoting interdisciplinary research that encompasses environments from micro to macro scales will support the formulation of more effective, health-oriented environmental policies.

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