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Invisible Invaders: Unmasking the Emerging Threats of Volatile Organic Compounds in Indoor Air

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Abstract: This review addresses the significant impact of volatile organic compounds (VOCs) on indoor air quality and human health. Given that individuals spend approximately 85% of their time indoors, understanding the sources, health risks, and mitigation strategies for VOCs is critical. VOCs originate from various indoor sources, including building materials, furnishings, cleaning products, and personal care items. Emerging VOCs present new challenges due to evolving emission patterns and potential health risks, such as respiratory issues and neurotoxicity. Current mitigation strategies, such as advanced air purification technologies and plant-based solutions, show promise in reducing VOC levels. However, continuous research and innovation are required to develop more effective solutions. This review underscores the need for increased public awareness, policy changes, and interdisciplinary collaboration to safeguard indoor air quality. Future research should focus on identifying and characterizing emerging VOCs, improving monitoring techniques, and assessing health risks to ensure that indoor environments remain safe and healthy for all occupants.

Keywords: Indoor Air Quality, Volatile Organic Compounds (VOCs), Health Risks, Mitigation Strategies, Environmental Monitoring

1. Introduction

Indoor air quality significantly impacts human health, as individuals spend approximately 85% of their time indoors[1]. Volatile organic compounds (VOCs) are a key component affecting indoor air quality, originating from various sources such as building materials, furnishings, cleaning products, and personal care items [2]. The ubiquitous presence of VOCs in indoor and outdoor environments underscores their importance in assessing air quality due to their substantial influence on both the environment and human health [2]. The evolving nature of VOC threats is highlighted by potential new VOCs and changing emission patterns, emphasizing the need for continuous monitoring and mitigation strategies to address emerging indoor air quality challenges[2].

Research indicates that indoor air pollution, driven by the release of diverse contaminants, poses a significant health threat to individuals occupying indoor spaces[3]. Plants have been identified as potential contributors to improving indoor air quality by impacting VOC levels, offering a green solution that can enhance human health by reducing indoor air pollutants[4]. Furthermore, the adverse effects of VOCs on human comfort, productivity, and health are well-documented, emphasizing the importance of addressing VOC emissions from both primary sources like building materials and secondary sources resulting from indoor chemical reactions [5].

Efforts to enhance indoor air quality have led to the exploration of various strategies, including the use of photocatalytic oxidation for removing VOCs, demonstrating the significance of emission source control, ventilation, and air cleaning in improving indoor air quality[6]. The toxic nature of many VOCs found in indoor environments necessitates accurate measurement and quantification to safeguard public health from the potential adverse effects of indoor air pollution[7]. Additionally, the development of innovative technologies such as plasma-based air cleaning systems reflects the ongoing research focus on mitigating the negative impact of VOCs on indoor air quality[8].

In essence, the dynamic nature of VOC threats in indoor environments underscores the importance of continuous research and monitoring to address emerging challenges and safeguard human health. Strategies such as plant-based solutions, advanced air treatment technologies, and effective ventilation systems play crucial roles in mitigating VOC emissions and improving indoor air quality.

2. Methodology

This systematic review was conducted following the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyzes) guidelines. The review aimed to synthesize current knowledge on emerging volatile organic compounds (VOCs) in indoor air, their health risks, and mitigation strategies.

Literature Search: A comprehensive literature search was performed using the following electronic databases: Web of Science, Scopus, PubMed, and Google Scholar. The search covered articles published between January 2000 and June 2024. The following keywords and their combinations were used: "volatile organic compounds", "VOCs", "indoor air quality", "emerging pollutants", "health risks", "mitigation strategies", "air purification", and "indoor air pollution".

