Wiley
Indoor Air
Volume 2025, Article ID 5945455, 19 pages
https://doi.org/10.1155/ina/5945455

WILEY

Review Article

Volatile Organic Compounds (VOCs) and Polycyclic Aromatic Hydrocarbons (PAHs) in Indoor Environments: A Review and Analysis of Measured Concentrations in Europe

Nikolina Račić,[1] **Ivana Terzić**,[2] **Nina Karlović**,[3] **Anja Bošnjaković**,[3] **Teo Terzić**,[4] **Ivana Jakovljević**,[1] **Gordana Pehnec**,[1] **Tajana Horvat**,[1] **Goran Gajski**,[5] **Marko Gerić**,[5] **Sandra Vitko**,[6] **Iva Šunić**,[3] **Michael Forsmann**,[7] **Pasquale Avino**,[8] **Ivana Banić**,[9] **Marcel Lipej**,[9] **Olga Malev**,[10] **Bojana Žegura**,[11] **Jon Switters**,[12] **Francesco Mureddu**,[12] **and Mario Lovrić**[2,3,7,12]

[1]*Division of Environmental Hygiene, Institute for Medical Research and Occupational Health, Zagreb, Croatia*
[2]*Research Department, Chemical Codes d.o.o., Zagreb, Croatia*
[3]*Department for Applied Bioanthropology, Institute for Anthropological Research, Zagreb, Croatia*
[4]*Research Department, Ascalia d.o.o., Čakovec, Croatia*
[5]*Division of Toxicology, Institute for Medical Research and Occupational Health, Zagreb, Croatia*
[6]*Department of Biology, Faculty of Science, University of Zagreb, Zagreb, Croatia*
[7]*Department for Prospective Studies on Asthma in Childhood, University of Copenhagen, Copenhagen, Denmark*
[8]*Department of Agricultural, Environmental and Food Sciences, University of Molise, Campobasso, Italy*
[9]*Department of Translational Medicine, Children's Hospital Srebrnjak, Zagreb, Croatia*
[10]*Division of Materials Chemistry, Ruđer Bošković Institute, Zagreb, Croatia*
[11]*Department of Genetic Toxicology and Cancer Biology, National Institute of Biology, Ljubljana, Slovenia*
[12]*The Lisbon Council, Brussels, Belgium*

Correspondence should be addressed to Mario Lovrić; mario.lovric@inantro.hr

Received 4 February 2025; Accepted 29 May 2025

Academic Editor: Poorani Gurumallesh

Indoor air quality is a significant aspect of public health, yet it remains less studied than outdoor air pollution. Understudied indoor pollutants include volatile organic compounds (VOCs) and polycyclic aromatic hydrocarbons (PAHs). This review focuses on these two groups of compounds known for their health effects, including respiratory issues, neurological disorders, and carcinogenicity. We systematically compiled and analyzed data from studies reporting measured concentrations of VOCs and PAHs in European indoor environments—homes, schools, and offices—published in the past two decades. Concentration levels vary substantially across studies, influenced by regional differences, climate, building type, ventilation systems, and indoor activities. Identified sources include tobacco smoke, cooking, heating (e.g., biomass burning), and off-gassing from construction and furnishing materials. Our analysis reveals clear geographic patterns: lower concentrations of VOCs and PAHs are consistently reported in Northern and Western European countries, likely due to stricter air quality regulations, cleaner outdoor air, greater use of electric heating, and more advanced ventilation systems. Conversely, higher concentrations are more commonly observed in Southern and Eastern Europe, where biomass heating and poorer ventilation remain more prevalent.

Seasonal variation also has a significant role, with higher indoor levels typically measured during colder months due to increased heating and reduced air exchange. This highlights the need for improved indoor air quality management practices and regulatory standards to minimize the health risks associated with VOCs and PAHs. This review of 46 scientific publications is aimed at informing future studies and guiding future field measurements and risk assessments in epidemiological studies.

Keywords: health risks; indoor air quality; PAHs; public health; VOCs

1. Introduction

According to the European Environment Agency, air pollution is the most important environmental health risk affecting millions [1]. Although a significant body of evidence exists for the effects of ambient air pollution on health, indoor air quality (IAQ) could also be regarded as a critical aspect of environmental health. Individuals spend a significant amount of their time indoors, particularly in developed urban settings where most of the population lives, thus increasing exposure to indoor air pollutants that account for more than 3 million deaths annually [2–6]. While efforts have been made to mitigate ambient air pollution, IAQ remains a concern due to the presence of various pollutants, including particulate matter (PM), volatile organic compounds (VOCs), and polycyclic aromatic hydrocarbons (PAHs). VOCs and PAHs are particularly interesting due to their different sources and potentially adverse effects on macromolecules [7]. Many studies have addressed these pollutants individually. However, a systematic review of the measured concentrations is needed to synthesize existing findings, identify knowledge gaps, and guide future research and policy efforts. This review provides a comprehensive overview of the current evidence on VOCs and PAHs in indoor air. It examines their sources, distribution, levels in various indoor environments, and potential health effects. Additionally, analysis of existing studies quantifies the overall levels of these pollutants and assesses regional or temporal trends. Ultimately, this review is aimed at contributing to efforts to promote a healthier indoor environment and protect public health.

PAHs are a significant group of air pollutants that impact human health. Their association with adverse health outcomes, including mutagenesis and carcinogenesis, underscores their potency in the development of chronic diseases and their involvement in increased morbidity and mortality in specific susceptible populations [8–11]. While individual PAH concentrations might not lead to immediate health effects, their mixtures can create additive, synergistic, or potentiating toxic effects [12–14]. Among them, benzo[a]-pyrene (BaP) is one of the most well-known carcinogenic PAHs, classified as a Group 1 carcinogen by the IARC (International Agency for Research on Cancer). It has been shown to form DNA adducts, leading to mutations and promoting tumor development, especially in lung and skin tissues [13, 15, 16]. Exposure to PAHs has been associated with adverse health outcomes, respiratory and cardiovascular diseases, cancer, and developmental abnormalities [17]. The mechanism underlying PAHs' toxicity involves DNA damage, oxidative stress induction, gene expression alterations, and epigenetic changes, all contributing to chronic disease development [18, 19]. Of particular concern is the chronic exposure and persistent nature of PAHs in the human body, which further exacerbates the health implications [20]. PAHs can enter indoor spaces through various pathways. Their primary source is the incomplete combustion of organic materials such as fuels, coal, gas, wood, and oil [21–25]. Other contributing sources may include cigarette smoke, cooking processes, and the use of certain building materials and consumer products [26, 27]. Understanding the impact and sources of IAQ and their adverse effects on human health is crucial for effective emission reduction strategies. The presence of PAHs in various environmental matrices, such as air, water, soil, and food, underscores the global significance of their impact on public health.

VOCs are another significant air pollutants that considerably impact IAQ and human health. According to the Environmental Protection Agency, VOCs are diverse chemicals that can easily evaporate at room temperature, typically with boiling points between 50°C and 250°C. Due to their volatility and relatively low molecular weight (LMW), they are commonly present in the air as gases. Some of the most frequently detected VOCs in indoor environments include benzene, toluene, ethylbenzene, xylenes (BTEX), and formaldehyde. These compounds are of concern due to their known health impacts, ranging from irritation and allergic responses to neurotoxicity and carcinogenicity, especially with long-term exposure [28, 29]. Despite the extensive research on VOCs, the relationship between individual indoor VOC concentrations and health outcomes remains insufficiently understood. Consequently, there are no universal health-based guideline values for VOCs in Europe. They are characterized by their high vapor pressure, allowing them to evaporate into the air at room temperature readily [30, 31]. Exposure to VOCs in indoor environments is of concern due to their association with adverse health effects. Several studies have linked VOC exposure to respiratory issues, allergic reactions, and other severe health outcomes, including neurodegenerative conditions [32–34] and cancer development, further emphasizing the importance of understanding and mitigating their presence in indoor air [35, 36]. Various sources contribute to VOCs in indoor spaces, including building materials, furniture, cleaning items, personal care products, and activities such as cooking and smoking [35, 37, 38].

Additionally, VOCs can originate from outdoor sources, such as vehicle emissions, industrial processes, and ambient air pollution, which can infiltrate indoor environments [39–41]. Chemical transformations and reactions occurring indoors can significantly affect the levels and composition of VOCs, leading to potential health risks [42]. This review is aimed at providing a comprehensive overview of the behavior, sources, exposure pathways, and health implications of VOCs in indoor environments. By synthesizing

research findings, we will explore the impact of VOCs on IAQ and human health. Strategies for measuring, monitoring, and controlling VOC levels in indoor settings will also be discussed.

The systematic review is aimed at understanding the sources, concentration levels, and routes of exposure of indoor air pollutants, which is also the main goal of the Horizon EU EDIAQI (Evidence-driven indoor air quality improvement, https://ediaqi.eu/) project (GA Number 101057497) [43]. This will help validate the user-friendly IAQ monitoring solutions proposed by the EDIAQI project and contribute to establishing standardized guidelines for improving IAQ. Ultimately, this review will support policymakers in revising IAQ standards and implementing effective regulatory measures.

2. Materials and Methods

2.1. Search Strategy and Selection Criteria. For this analysis, a systematic search of the PubMed database was performed, including all relevant studies from 1 January 2010 till 1 April 2024 related to indoor measurements and health effects of PAHs and VOCs. The entire search strategy is described in the Supporting Information. The leading search criteria involved scanning all publications (title/abstract) with several keywords: Polycyclic Aromatic Hydrocarbons OR PAH OR PAHs OR Volatile Organic Compounds OR VOC OR VOCs AND indoor (or school, schools, office, offices, etc.) AND exposure, OR monitoring OR measurements, etc. The initial results contained 4225 papers. Limiting the review period to 2010–2024 reduced the results to 3101 publications. Applying the "free full text" filter narrowed the results to 1276 publications. Abstracts of these 1276 papers were extracted using Python and stored in a designated folder.