Inclusion and Exclusion Criteria
Inclusion criteria:

- Peer-reviewed articles published in English
- Studies focusing on VOCs in indoor environments
- Research on emerging VOCs, their health impacts, or mitigation strategies
- Original research articles, systematic reviews, and meta-analyses

Exclusion criteria:

- Studies focused solely on outdoor air pollution
- Articles not peer-reviewed or published in languages other than English
- Publications before 2000
- Conference abstracts, letters to the editor, and opinion pieces

Study Selection and Data Extraction: Two independent reviewers screened titles and abstracts of the identified articles. Full-text articles meeting the inclusion criteria were then assessed for eligibility. Any disagreements were resolved through discussion with a third reviewer. Data extraction was performed using a standardized form, capturing information on study design, VOC types, health effects, mitigation strategies, and key findings.

Quality Assessment: The quality of included studies was assessed using the Newcastle-Ottawa Scale for observational studies and the Cochrane Risk of Bias tool for experimental studies. For systematic reviews, the AMSTAR-2 (A Measurement Tool to Assess Systematic Reviews) checklist was employed. **Data Synthesis** Due to the heterogeneity of the included studies in terms of VOC types, health outcomes, and mitigation strategies, a narrative synthesis approach was adopted. The findings were organized thematically, addressing the characterization of emerging VOCs, associated health risks, current mitigation strategies, and future research directions. This methodology ensures a comprehensive and systematic approach to reviewing the literature on emerging VOCs in indoor air, aligning with the standards expected in top-tier journals in the field of environmental science and public health.

3. Characterizing Emerging VOCs

Identifying and monitoring emerging volatile organic compounds (VOCs) in indoor air poses significant challenges due to their diverse types, low concentrations, and complex interactions. VOCs can originate from various sources such as building materials, furnishings, household products, and outdoor emissions like traffic and industry [9, 10]. These compounds include aromatic and aliphatic hydrocarbons, halogenated hydrocarbons, acetone, and Freons[11]. The detection and quantification of VOCs typically involve analytical techniques like gas chromatography-mass spectrometry **(As seen in figure 1)** and sensor technologies[12]. Studies have identified a range of VOCs in indoor environments, with common compounds including 2-(2-ethoxyethoxy) ethanol, acetic acid, 1,2-propanediol, and toluene[13].

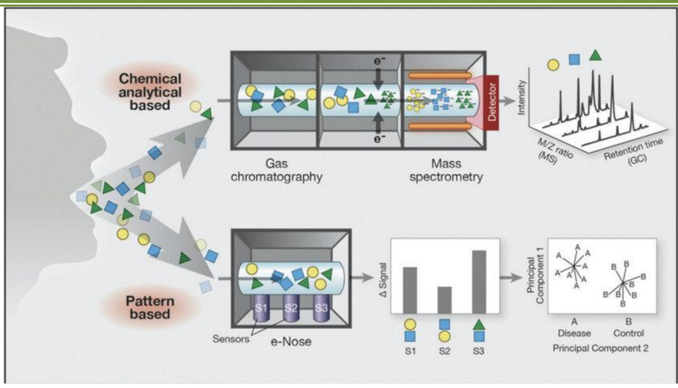

Figure 1 shows a comparative evaluation of volatile organic compounds using gas chromatography-mass spectrometry (GC-MS) (top) and electronic nose (nose) detection (bottom).
Top (GC-MS): Gas Chromatography-Mass Spectrometry separates VOCs and identifies each molecule by its unique mass fingerprint, offering precise identification and quantification.
Bottom (eNose): The electronic nose detects a broad pattern of VOCs, providing rapid detection and differentiation between samples, suitable for screening purposes. Source: [14]

Recent research has focused on characterizing newly identified VOCs in indoor settings. For instance, studies have detected aromatics like benzene, ethyl benzene, toluene, m,p-xylene, and o-xylene in indoor air[15]. Additionally, investigations have highlighted the presence of terpenes and fragrance compounds that warrant further evaluation for potential health concerns[16]. VOC emissions from sources **(As seen in table 1)** like building materials, combustion processes, and household products contribute to indoor air pollution[7]. The use of mineral binders and activated carbon fiber cloths has been explored to reduce VOC emissions indoors[17].

The identification and monitoring of emerging VOCs in indoor air require advanced analytical techniques and a comprehensive understanding of their sources and interactions. Recent studies have shed light on the presence of various VOCs in indoor environments, emphasizing the need for continued research to mitigate their potential health impacts.

Table 1 shows Common Sources of Indoor VOCs and Their Typical Concentrations

Source	**Examples of VOCs Emitted**	**Typical Concentrations (Indoors)**
Household products	Paints, varnishes, cleaning agents, disinfectants, air fresheners	Up to 1,000 times background outdoor levels during and after use
Building materials and furnishings	Plywood, particleboard, carpets, upholstery	Varies based on materials and ventilation
Office equipment	Copiers, printers, correction fluids	Varies based on usage and ventilation
Personal care products	Perfumes, hair sprays, cosmetics	Varies based on product type
Automotive products	Gasoline, stored fuels	Varies based on storage and use

Source: [18]

4. Health Risks of Emerging VOCs:

Exposure to volatile organic compounds (VOCs) poses significant health risks due to their potential carcinogenicity and non-carcinogenic effects, which are influenced by exposure concentrations and health risk coefficients[19]. High levels of VOC exposure can lead to health issues such as eye, nose, and throat irritation, headaches, nausea, and dizziness[20]. Specific VOCs like benzene have been identified as having both high emission**(A seen in figure 2)** rates and health risks, while trichloroethylene has a high emission rate but lower health risk [21].

In comparison to well-established indoor air pollutants like formaldehyde and benzene, emerging VOCs present unique challenges. VOCs, including those from automobile repair industries and dental clinics, can induce respiratory irritation, allergic reactions, neurotoxicity, and developmental effects [22, 23] These health effects are similar to those associated with established indoor air pollutants, highlighting the importance of understanding and mitigating exposure to both emerging and well-known VOCs.

Research has shown associations between impaired respiratory function, asthma, and increased symptoms with exposure to common indoor air pollutants like tobacco smoke and VOCs[24]. This underscores the importance of considering the impact of VOCs on respiratory health, especially in vulnerable populations such as adolescents.

Moreover, emerging VOCs, such as those associated with SARS-CoV-2 variants, have raised concerns due to their ability to evade immune responses and potentially reinfect individuals[25]. These VOCs, including Alpha, Beta, Gamma, Delta, and Omicron variants, have demonstrated increased transmissibility and altered clinical presentations, posing challenges for disease control and management.

Understanding the health risks associated with emerging VOCs is crucial for developing effective mitigation strategies. By comparing these risks with those posed by established indoor air pollutants and considering factors like toxicity, exposure levels, and individual susceptibility, researchers and policymakers can work towards safeguarding public health from the adverse effects of VOC exposure.

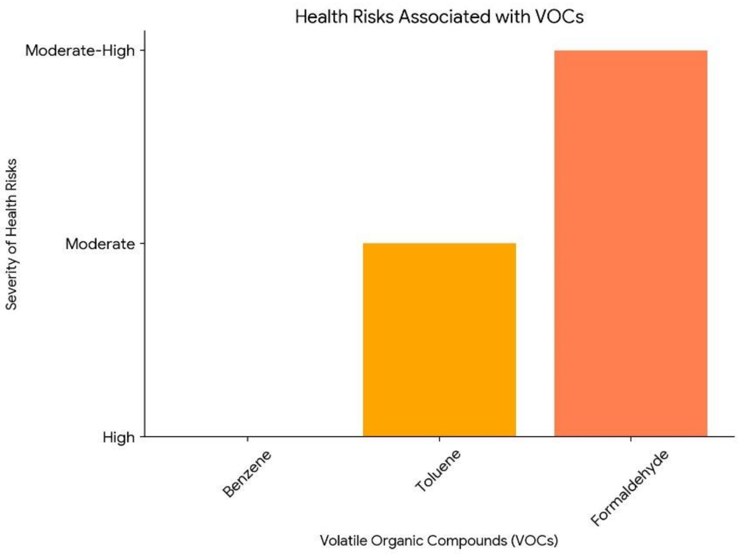

Figure 2 compares the severity of health risks associated with exposure to three common Volatile Organic Compounds (VOCs): benzene, toluene, and formaldehyde. Exposure severity can vary based on duration and concentration, with benzene posing the highest health risk, followed by formaldehyde and then toluene. It's important to note that all three VOCs can cause respiratory irritation and other health problems. Reference:[26]