Each abstract was then manually reviewed to determine if it included the necessary measurements for the analysis. Only studies conducted within the European Union were considered, as this area was the review's focus. The diagram of the systematic search process and the included studies is presented in Figure 1. A total of 46 studies were included in the further analysis. PubMed was selected as the primary database because it best matched the scope of our study, which focused on measured indoor concentrations of VOCs and PAHs, with an additional interest in studies that also reported health-relevant information or context. While our main objective was not to assess health effects directly, we aimed to include studies that also provided basic interpretation of exposure implications. Given the extensive volume of initial results over 1.200 full-text papers after filtering, we decided to limit our search to a single database to maintain the feasibility of manually reviewing abstracts and extracting data. Our inclusion criteria required detailed, tabulated concentration data for VOCs and PAHs, which had to be verified manually across all selected studies. Expanding the search across multiple databases would have resulted in thousands of additional hits, rendering the screening process impractical and potentially introducing inconsistencies. To support reproducibility and efficient data handling, we used

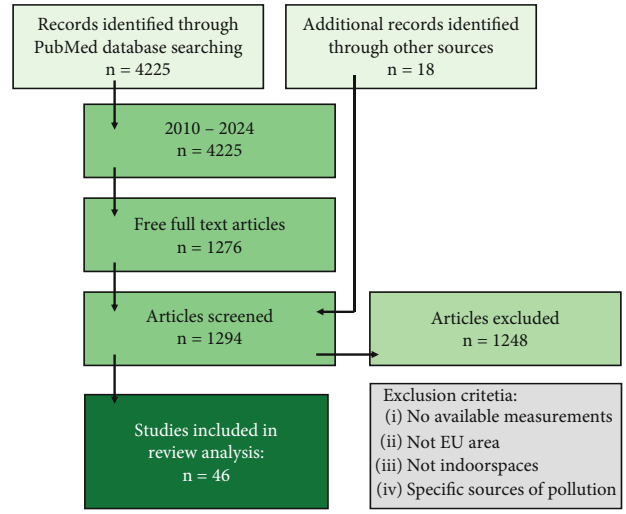

FIGURE 1: PRISMA flow diagram of the systematic literature search and study selection process [44].

custom Python scripts from our previous work to automate the initial search and filtering process via PubMed's open and well-documented API, which offers robust access compared to more restricted or commercial alternatives [45]. However, this approach may have led to the exclusion of valuable information available in other scientific disciplines or studies that are not easily accessible, potentially impacting the comprehensiveness of the findings, which is the main limitation of this study.

3. Results and Discussion

After thoroughly reviewing the abstracts of papers that met the search criteria, 46 papers were selected that fit the specified requirements (Figure 2). Of these, 24 and 25 focus on indoor measurements of PAHs and VOCs, respectively, in Europe. Some papers cover measurements of both PAHs and VOCs, which is why the total number of studies across different environments does not match the overall number of selected studies. Within the VOC papers, the studies are divided into measurements of concentrations in the air in offices, homes, and schools: 3 papers on offices, 10 on homes, and 12 on schools. For PAHs, the division is as follows: nine papers on dust-bound PAHs, six on PM-bound PAHs in the air in homes, and nine on PM-bound PAHs in the air in schools.

As illustrated in the map (Figure 2), most studies are concentrated in the southern regions of the European Union, which is in line with the EEA's report on European air quality [46]. Despite the regional imbalance, the included studies collectively span various climatic zones and urban settings. Countries with similar climatic and regulatory contexts (e.g., Scandinavian countries and Southern Europe) tend to report comparable concentration patterns, suggesting that the observed trends may be cautiously generalizable to other regions with similar environmental and indoor characteristics. Italy has the highest number of studies, with 10, followed by Portugal with 8 studies, and Poland and Spain with 5 and 4 studies, respectively. A limitation might

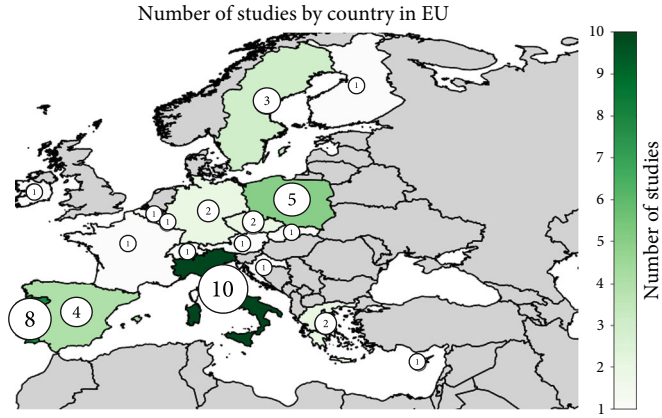

FIGURE 2: Map with the number of studies per country in the European Union included in the review.

be that the needed data quality looked for during the search was a limiting factor and could drive a bias towards such a geographical distribution. In the following subsection, indoor spaces' individual categories (offices, homes, schools, and dust-bound) will be assessed for either/or PAHs and VOCs.

3.1. VOCs in Indoor Spaces. Within the VOC papers, the studies are divided into measured concentrations in offices, homes, and schools: 3 papers on offices, 10 on homes, and 12 on schools (Table S1). These studies' most commonly measured VOCs were benzene, toluene, ethylbenzene, formaldehyde, styrene, and xylenes. These compounds were chosen due to their prevalence and potential health impacts in indoor environments, providing a comprehensive overview of VOC exposure in different settings. The table with mean VOC concentrations in households, schools, and offices and total volatile organic compound (TVOC) concentrations in various indoor environments can be found in the Supporting Information (Table S1), and the average VOC concentrations are shown as figures in the following subsections.

3.1.1. VOC Concentrations in Offices. This section presents the findings from studies investigating VOC levels in office environments (Tables S3–S5). Figure 3 summarizes the results of three studies that measured the concentrations of various VOCs in office settings. Five common VOCs identified in all three studies were selected: benzene, toluene, ethylbenzene, *m,p*-xylene, and *o*-xylene. These VOCs are among the most commonly measured in indoor spaces. The results compare the average concentrations of these common VOCs in three different office environments in Italy, France, and Poland. Benzene concentrations varied across the studies, with the highest level recorded in the survey by Gallon et al. [47] at $6.12 \pm 10.09\,\mu g/m^3$ and the lowest concentration recorded in the study by Kozielska et al. [48] at $1.15 \pm 0.99\,\mu g/m^3$. Toluene concentrations also varied significantly, with the highest concentration reported at $12.73 \pm 4.35\,\mu g/m^3$ and the lowest concentration at $4.01 \pm 2.15\,\mu g/m^3$. The levels of ethylbenzene were relatively low across all studies, with the highest being $2.00 \pm 0.96\,\mu g/m^3$ and the lowest $0.63 \pm 0.16\,\mu g/m^3$ in Kozielska et al. Gallon et al. reported the highest *m,p*-xylene concentration at $8.03 \pm 2.50\,\mu g/m^3$, while Kozielska et al. reported the lowest at $0.53 \pm 0.15\,\mu g/m^3$. Concentrations of *o*-xylene ranged from $1.47 \pm 0.52\,\mu g/m^3$ in Fuselli et al. [49] to $3.68\,\mu g/m^3$ in Gallon et al., with Kozielska et al. reporting $1.18 \pm 0.48\,\mu g/m^3$.

These findings illustrate the variability in VOC concentrations in office environments depending on the location, the specific VOCs measured, and possibly the measurement methods (given in the Supporting Information). The differences in VOC levels can be attributed to various factors such as building materials, office equipment, ventilation systems, and indoor activities, such as different phases of the construction process and materials and solvents used for furnishing [47]. The study by Gallon et al. differs from the other two studies (Figure 3) as it was conducted during the construction process of an office building. This context likely contributed to the higher concentrations of certain VOCs observed in this study. The elevated levels of benzene and other VOCs such as *m,p*-xylene ($8.03\,\mu g/m^3$) can be attributed to emissions from construction materials, adhesives, paints, and solvents used during the building process [47]. This finding was also reported by Liang et al. [50] in a study from China, where similar results were observed.

In contrast, the studies by Fuselli et al. and Kozielska et al. measured VOC levels in fully operational office environments, where the primary sources of VOCs are typically furniture, office equipment, and cleaning products rather than construction materials. This difference in context explains why the TVOC levels in Gallon et al. ($23.8\,\mu g/m^3$) are higher compared to Fuselli et al. ($22.17\,\mu g/m^3$) and Kozielska et al. ($14.33\,\mu g/m^3$). These findings highlight the importance of considering the building phase and activities when assessing IAQ and indicate the need for appropriate ventilation and mitigation strategies during and after construction to protect IAQ. The European project OFFICAIR [51] is aimed at broadening the existing knowledge regarding IAQ in modern office buildings. Thirty-seven office buildings participated in the summer campaign (2012), and 35 participated in the winter campaign (2012–2013). Indoor concentration means (micrograms per cubic meter) of VOCs monitored in office buildings during the OFFICAIR project were as follows: benzene at 1.4 ± 1.3, toluene

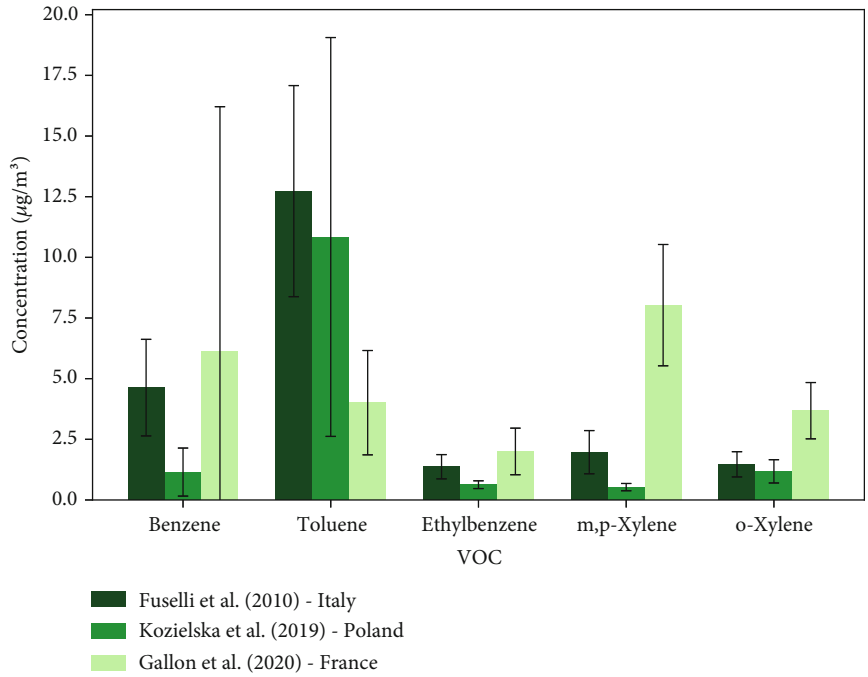

FIGURE 3: The mean volatile organic compound (VOC) concentrations and standard deviations quantified in office environments (micrograms per cubic meter) from reviewed papers.

at 8.1 ± 8.5, and ethylbenzene at 1.8 ± 2.0 during the summer and benzene at 2.1 ± 1.7, toluene at 6.1 ± 8.8, and ethylbenzene at 1.3 ± 1.2 during the winter. These concentrations also align with those measured in the studies discussed, suggesting that standardizing the measurement of specific VOCs could enhance the comparability of research findings.