5. Current Mitigation Strategies:

To reduce indoor volatile organic compound (VOC) concentrations, various strategies**(As seen in table 2)** have been developed and studied. These strategies include source control through product selection and ventilation, air filtration, and adsorption techniques. Push-pull local exhaust ventilation has been identified as an effective measure for mitigating VOC exposure[27]. Adsorption is recognized as a promising strategy for VOC abatement due to its cost-effectiveness, simplicity, and low energy consumption[28]. Additionally, photocatalysis has emerged as an efficient technology for removing indoor VOCs, breaking them down into harmless byproducts[29].

While advancements have been made in researching VOCs and implementing mitigation technologies, challenges persist in quantifying VOCs, evaluating their environmental impacts and health risks, and developing effective mitigation strategies[30]. The diverse nature of VOCs, some of which are carcinogenic, presents significant challenges in devising comprehensive mitigation strategies[31]. Previous studies have predominantly qualitatively suggested VOC control measures, with limited quantitative source-specific mitigation strategies proposed[32].

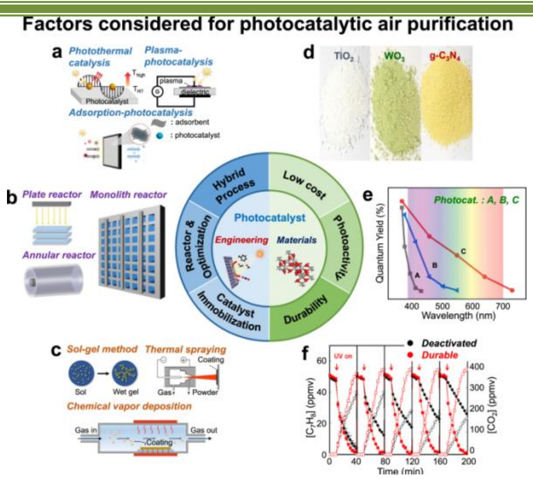

Figure 3 shows an approach to the practical applications of photocatalytic air purification with considering various engineering and materials aspects. Source: [33]

To address emerging VOCs, it is crucial to first identify major indoor and outdoor sources to effectively mitigate exposures and risks[34]. Various technologies such as catalytic oxidation and biological treatment have been employed for VOC abatement, with catalytic oxidation proving to be a reliable technology for over 60 years[35]. Moreover, the use of plants and microorganisms has been acknowledged for their ability to significantly eliminate VOCs from indoor air, underscoring the importance of biological components in indoor air purification[36].

In essence, while existing strategies like adsorption and photocatalysis demonstrate promise in reducing indoor VOC concentrations, ongoing research is vital to address challenges in quantification, health risk assessment, and the development of comprehensive and effective mitigation technologies.

Table 2 compares various mitigation strategies for improving indoor air quality (IAQ) based on four key aspects:

Strategy	Effectiveness	Cost	Ease of Implementation	Energy Consumption
Source Control	High (addresses root cause)	Low - Moderate (often cost-effective)	Moderate (requires identifying sources)	Low
Improved Ventilation	Moderate (dilutes pollutants)	Moderate (varies with adjustments)	Moderate (may require system modifications)	Moderate - High (increased airflow)
Air Cleaners	Variable (depends on type)	Variable (technology & maintenance)	Easy (installation, filter changes)	Variable (some use electricity)
Adsorption	High (specific pollutants removal)	Moderate (depends on adsorbent)	Moderate (integration into ventilation/standalone devices)	Low
Photo catalysis	Moderate (breaks down pollutants)	Moderate - High (installation & maintenance)	Difficult (specialized materials & UV light)	Moderate (UV lamp energy use)