The IAQ analysis in office environments reveals significant challenges related to VOCs and other pollutants, underscoring the need for proactive management strategies. Studies by Kozielska et al., Fuselli et al., and Gallon et al. frequently identify toluene as a primary concern, suggesting that materials used in office construction and furnishings contribute substantially to indoor pollution. Its prevalence is linked to emissions from paints, varnishes, adhesives, carpets, and office furniture, especially in newly constructed or recently renovated buildings. Given toluene's known neurotoxic effects and potential to irritate the eyes and respiratory tract, its frequent occurrence raises essential concerns for occupant health [52]. This shows the importance of choosing low-emission building materials and ensuring adequate ventilation, especially during and after renovation. Moreover, consistently high toluene levels across several geographically distinct studies suggest that this issue is not isolated but may reflect a broader trend in office environments across Europe. Newly constructed or renovated office spaces are particularly vulnerable, as VOC emissions can be heightened due to using conventional materials, emphasizing the importance of adopting low-emissive options to mitigate health risks and comply with evolving regulatory standards. Furthermore, the relationship between indoor and outdoor air quality indicates that while some VOCs originate from external sources, many originate from indoor conditions. The presence of semivolatile organic compounds (SVOCs) and mold, linked to increased humidity in well-insulated buildings, raises additional health concerns, particularly respiratory issues among occupants. Therefore, effective moisture management and continuous IAQ monitoring are essential to create healthier work environments.

3.1.2. VOC Concentration in Houses. Given the search criteria, 10 studies were included in our dataset examining VOCs in homes or apartments (Tables S6–S15). These studies were grouped into two categories to enhance comparability based on whether they reported TVOC or individual VOC concentrations. First, four studies focused exclusively on TVOC measurements, as shown in Table S1. Salthammer has provided a critical assessment of TVOC [53], and we advise readers to refer to that work when interpreting these results. In a study by Rodrigues Dos Santos et al. [54], the highest TVOC concentration reported in Portugal was 3110 $\mu g/m^3$ over 2 years.

In contrast, Wallner et al. [55] found a significantly lower concentration of 334.5 $\mu g/m^3$ in Austria. Mečiarová et al. [56] reported a concentration of 425 $\mu g/m^3$ in Slovakia, which is higher than in Austria but much lower than in Portugal. Pietrogrande et al. [57] measured a concentration of 348.6 ppb in Italy, which is considerably higher than in Austria and Slovakia but lower than in Portugal when expressed in micrograms per cubic meter. The remaining six studies reported concentrations of individual VOCs, offering more detailed insights into specific pollutants. Figure S1 illustrates the number of individual VOCs measured per study: Martins et al. measured 10 VOCs, Ninyà et al. 15, Rösch et al. 50, Alves et al. 20, Alvarez-Vaca et al. 30, and Yang et al. 25. To maintain focus, we discuss only the five most commonly reported compounds, as listed in Table S1.

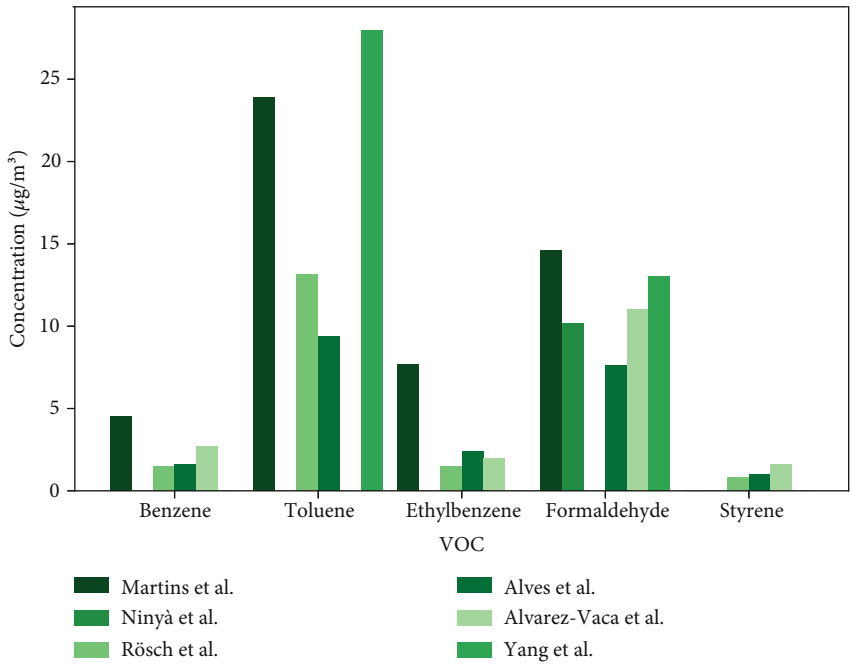

FIGURE 4: The mean volatile organic compound (VOC) concentrations quantified in houses (micrograms per cubic meter) from reviewed papers. Standard deviation values were not available for most of these studies.

In the study by Martins et al. [58] conducted in Portugal, VOC concentrations were notably the highest among all reviewed papers, with values of 4.53 $\mu g/m^3$ for benzene, 23.93 $\mu g/m^3$ for toluene, 7.68 $\mu g/m^3$ for ethylbenzene, and 14.6 $\mu g/m^3$ for formaldehyde (Figure 4). This study is aimed at assessing the link between pollutant exposure and airway changes in 51 children with respiratory symptoms and found significant associations between VOCs and adverse outcomes. The study found significant associations between increased exposure to pollutants like PM_{10}, NO_2, benzene, toluene, and ethylbenzene and adverse respiratory outcomes. These findings explain the impact of VOCs on respiratory health, particularly in vulnerable populations such as children. In several studies, toluene is the dominant VOC, with Martins et al. in Portugal and S. Yang et al. [59] in Switzerland showing the highest mean concentrations at 23.93 and 28 $\mu g/m^3$, respectively. Formaldehyde levels are also among the highest, with Ninyà et al. [60] in Spain reporting 10.15 $\mu g/m^3$. Rösch et al. [61] in Germany recorded a notable concentration of 13.18 ± 16.91 $\mu g/m^3$ of toluene and a lower level of styrene at 0.83 ± 1.9 $\mu g/m^3$. Similarly, Alves et al. [62] in Portugal and Alvarez-Vaca et al. [63] in Luxembourg reported moderate levels of benzene and formaldehyde.

Several studies also investigated the influence of specific indoor activities and building characteristics. Ninyà et al. [60] monitored VOCs and semi-VOCs in homes and school settings in Tarragona, Spain, and found that the concentrations of solvents were significantly higher indoors than outdoors, particularly due to anti-COVID-19 measures. Rösch et al. identified the role of ventilation and furnishings in shaping VOC profiles. Alves et al. studied VOCs in kitchens and found that indoor sources significantly contributed to overall VOC levels, with variations depending on the type of cooking appliances used. Alvarez-Vaca et al. [63] analyzed VOC levels in Luxembourg households, identifying health risks associated with certain VOCs emitted from kitchen appliances. Finally, S. Yang et al. [59] examined VOC concentrations in energy-efficient dwellings in Switzerland, finding that energy renovation measures without adequate ventilation could lead to higher levels of indoor pollutants.

In the home, activities like cooking, cleaning, and the use of household products were identified as major sources of VOCs and semi-VOCs [57, 60, 62]. Building characteristics, such as energy-efficiency renovations, the presence of attached garages, and the absence of mechanical ventilation systems, contributed significantly to VOC concentrations [59, 63]. The studies highlight concerns over the health impacts of indoor air pollution. Some studies noted low cancer risk but emphasized the importance of long-term exposure monitoring [62, 63]. The shift to energy-efficient buildings has sometimes exacerbated IAQ problems, mainly due to reduced ventilation and the use of materials emitting VOCs. The combination of energy renovation and poor ventilation increased levels of VOCs, especially formaldehyde and toluene, which can lead to health risks [59, 61].

In most cases, indoor VOC levels were significantly higher than outdoor concentrations, suggesting that indoor environments are major sources of pollution. Traffic and industrial activities largely influenced outdoor VOC levels, whereas indoor VOCs were primarily linked to household activities and indoor sources. Several studies observed the influence of outdoor air quality and environmental factors like ventilation and temperature on indoor VOC levels. For example, outdoor $PM_{2.5}$ during winter could increase indoor particle levels due to less frequent ventilation [57], while seasonal variations and proximity to traffic influenced VOCs'

indoor/outdoor ratios [61, 62]. The findings suggest that even in energy-efficient and well-maintained dwellings, IAQ management needs to prioritize reducing long-term exposure to pollutants, particularly VOCs like formaldehyde and benzene. Combining VOCs from different sources can create complex exposure scenarios, complicating risk assessments.

3.1.3. VOC Concentration in Schools. In this section, 12 studies were selected for comparison in measuring VOCs in schools (Tables S16–S28). The challenges associated with different VOC measurements remain consistent with those previously described for offices and households, including differences in units of measurement, especially for TVOC concentrations. Four studies reported only TVOC concentrations, as shown in Table S1.

In the study by Konstantinou et al. [64], the median TVOC measured in primary schools was 2991.78 ppb, which is approximately 4240.18 $\mu g/m^3$. Rufo et al. [65] and Fuentes-Ferragud et al. [66] reported TVOC concentrations of 170 $\mu g/m^3$ and 0.08 ppm, while Ferreira and Cardoso [67] reported TVOC concentrations of 94.04 ppb. Individual VOC concentrations were measured in school environments in the remaining nine studies. Table S1 shows the concentration of the five common VOCs in these studies, which is graphically shown in Figure S2. As can be seen, the concentrations of the same VOCs in different schools of different countries are similar, with two outliers for formaldehyde in Madureira et al. [68] and Settimo et al. [69]. The high concentration of formaldehyde could be attributed to factors such as the presence of new building materials, furniture, or high usage of formaldehyde-based products in the school environment during the time of the study. Additionally, poor ventilation systems can exacerbate the accumulation of formaldehyde indoors. Benzene concentrations are relatively low across all studies, with the highest values reported by Settimo et al. (2.17 $\mu g/m^3$). Toluene concentrations vary, with the highest values reported by Martins et al. [58] (20.68 $\mu g/m^3$), Madureira et al. (15.1 $\mu g/m^3$), and Vornanen-Winqvist et al. [70] (16 $\mu g/m^3$). Marzocca et al. [71] and De Gennaro et al. [72] reported the lowest concentration values of all VOCs compared to other studies. Xylenes show moderate variability, with Madureira et al. (21.6 $\mu g/m^3$) reporting the highest concentration. Ethylbenzene has the highest values in Martins et al. and Ninyà et al. [60]. Gibson et al. [73] reported low VOC concentrations instead of formaldehyde, which was on average 12 $\mu g/m^3$. The study by Raffy et al. [74] only measured three infrequent VOCs: α-hexachlorocyclohexane (0.4 ng/m^3), γ-hexachlorocyclohexane (1 ng/m^3), and dichlorodiphenyltrichloroethane (1 ng/m^3), which were not measured in any of the other studies for comparison.

The studies on VOCs in schools show significant variations in IAQ due to different sources and activities. Martins et al. evaluated the relationship between air pollution and airway changes in children. They found that increased exposure to VOCs like benzene, toluene, and ethylbenzene was associated with decreased lung function and increased airway inflammation. Ninyà et al. [60] monitored VOCs and semi-VOCs in a school in Tarragona, Spain, and noted that indoor concentrations were significantly higher than outdoor levels, mainly due to increased cleaning activities and the use of hydroalcoholic gels as part of anti-COVID-19 measures. Madureira et al. [68] studied CO_2, PM_{10}, and VOCs in naturally ventilated primary schools in Porto, Portugal, and identified that reduced ventilation and indoor activities were major contributors to indoor air pollution. Their study indicated that indoor sources, occupant behavior, and maintenance activities influenced VOC levels. Vornanen-Winqvist et al. investigated the effects of a hybrid ventilation system on IAQ in a school building in Finland. They found that proper ventilation significantly reduced the concentrations of VOCs, particularly toluene, and improved perceived IAQ. Marzocca et al. [71] investigated a primary school in Taranto, Italy, near an industrial complex. They found that indoor VOC concentrations, particularly terpenes and 2-butoxyethanol, were significantly higher than outdoor levels, indicating strong indoor sources likely related to cleaning activities. Settimo et al. [69] emphasized the importance of understanding the impact of students' activities on IAQ. The study highlighted that regular air exchange and modernization of school facilities are crucial for improving IAQ, especially given the high occupancy and diverse school activities. De Gennaro et al. [72] monitored VOCs in eight naturally ventilated school buildings in Italy and identified high concentrations of terpenes such as α-pinene and limonene indoors, with lower outdoor levels. Gibson et al. [73] focused on libraries and archives. They found higher concentrations of acetic acid and furfural in locations with paper-based collections, suggesting these compounds as markers of cellulose degradation.

The studies on IAQ in schools reveal several findings regarding the health impacts and challenges of maintaining air quality in educational settings. Across multiple studies, high levels of $PM_{2.5}$, PM_{10}, CO_2, VOCs, and bioaerosols were consistently observed, often exceeding recommended guidelines. Poor ventilation emerged as a key issue contributing to elevated pollutant concentrations, particularly in classrooms with limited natural ventilation. This leads to high pollutant levels despite efforts to improve air exchange. For example, studies such as those conducted by Rufo et al. and Konstantinou et al. showed that even with interventions, high levels remained problematic, indicating that school ventilation strategies are often inadequate, failing to maintain air quality within safe limits. VOCs, especially those derived from indoor activities like cleaning (e.g., 2-butoxyethanol and terpenes) and outdoor infiltration (e.g., BTEX compounds), were a recurring theme. Fuentes-Ferragud et al.'s study on university classrooms highlights the role of poor ventilation in exacerbating pollutant levels and contributing to the presence of respiratory viruses such as rhinovirus/enterovirus. Interestingly, several studies pointed to specific indoor sources, such as cleaning products, materials used in classrooms, and student activities, which significantly impacted IAQ, increasing PM and VOC levels. For instance, Settimo et al.'s work shows the direct impact of student activities on pollutant concentrations, showing a sharp rise in pollutant concentrations during school hours compared to nonactive periods. Seasonal variations also have a significant role, as demonstrated in Ferreira

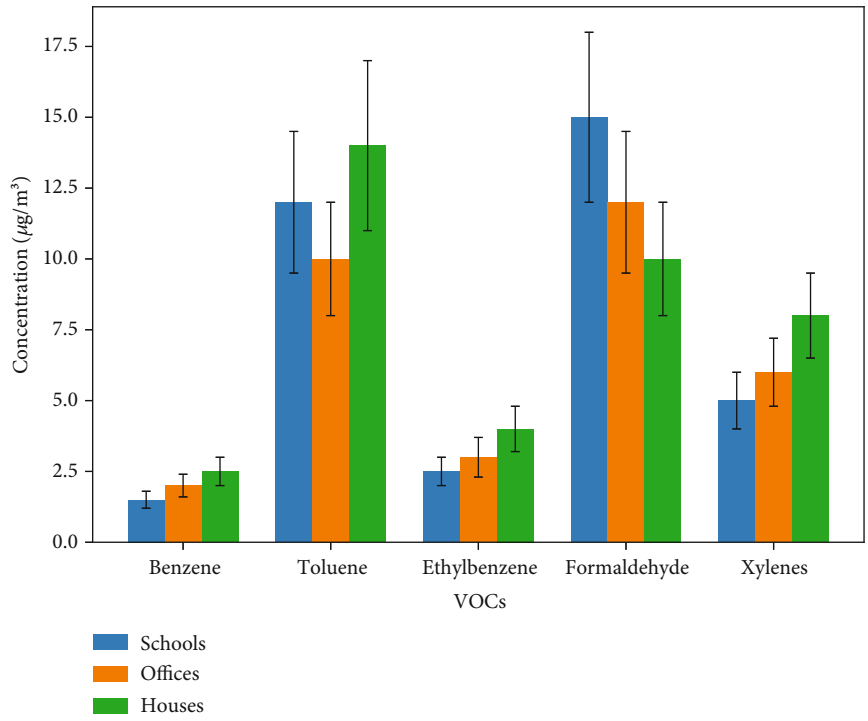

FIGURE 5: The mean VOC concentrations (micrograms per cubic meter) quantified in different environments with error bars indicating standard deviations.

and Cardoso's study in Portugal, where pollutant levels were higher in autumn/winter due to reduced ventilation caused by closed windows. Studies from Southern Europe, including Cyprus and Spain, studied the impact of the COVID-19 pandemic measures, where increased ventilation reduced pollutant levels but simultaneously led to higher indoor PM, suggesting that existing ventilation practices were not enough to ensure a healthy balance between controlling viral spread and reducing other pollutants.

In summary, the reviewed studies reveal that IAQ in schools across Europe varies considerably depending on building characteristics, ventilation strategies, and local activities. Portugal and Spain report some of the highest formaldehyde levels, particularly in poorly ventilated or newly renovated schools. Italy and Germany showed moderate to low levels of VOCs, while Finnish and Swedish schools demonstrated significantly lower levels of pollutants, especially after targeted ventilation improvements. Commonly elevated pollutants include toluene, formaldehyde, and benzene, while specific schools in industrial or densely urbanized areas recorded spikes in ethylbenzene and 2-butoxyethanol. Notably, Northern European countries tend to have cleaner indoor air in schools, likely reflecting stricter building codes, higher ventilation standards, and less reliance on emission-prone materials or cleaning agents.

Overall, these studies highlight the need for better IAQ strategies that involve regular monitoring, better ventilation systems, and reduced reliance on pollutant-heavy products and activities. The research calls for policy-level interventions to ensure that schools are equipped to maintain healthy IAQ levels, particularly in older buildings or during times of high occupancy.

Figure 5 visualizes the concentrations of five VOCs—benzene, toluene, ethylbenzene, formaldehyde, and xylenes across three different environments: schools, offices, and houses. The benzene concentration is relatively low across all environments, with minor variations. Concentrations are lower in schools and offices and slightly higher in houses. Toluene concentrations are highest in houses, followed by schools and offices. The high/large error bars indicate a significant variation in toluene concentrations, especially in houses. Ethylbenzene concentrations are relatively low across all environments, similar to benzene, with minimal differences. The measurement variation is also small, as indicated by the error bars. Formaldehyde shows a notably high concentration in schools, followed by offices and houses. The variation in formaldehyde concentrations is significant in all environments, particularly schools. Xylene concentrations are higher in houses, offices, and schools. The error bars show a moderate variation in xylene concentrations across different environments. The concentrations of toluene and formaldehyde were the highest among the measured VOCs, with considerable variability. The studies show that VOC concentrations differ significantly across various indoor environments like schools, homes, and offices due to diverse sources and ventilation conditions. In schools, VOC levels tend to increase due to materials like paints, cleaning products, and furniture, with insufficient ventilation worsens the issue. Formaldehyde, in particular, often exceeds recommended levels, posing health risks to occupants, especially in poorly ventilated classrooms. Similarly, homes show higher concentrations of toluene, xylenes, and formaldehyde, likely linked to the use of household chemicals, furniture, and building materials. Offices, although generally lower in VOC concentrations compared to homes, still exhibit

harmful levels of compounds like formaldehyde and benzene, likely originating from office equipment, furniture, and cleaning activities. Across all environments, poor ventilation remains a main factor contributing to higher VOC levels. The presence of high concentrations of formaldehyde and other VOCs in poorly ventilated areas underscores the importance of adopting IAQ monitoring and control strategies to reduce negative health effects in schools, offices, and homes.