6. Future Directions and Research Needs

Identifying gaps in our knowledge about emerging VOCs in indoor air, including their sources, health effects, and effective mitigation strategies:

- **Sources**: There is a need to comprehensively map the diverse sources of emerging VOCs, which include not only traditional building materials and consumer products but also new and evolving sources such as electronic devices and novel construction materials.
- **Health Effects**: The health impacts of many emerging VOCs are not fully understood, particularly their long-term effects and interactions with other indoor pollutants. Detailed epidemiological studies are necessary to elucidate these impacts.

- **Mitigation Strategies**: Current mitigation techniques, while promising, require further refinement to be effective against a broader spectrum of VOCs. There is a need for strategies that are adaptable to various indoor environments and different VOC profiles.

Propose areas for future research to address these knowledge gaps, focusing on improved monitoring, health risk assessment, and development of innovative mitigation solutions:

- **Improved Monitoring**: Developing advanced, real-time monitoring technologies that can accurately detect and quantify low concentrations of a wide range of VOCs is critical. These technologies should be user-friendly and deployable in various indoor settings.
- **Health Risk Assessment**: Enhanced risk assessment models that take into account the cumulative and synergistic effects of multiple VOCs are needed. Research should focus on vulnerable populations such as children, the elderly, and those with preexisting health conditions.
- **Innovative Mitigation Solutions**: Future research should explore the potential of emerging technologies such as nanomaterials, advanced photocatalysts, and bio-based solutions. Additionally, the integration of smart building systems that can dynamically adjust ventilation and purification processes based on real-time air quality data holds promise.

Emphasize the need for interdisciplinary collaboration and coordinated efforts among researchers, policymakers, and the building industry to effectively address the challenge of emerging VOCs in indoor air:

- **Researchers**: Collaborative efforts among chemists, environmental scientists, health professionals, and engineers are essential to develop a holistic understanding of VOCs and effective solutions.
- **Policymakers**: Engaging policymakers to develop regulations and guidelines that limit VOC emissions from consumer products and building materials is crucial. Policies should also promote the adoption of proven mitigation technologies.
- **Building Industry**: The building industry plays a pivotal role in implementing these strategies. Collaboration with architects, builders, and facility managers is necessary to design and maintain buildings that minimize VOC emissions and optimize indoor air quality.

Significant progress can be made in mitigating the risks associated with VOCs in indoor environments by addressing these areas. This will ultimately lead to the protection of public health and an enhanced quality of life for building occupants.

7. Conclusion

This review has highlighted the significant threats posed by emerging VOCs to indoor air quality and human health. Key findings underscore the diverse sources of VOCs, ranging from building materials and household products to newer sources such as electronic devices. The health risks associated with VOC exposure, including respiratory issues, neurotoxicity, and potential carcinogenic effects, emphasize the critical need for effective mitigation strategies.

Developing comprehensive mitigation strategies is essential. Current approaches, such as advanced air purification technologies and source control measures, show promise but require further refinement and adaptation to address the evolving nature of VOC emissions. There is also a pressing need for innovative solutions, including plant-based interventions and advanced photocatalytic systems.

Increased public awareness and advocacy for healthier indoor environments are paramount. Educating the public on the sources and health impacts of VOCs, as well as promoting the adoption of effective mitigation technologies, can lead to significant improvements in indoor air quality.

Finally, a call to action is warranted for further research, policy changes, and technological advancements. Future research should focus on the identification and characterization of emerging VOCs, development of real-time monitoring technologies, and comprehensive health risk assessments. Policy changes should aim to regulate VOC emissions from various sources, while the building industry must prioritize the implementation of air quality improvement measures. Through interdisciplinary collaboration among researchers, policymakers, and industry stakeholders, we can ensure that future buildings provide safe and healthy air for all occupants.

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