3.1.4. Geographic, Seasonal, and Structural Variability in VOC Levels. The variability in indoor VOC concentrations observed across studies can be attributed in part to geographical differences, seasonal variation, and structural building characteristics. Many studies emphasize regional differences, with VOC profiles often reflecting local outdoor pollution levels, building materials, heating practices, and proximity to roads or industrial sources [59, 61, 64, 72]. For instance, VOCs linked to vehicular traffic or attached garages were reported in Switzerland and Australia [56, 59], while in Italy, emissions from indoor sources such as household products and furniture dominated IAQ [49]. Seasonal differences are also well documented, with higher VOC levels typically observed in winter due to reduced ventilation and increased heating demand [49, 57, 61]. Several studies, explicitly point to wintertime accumulation of VOCs, show the importance of seasonally contextualized analysis. Furthermore, building-related factors like construction year, materials, and energy-efficiency retrofits significantly affect VOC concentrations. For example, studies from Sweden and France found higher levels of TVOC and formaldehyde in energy-efficient dwellings with poor ventilation or recent retrofitting [56, 59]. Mechanical ventilation systems were consistently associated with lower VOC levels across several studies [59, 68], confirming the important role of air exchange. Newly built or recently renovated buildings showed elevated VOC levels, particularly during the first few months of occupancy [56], who reported VOC decay trends over time.

Differences also showed based on indoor activities and occupant behavior. Studies such as those by Gallon et al. [47], Martins et al. [58], and Rodrigues dos Santos et al. [54] show the contribution of consumer products, smoking, and human presence to overall VOC burdens. Finally, while a full quantitative harmonization was not feasible due to methodological heterogeneity, these diverse studies collectively revealed the importance of local context, building features, and temporal variability in interpreting indoor VOC levels. When comparing indoor VOC concentrations across Europe, some regional patterns become apparent. Homes, schools, and offices in Southern Europe—particularly in Portugal, Spain, and parts of Italy—tend to report higher concentrations of common VOCs such as toluene, formaldehyde, and TVOCs. This may reflect a combination of factors including warmer climates, more limited use of mechanical ventilation systems, and specific indoor sources like cleaning products or furnishings. For instance, Portuguese and Spanish schools frequently showed elevated formaldehyde and toluene levels, while Italian studies often reported high indoor concentrations of benzene and xylenes. In contrast, Northern and Central European countries such as Finland, Germany, and Poland generally show lower VOC concentrations in indoor environments, likely due to stricter building codes, more widespread mechanical ventilation, and colder climates that may reduce off-gassing from materials. Offices in France and Italy appeared to have higher VOC burdens than those in Poland, again possibly linked to differences in air exchange, building age, or occupancy density. In addition, the generally cleaner outdoor air in northern countries—driven by stronger regulatory frameworks, reduced use of fossil fuels for heating, and greater adoption of electric vehicles—likely contributes to lower indoor infiltration of VOCs from traffic and other urban sources.

3.2. PAHs in Indoor Spaces. Regarding the assessment of PAHs, the existing literature is divided into categories based on the environments studied (Table S2). A total of nine papers focus on the concentrations of dust-bound PAHs, while six studies investigate the concentrations of PM-bound PAHs within residential homes, offering a detailed analysis of IAQ and potential exposure risks in domestic settings. Furthermore, nine papers address PM-bound PAH concentrations in school environments.

3.2.1. Dust-Bound PAH Concentrations in Houses. Table S2 shows the concentrations of various PAHs measured in dust-bound samples within indoor houses across different studies (Tables S29–S37). The concentrations are given in two different units: picograms per cubic meter for Lim et al. [75] from Sweden and nanograms per gram of dust for the other studies. Lim et al. reported PAH concentrations such as BaP at 13.7 pg/m^3, benzo[a]anthracene (BaA) at 6.6 pg/m^3, and pyrene (Pyr) at 20.4 pg/m^3, with a total PAH concentration of 238.8 pg/m^3. In contrast, Fromme et al. [76] from Germany reported PAH concentrations with BaP at 270 ng/g, BaA at 290 ng/g, and Pyr at 670 ng/g, giving a total of 6340 ng/g. Studies from Croatia [77], Greece [78], Italy [79], and the Czech Republic [80] also reported varying levels of PAHs in indoor dust. Notably, the Greek study by Besis et al. [81] presented an exceptionally high total PAH concentration of 4650 ng/g, as well as individual PAH concentrations. This diversity of PAH concentrations highlights the variability in indoor air pollution across different regions and methodologies, and the differences in units in the Lim et al. study indicate a need for careful unit standardization when comparing such data. Simonetti et al. [82] reported that only total PAHs in two domestic environments were 417.2 and 5247.9 ng/g in indoor dust, represented here as an average. The average concentrations of dust-bound PAHs in the five studies with the most available data and the same unit of measurement are shown in Figure 6.

Lim et al. conducted a study in preschools in Stockholm, Sweden, analyzing PAHs in indoor dust and in PM in both indoor and ambient air. They identified vehicle emissions and biomass burning as significant sources of PAHs, with outdoor PM_{10} and indoor dust showing significant genotoxic potential despite relatively low PAH levels. Fromme

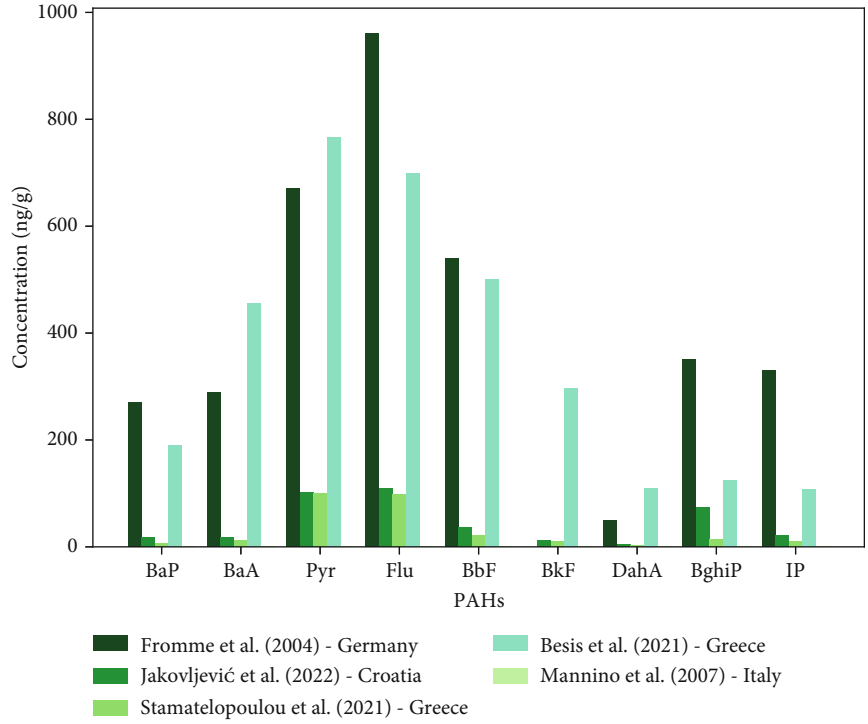

FIGURE 6: Concentration of dust-bound polycyclic aromatic hydrocarbons (PAHs) in households from reviewed papers. Standard deviation values were not available for most of these studies. Only studies that measured PAHs in settled indoor dust and reported individual compound concentrations in nanograms per gram using comparable analytical methods (e.g., GC-MS and HPLC) are included.

et al. [76] explored PAH concentrations in indoor and ambient air in Berlin residences, finding no significant differences between smoker and nonsmoker apartments, with vehicular emissions identified as a primary source for nonsmoker residences. Pieters et al. [83] focused on the impact of PAHs on mitochondrial DNA content in house dust and revealed that PAH exposure during winter is associated with mitochondrial damage, though no similar association was found during summer.

Jakovljević et al. [77] provided the first data on PAH levels in Croatian households, finding lower PAH levels compared to global reports but highlighting the elevated cancer risk for individuals exposed to the highest PAH concentrations, mainly from wood heating. Stamatelopoulou et al. [78] examined house dust in residences with young children in Athens, Greece, and found that PAHs and metals were the prevalent pollutants, with smoking, combustion processes, and traffic being significant contributors. The study concluded that the carcinogenic risk from PAHs was generally low, but ingestion of house dust posed the most important route of exposure to metals, particularly for children. Besis et al. [81] conducted the first comprehensive analysis of PAHs, polybrominated diphenyl ethers (PBDEs), polychlorinated biphenyls (PCBs), and nitrated polycyclic aromatic hydrocarbons (NPAHs) in Greek house dust. The study revealed that PAHs had the highest median concentrations among the contaminants, but the health risk assessment indicated that the hazard index for all groups was below one, suggesting a low level of concern for both adults and children. Mannino and Orecchio [79] investigated PAH concentrations in indoor dust samples from the Palermo area in Italy. The study demonstrated a wide range of PAH concentrations, where the presence of smokers significantly influenced PAH levels. Melymuk et al. [80] examined the distribution of SVOCs in different indoor matrices within a residential environment. The study showed that airborne SVOC concentrations can be estimated from dust and surface concentrations, while compounds like PAHs require direct measurement due to ongoing primary emissions. Simonetti et al. [82] focused on the occurrence of halogenated pollutants in indoor dust from homes and workplaces in Italy. The study revealed higher concentrations of these pollutants in electrotechnical and mechanical workshops compared to homes and offices. The study highlighted the importance of monitoring both domestic and occupational settings for comprehensive exposure assessment.

The analysis of dust-bound PAHs across various indoor environments shows that PAH contamination in indoor dust is influenced by both indoor activities, such as smoking, cooking, and the presence of electronic devices, as well as outdoor pollution sources, including vehicular emissions and residential heating [79]. Higher concentrations of PAHs are often detected in urban environments or locations with poor ventilation, revealing the significant role of outdoor air impact in indoor pollution. The presence of specific PAHs, such as BaP and other heavy PAHs, consistently shows a strong correlation with combustion-related activities, such as vehicle emissions, smoking, and biomass burning [77]. Seasonal variations also have a significant impact, with higher PAH concentrations observed during colder

months due to increased heating activities and reduced ventilation. Moreover, while the total PAH concentrations in household dust tend to be lower than in outdoor air, the presence of fine PM in indoor dust is a significant concern, especially for vulnerable populations such as children, the elderly, and those with compromised health. PAH exposure through ingestion, inhalation, and dermal contact, particularly in homes with young children, indicates that dust ingestion remains the primary route of exposure. However, most studies show that the estimated daily intake of PAHs is generally below harmful levels, although long-term exposure risks should not be overlooked.

Several studies included in this review reported PAH diagnostic ratios to help with understanding the dominant emission sources contributing to indoor dust contamination. For example, Jakovljević et al. calculated fluoranthene (Flu)/(Flu + Pyr) ratios ranging from 0.46 to 0.65, indicating mixed sources, primarily traffic-related and biomass combustion. Ratios such as BaP/benzo[g,h,i]perylene (BghiP) (0.14–0.86) and indeno[1,2,3-cd]pyrene (IP)/(IP + BghiP) (0.07–0.49) further suggested contributions from gasoline combustion and pyrogenic sources. Similarly, Stamatelopoulou et al. and Besis et al. applied diagnostic ratios, confirming biomass burning and vehicle emissions as primary PAH sources in Greek households. These findings support the broader interpretation that combustion processes—both indoor and outdoor—are the main contributors to indoor PAH concentrations. However, the interpretation of diagnostic ratios in indoor environments should be approached with caution, as aging, degradation, and mixed-source inputs can complicate source apportionment.

The conclusions from these studies emphasize the need for regular monitoring of indoor PAHs, particularly in environments with continuous human exposure. The use of indoor dust as a passive sampler offers a cost-effective and representative method to assess PAH contamination and human exposure. However, these findings suggest that ongoing emissions from both outdoor and indoor sources must be addressed through better ventilation practices and emission control to reduce health risks.

3.2.2. PAH Concentration in Air in Houses. In comparing PAHs measured in homes, it is important to note that different studies employed various methodologies, making direct comparisons challenging. For instance, some studies measured PAHs in $PM_{2.5}$, and other studies focused on PM_{10}. Additionally, certain studies reported the sum of gaseous PAHs and PM-bound PAHs, providing a more comprehensive picture of the total PAH burden but complicating direct comparisons with studies measuring only particulate-bound PAHs. To address these differences, this review categorizes the findings based on the measurement method and discusses them within these contexts. While quantitative comparisons are limited due to methodological variations, qualitative assessments can still provide valuable information about the trends and patterns of PAH concentrations in residential environments. Tables S38–S43 summarize the concentrations of indoor PAHs in house environments across several studies. Choi and Spengler [84] reported concentrations of PAHs in $PM_{2.5}$ in Poland, with a total of 6.37 ng/m^3 of seven measured PAHs. They found significant contributions of ambient sources to indoor PAH levels, especially in nonsmoking homes, whereas indoor smoking notably increased PAH levels. Alves et al. [62] also measured PAH concentrations in $PM_{2.5}$ in Portugal and reported lower concentrations for most PAHs, such as BaP at 0.41 ng/m^3 and benzo[b]fluoranthene (BbF) at 0.53 ng/m^3, with a total of 5.53 ng/m^3 for 13 measured PAHs. Rybak et al. [85] observed a total concentration of 31.51 ng/m^3 in Poland. This study measured 15 PAHs using spider webs prepared in the laboratory and exposed to indoor air pollution, considering variables such as location, type of room, inhabitants' habits, and heating devices. Gustafson et al. [86] measured gaseous and PM-bound PAHs in Sweden, reporting moderate levels, such as Pyr at 1.72 ng/m^3 and Flu at 2.2 ng/m^3. They reported significantly higher PAH levels in homes using wood-burning appliances, raising concerns about the associated health risks. Gaseous and PM-bound PAHs were also measured in Loive et al. [87] in Sweden with a wide range of concentrations for some PAHs, such as BaP ranging from 0.01 to 0.85 ng/m^3 and Flu ranging from 0.25 to 81 ng/m^3, showing the variability in indoor PAH levels. De Gennaro et al. [88] in Italy measured concentrations of PAHs in PM_{10}, with BaA at 18.96 ng/m^3 and BghiP at 12.42 ng/m^3. The concentrations were high in homes with wood stoves, emphasizing the impact of biomass combustion on IAQ.

Indoor PAHs originate from various sources, including biomass burning, cooking, tobacco smoke, and materials treated with creosote or other chemicals, as well as infiltration from outdoor air pollution. Studies like those by Gustafson et al. [86] and De Gennaro et al. [72] focus on the impact of wood-burning stoves and fireplaces, showing that homes utilizing such heating systems have markedly higher indoor PAH concentrations, especially during combustion phases. Indoor BaP levels often exceeded health guidelines, revealing a significant carcinogenic potential due to incomplete combustion by-products. The heterogeneity in pollution levels, even among houses with similar heating systems, suggests that combustion practices, ventilation, and stove designs play major roles in determining exposure risks. Several studies, such as Choi and Spengler and Alves et al. [62, 84], demonstrate that outdoor air is a dominant source of PAH contamination in indoor environments, particularly for homes located near traffic or other combustion sources. In many cases, PAHs of outdoor origin, such as BaA, BbF, and benzo[k]fluoranthene (BkF), make up a significant part of the indoor air concentrations. Smoking and cooking are repeatedly identified as major indoor sources of PAHs. The study by Loive et al. [87] emphasizes that even materials like creosote-treated wood can act as persistent sources of PAHs over long periods, contributing significantly to indoor pollution levels. Across multiple studies, BaP and other high molecular weight (HMW) PAHs are frequently identified as the most concerning due to their carcinogenic properties. The cancer potency of PAH mixtures, often measured in BaP equivalents, commonly exceeds safety thresholds, particularly in environments with biomass

burning or creosote-treated materials. However, as noted in Loive et al., other PAHs such as Flu, phenanthrene, and NPAHs also contribute significantly to overall cancer risk. Poor ventilation practices can exacerbate the accumulation of PAHs indoors, while regular ventilation during combustion can significantly reduce the risk of prolonged exposure. These findings suggest that improving building ventilation and adopting cleaner combustion technologies are key strategies to reduce PAH exposure and improve IAQ.

Across the reviewed studies, PAH concentrations in residential indoor environments show considerable variability, driven by regional differences, building characteristics, and indoor activities. Homes in Southern and Eastern Europe generally reported higher PAH levels, with standout concentrations in Greece and Germany, often linked to the use of wood stoves, tobacco smoke, and poor ventilation. The most frequently detected PAHs include BaP, BaA, BbF, and Pyr—compounds associated with combustion sources. Diagnostic ratios, when available, confirm that biomass burning and traffic emissions are dominant contributors to indoor PAH profiles. Seasonal trends were also noted, with winter months typically associated with elevated PAH concentrations due to increased heating and reduced air exchange. While some studies like those from Sweden and Portugal indicated relatively low PAH concentrations, even these environments showed evidence of genotoxicity or source infiltration from ambient air. Overall, the studies revealed that indoor PAH exposure in homes is not negligible and may exceed health-based guidelines, especially in settings with poor ventilation or intensive combustion activities. To conclude, there is a need for continued monitoring of PAHs and other toxic organic compounds in indoor environments, particularly in homes using biomass for heating or containing older construction materials like creosote-treated wood. The findings consistently show that indoor PAH levels are strongly influenced by both outdoor pollution and indoor sources like smoking, cooking, and heating practices. The carcinogenic risk associated with indoor PAH exposure, particularly from compounds like BaP and its equivalents, underscores the need for comprehensive risk assessments, which consider both gas- and particulate-phase compounds, to protect human health. Enhanced ventilation, improved combustion technologies, and targeted mitigation strategies for homes with high PAH emissions are essential to reduce exposure and associated health risks.

3.2.3. PAH Concentrations in Air in Schools. Tables S44–S52 present the concentrations of various PAHs in the indoor air of schools from multiple studies, showing significant variation across different regions. As well as in measurements in houses, different studies employed various methodologies, making direct comparisons of the studies challenging. Lim et al. [75] from Sweden reported PAH concentrations in PM_{10}, with individual PAHs ranging from 0.002 ng/m^3 for dibenzo[a,h]anthracene (DahA) to 0.021 ng/m^3 for Flu. Rogula-Kozłowska et al. [89] from Poland showed a total PAH concentration of 16.1 ng/m^3, with individual levels from 0.25 ng/m^3 for DahA to 2.38 ng/m^3 for BaP measured in PM_1. Romagnoli et al. [90] from Italy reported concentrations in $PM_{2.5}$ with a total of 2.79 ng/m^3, where individual PAHs range from 0.05 ng/m^3 for DahA to 0.5 ng/m^3 for BbF. PAHs in $PM_{2.5}$ were also measured in Błaszczyk et al. [91] from Poland with a total concentration of 33.75 ng/m^3 and individual PAHs ranging from 0.4 ng/m^3 for DahA to 3.65 ng/m^3 for BghiP. Oliveira et al. [92] from Portugal indicated a total gaseous and PM-bound PAH concentration of 35.78 ng/m^3, with individual levels from 0.13 ng/m^3 for BaA to 1.9 ng/m^3 for DahA. Additional context includes measured SUM of PAHs in Cirillo et al. [93] from Italy with 1.9 ng/m^3 for gaseous PAHs and for PM-bound PAHs in Fiala et al. [94] from the Czech Republic with 7.04 ng/m^3, Mortamais et al. [95] from Spain with 1107 pg/m^3, and Van Drooge et al. [96] from Spain with 500–3900 pg/m^3.

Lim et al. [75] investigated PAHs in Stockholm preschools, finding significant correlations between outdoor and indoor PM_{10} levels, with vehicle emissions and biomass burning as main sources. Rogula-Kozłowska et al. [89] studied PAH concentrations in teaching rooms in Poland and noted higher outdoor concentrations and a potential unidentified indoor source of gaseous PAHs in Warsaw. Romagnoli et al. [90] assessed air quality in various microenvironments in Rome and identified motor vehicles, biomass burning, and soil resuspension as primary PAH sources. Oliveira et al. [92] focused on a preschool in Portugal, emphasizing the predominance of gaseous PAHs and the significant impact of outdoor emissions on IAQ. Błaszczyk et al. [91] examined $PM_{2.5}$-bound PAHs in Polish kindergartens and reported high levels of $PM_{2.5}$ and PAHs both indoors and outdoors, with solid fuel combustion identified as a significant source. Cirillo et al. [93] focused on multipathway exposure to PAHs among children in urban and rural areas of Campania, Italy, and highlighted that food was the primary source of PAH exposure. Fiala et al. [94] assessed PAH intake in children in a Czech city and found that food consumption was a more significant contributor to PAH exposure than air inhalation or soil ingestion. Mortamais et al. [95] investigated the association between PAH exposure and ADHD (attention-deficit hyperactivity disorder) symptoms in children in Barcelona, Spain, and noted a significant link between PAH levels and changes in brain structures, although behavioral effects were not identified. Van Drooge et al. [96] analyzed $PM_{2.5}$ aerosols in Barcelona primary schools and identified traffic emissions as the primary source of PAHs in both indoor and outdoor environments. The concentrations were higher in schools located in high-traffic areas, with a significant transfer of outdoor pollutants to indoor air.

Across multiple studies, outdoor sources, especially traffic emissions and biomass burning, were identified as major contributors to indoor PAH levels in schools. Even in well-regulated environments like Sweden and Italy, significant amounts of PAHs penetrate indoors from external sources. Fine PM containing PAHs is particularly concerning due to its ability to reach the alveoli and enter the bloodstream. Several studies pointed to the heightened toxicity of these particles and their association with mutagenic and carcinogenic effects, especially in urban or industrial areas. Smoking, cleaning products, and cooking activities were

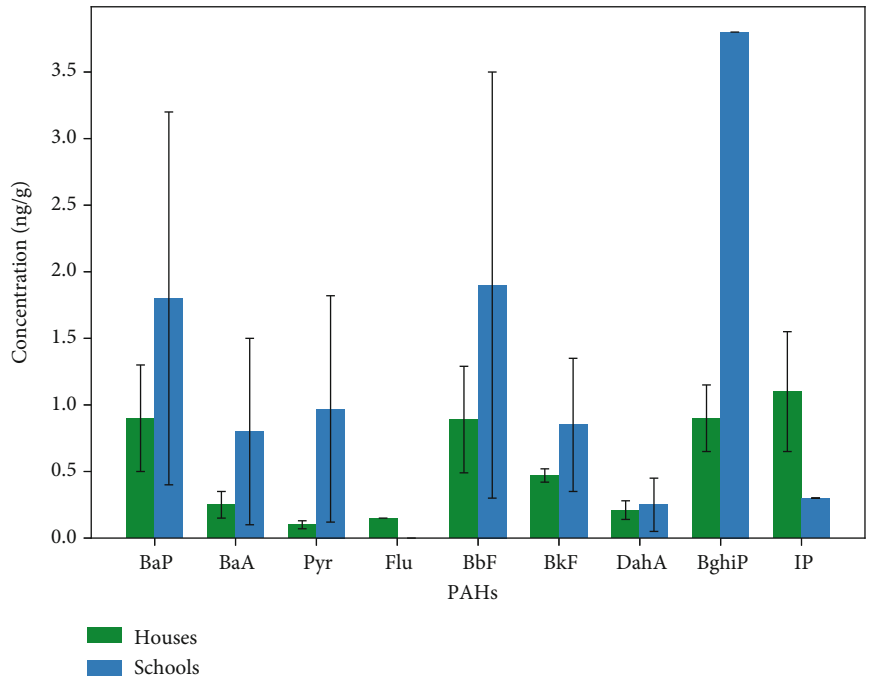

FIGURE 7: Differences in concentration of PAHs in $PM_{2.5}$ in houses and schools.

identified as significant contributors to indoor PAH levels in schools. These sources complicate air quality management because they can lead to higher indoor concentrations of specific PAHs, even when outdoor air is relatively clean. While inhalation is a significant route of exposure, several studies highlighted the importance of food as a major contributor to children's overall PAH intake. This points to the need for multipathway exposure assessments in studies of school environments. Children, as one of the most vulnerable groups, are disproportionately affected by PAH exposure due to their developing physiology and higher intake per body weight. The neurodevelopmental impact, as seen in the study linking PAHs to reduced caudate nucleus volume, further underscores the need for stringent air quality control in schools [95].

Figure 7 compares the concentrations of $PM_{2.5}$-bound PAHs between houses and schools. The results show that schools have significantly higher concentrations of PAHs compared to houses for most of the compounds. Specifically, the concentrations of BaA, Pyr, BbF, and BghiP are notably higher in schools. In contrast, the concentration of IP is higher in houses than in schools. Other PAHs such as BaP, BkF, and DahA also show higher concentrations in schools, but the differences are less pronounced compared to others. Among the PAHs most frequently reported in the reviewed studies, several belong to the Group B2 carcinogens as classified by the United States Environmental Protection Agency (US EPA). These include BaA, BbF, BkF, BaP, IP, DahA, and chrysene (Chry). This group is considered a "probable human carcinogen" based on sufficient evidence from studies. Notably, most of these HMW PAHs are consistently detected in both dust- and PM-bound indoor samples, often in homes using biomass for heating or with poor ventilation. Their presence across multiple indoor environments emphasizes the need for targeted risk assessments that account for their higher toxicological relevance. In addition to US EPA Group B2 classification, PAHs are commonly divided by molecular weight into LMW PAHs (two to three aromatic rings, e.g., naphthalene, fluorene, phenanthrene, and Flu) and HMW PAHs (four or more rings, e.g., BaP, BbF, BkF, IP, and DahA). This classification is important because HMW PAHs tend to be more carcinogenic and mutagenic and are typically bound to particles, while LMW PAHs are more volatile, often found in the gas phase, and associated with short-term respiratory effects. Across the reviewed studies, HMW PAHs such as BaP, BbF, BkF, IP, and DahA were consistently reported to have higher concentrations in homes using wood stoves or located near traffic or industrial sources [86, 88]. In contrast, LMW PAHs such as fluorene, phenanthrene, and Pyr were more evenly distributed across different settings and showed higher variability, especially in studies measuring total (gas + particulate) phases [86, 87]. This suggests that while both LMW and HMW PAHs contribute to overall exposure, HMW PAHs pose a greater long-term health risk, particularly in poorly ventilated indoor environments or those with combustion-related activities.

Across all studies focusing on PAHs in dust and PM, both houses and schools are significantly impacted by these pollutants, but schools present some unique challenges and exposure patterns. In educational settings, elevated PAH concentrations are consistently observed in environments near traffic or biomass burning sources, such as in Poland, Spain, and Portugal. The studies show that indoor PAH levels in schools are often closely tied to outdoor concentrations, particularly in urban and high-traffic areas, with limited ventilation exacerbating pollutant accumulation indoors. Certain compounds like BaA, BbF, and BghiP were more frequently detected at higher levels in schools than in

homes, possibly due to specific building materials, maintenance activities, and cleaning routines. Importantly, children's vulnerability and prolonged occupancy during school hours raise serious concerns, especially as some measured BaP levels approached or exceeded health guideline thresholds. Studies from Southern Europe also show the compounding impact of inadequate ventilation during colder seasons, which intensified indoor PAH levels. These findings underscore the need for targeted air quality interventions in school environments, including improved ventilation design, source control, and regular monitoring to protect child health.

3.2.4. Geographic, Seasonal, and Structural Variability in PAH Levels. Indoor PAH concentrations vary widely across Europe due to differences in climate, building design, heating practices, urbanization, and ambient air quality. A clear geographic pattern is evident when comparing dust- or PM-bound PAH levels across homes, schools, and other buildings. Southern and Eastern European countries—such as Greece [78, 81], Italy [79, 90], and Poland [85, 89]—tend to report significantly higher indoor PAH concentrations than Northern or Western European countries like Sweden [75, 87], Germany [76], or Luxembourg [63]. This likely reflects the combined influence of outdoor pollution infiltration, more frequent use of solid fuel heating, and less strict regulatory control on emissions in some regions. In contrast, Scandinavian countries generally show lower PAH levels indoors, attributed to cleaner ambient air due to strict environmental regulations, increasing adoption of electric vehicles, and widespread use of district heating instead of wood combustion. Seasonal variability also has an influence on PAH levels. Many studies observe higher indoor PAH concentrations during colder months due to increased heating demand, particularly from wood-burning stoves or fireplaces [77, 86, 92]. For example, Loive et al. reported that winter outdoor PAH levels in Sweden were seven times higher than in summer, but indoor concentrations remained stable in buildings with creosote-impregnated materials, underscoring the importance of persistent indoor sources. In southern and eastern countries, where winter heating often relies on solid fuels, the seasonal differences in indoor PAHs were even more pronounced. Structural characteristics of buildings also influence indoor PAH levels. Buildings with older construction materials, such as those impregnated with creosote, show elevated and sustained PAH emissions independent of season. Likewise, houses with poor ventilation, frequent indoor smoking, or proximity to traffic sources exhibit higher levels. Building use also matters—schools, homes, and offices show different exposure profiles. Homes typically exhibit higher variability due to individual behaviors like cooking or heating, while schools show more consistent levels but are often closer to traffic sources, as seen in Van Drooge et al., where indoor and outdoor PAH levels in Barcelona schools were nearly identical due to infiltration.

3.2.5. Methodological Variability and Limitations. Across the included studies, there is substantial heterogeneity in the measurement approaches for PAHs, including differences in particle size fractions (e.g., PM_1, $PM_{2.5}$, and PM_{10}), inclusion of gaseous and/or particulate phases, sampling media (e.g., air and dust), and reporting units (e.g., nanograms per cubic meter, picograms per cubic meter, and nanograms per gram). These differences limit the potential for direct quantitative comparisons between studies. To address this, we categorized studies based on their measurement matrix (e.g., dust-bound vs. PM-bound PAHs) and were careful not to directly compare concentrations across fundamentally different methodologies. The inconsistency in reporting practices reinforces the goal of initiatives like the EDIAQI project, which seek to standardize data collection and facilitate robust cross-study comparisons. Among the included dust-bound PAH studies, we observed considerable methodological variation in terms of sampling techniques, analytical procedures, and units of measurement. To ensure valid comparisons, we only compared (Figure 6) studies that used settled indoor dust as sampling media, reported individual PAH concentrations in nanograms per gram, and applied similar analytical techniques (e.g., GC-MS or HPLC). Other studies, which reported picograms per cubic meter or total PAHs, were excluded from this comparison and are compared to other similar studies.

For air-based PAH measurements, studies varied in both sampling and analysis. Airborne PAHs were typically collected using active air samplers with filters (e.g., quartz filters) or polyurethane foam (PUF) cartridges. Filters targeted PM-bound PAHs (with size cutoffs like $PM_{2.5}$ or PM_{10}), while PUFs captured gas-phase compounds. Sampling durations ranged from 8 h to several days. After collection, PAHs were extracted and analyzed mostly via GC-MS or HPLC. In some studies, simultaneous indoor and outdoor sampling was conducted to evaluate infiltration. Differences in sampling duration, flow rate, and particle phase inclusion (gas vs. particle) make it inappropriate to compare air-based and dust-based concentrations directly. These methodological differences were accounted for in our analysis by organizing studies according to sampling matrix and reporting units and ensuring that comparisons were only made within compatible categories.

4. Conclusion

This review represents differences in indoor air pollution across Europe, explaining relationships between indoor sources, building characteristics, regional practices, and ambient air quality. VOC levels tend to be higher in Southern and Eastern European countries, where ventilation practices, heating methods, and building materials may contribute to elevated concentrations. Compounds such as BTEX and formaldehyde were most frequently reported, particularly in naturally ventilated environments and energy-efficient homes without adequate air exchange. Evidence from studies also indicates that human activities, such as cleaning, cooking, and the use of consumer products, remain dominant indoor VOC sources. PAHs, on the other hand, showed strong seasonal and geographical variability. Higher concentrations were typically observed in colder regions with greater reliance on biomass combustion and limited ventilation. While dust-bound PAHs provided

information about long-term accumulation and ingestion-related exposure, airborne PM-bound PAHs posed a greater concern for respiratory and systemic health effects due to their particle-bound carcinogenic compounds, such as BaP. Diagnostic ratios and molecular weight differences across studies pointed to combustion-related sources (e.g., traffic and wood burning) as dominant contributors, with limited influence from petrogenic or industrial emissions in most indoor settings.

The integration of these findings shows the need for targeted policy action and harmonized measurement approaches. Current inconsistencies in sampling, analysis, and reporting limit the comparability of data across Europe. Without standardized protocols, robust risk assessment and cross-country policy alignment remain difficult. This review highlights the urgency of EU-wide efforts to develop unified IAQ guidelines and monitoring strategies. Coordinated regulatory frameworks, public health education, and technological improvements in ventilation and materials are essential to reduce exposure and improve indoor environments across Europe.

Data Availability Statement

The datasets generated and/or analyzed during the current study are available from the corresponding author upon reasonable request.

Ethics Statement

Since this study did not collect personal information, no ethical approval was required.

Conflicts of Interest

The authors declare no conflicts of interest.

Author Contributions

Conceptualization: Nikolina Račić and Mario Lovrić. Data curation: Nikolina Račić, Ivana Terzić, and Nina Karlović. Formal analysis: Nikolina Račić. Investigation: Nikolina Račić, Ivana Terzić, Nina Karlović, Anja Bošnjaković, Teo Terzić, Ivana Jakovljević, Tajana Horvat, Goran Gajski, Marko Gerić, Sandra Vitko, Iva Šunić, Michael Forsmann, Ivana Banić, Marcel Lipej, Olga Malev, and Bojana Žegura. Methodology: Nikolina Račić and Mario Lovrić. Supervision: Mario Lovrić. Validation: Mario Lovrić and Gordana Pehnec. Visualization: Nikolina Račić and Mario Lovrić. Roles/writing—original draft: Nikolina Račić. Writing—review and editing: Nikolina Račić, Mario Lovrić, Gordana Pehnec, Pasquale Avino, Francesco Mureddu, and Jon Switters.

Funding

This work was supported by the Horizon Europe (EDIAQI Project #101057497), European Regional Development Fund Project KK.01.1.1.02.0007 (Rec-IMI), the Croatian Science Foundation (HUMNap Project #1192), the European Union—Next Generation EU 533-03-23-0006 (BioMolTox and EnvironPollutHealth), and the Slovenian Research and Innovation Agency (P1–0245).

Supporting Information

Additional supporting information can be found online in the Supporting Information section. *(Supporting Information)* Supporting Information includes a detailed description of the search strategy and the compounds assessed in this review. Tables S1 and S2 provide summary data on average VOC and PAH concentrations across different indoor environments, including standard deviations where available. Tables S3–S52 present measured concentration values from all included studies.

References

[1] European Environment Agency, "Europe's Air Quality Status 2023" 2023, http://www.eea.europa.eu/publications/europes-air-quality-status-2023.

[2] J. A. Becerra, J. Lizana, M. Gil, A. Barrios-Padura, P. Blondeau, and R. Chacartegui, "Identification of Potential Indoor Air Pollutants in Schools," *Journal of Cleaner Production* 242 (2020): 118420, https://doi.org/10.1016/j.jclepro.2019.118420.

[3] S. Raju, T. Siddharthan, and M. C. McCormack, "Indoor Air Pollution and Respiratory Health," *Clinics in Chest Medicine* 41, no. 4 (2020): 825–843, https://doi.org/10.1016/j.ccm.2020.08.014.

[4] K. W. Tham, "Indoor Air Quality and Its Effects on Humans—A Review of Challenges and Developments in the Last 30 Years," *Energy and Buildings* 130 (2016): 637–650, https://doi.org/10.1016/j.enbuild.2016.08.071.

[5] W.-T. Tsai, "An Overview of Health Hazards of Volatile Organic Compounds Regulated as Indoor Air Pollutants," *Reviews on Environmental Health* 34, no. 1 (2019): 81–89, https://doi.org/10.1515/reveh-2018-0046.

[6] World Health Organization, "Household Air Pollution Attributable Deaths" 2023, https://www.who.int/data/gho/data/indicators/indicator-details/GHO/household-air-pollution-attributable-deaths.

[7] L. Kazensky, K. Matković, M. Gerić, B. Žegura, G. Pehnec, and G. Gajski, "Impact of Indoor Air Pollution on DNA Damage and Chromosome Stability: A Systematic Review," *Archives of Toxicology* 98, no. 9 (2024): 2817–2841, https://doi.org/10.1007/s00204-024-03785-4.

[8] K.-H. Kim, S. A. Jahan, E. Kabir, and R. J. C. Brown, "A Review of Airborne Polycyclic Aromatic Hydrocarbons (PAHs) and Their Human Health Effects," *Environment International* 60 (2013): 71–80, https://doi.org/10.1016/j.envint.2013.07.019.

[9] M. Masiol, A. Hofer, S. Squizzato, R. Piazza, G. Rampazzo, and B. Pavoni, "Carcinogenic and Mutagenic Risk Associated to Airborne Particle-Phase Polycyclic Aromatic Hydrocarbons: A Source Apportionment," *Atmospheric Environment* 60 (2012): 375–382, https://doi.org/10.1016/j.atmosenv.2012.06.073.

[10] R. Stading, G. Gastelum, C. Chu, W. Jiang, and B. Moorthy, "Molecular Mechanisms of Pulmonary Carcinogenesis by Polycyclic Aromatic Hydrocarbons (PAHs): Implications for Human Lung Cancer," *Seminars in Cancer Biology* 76 (2021): 3–16, https://doi.org/10.1016/j.semcancer.2021.07.001.

[11] P. K. Verma, D. Sah, J. Dubey, K. M. Kumari, and A. Lakhani, "Mutagenic and Cancer Risk Estimation of Particulate Bound

Polycyclic Aromatic Hydrocarbons From the Emission of Different Biomass Fuels," *Chemical Research in Toxicology* 34, no. 3 (2021): 743–753, https://doi.org/10.1021/acs.chemrestox.0c00378.

[12] M. Engraff, C. Solere, K. E. C. Smith, P. Mayer, and I. Dahllöf, "Aquatic Toxicity of PAHs and PAH Mixtures at Saturation to Benthic Amphipods: Linking Toxic Effects to Chemical Activity," *Aquatic Toxicology* 102, no. 3–4 (2011): 142–149, https://doi.org/10.1016/j.aquatox.2011.01.009.

[13] Z. Nováková, J. Novák, Z. Kitanovski, et al., "Toxic Potentials of Particulate and Gaseous Air Pollutant Mixtures and the Role of PAHs and Their Derivatives," *Environment International* 139 (2020): 105634, https://doi.org/10.1016/j.envint.2020.105634.

[14] A. C. Olsson, J. Fevotte, T. Fletcher, et al., "Occupational Exposure to Polycyclic Aromatic Hydrocarbons and Lung Cancer Risk: A Multicenter Study in Europe," *Occupational and Environmental Medicine* 67, no. 2 (2010): 98–103, https://doi.org/10.1136/oem.2009.046680.

[15] B. Bukowska, K. Mokra, and J. Michałowicz, "Benzo [a]pyrene—Environmental Occurrence, Human Exposure, and Mechanisms of Toxicity," *International Journal of Molecular Sciences* 23, no. 11 (2022): 6348, https://doi.org/10.3390/ijms23116348.

[16] C. B. B. Guerreiro, J. Horálek, F. De Leeuw, and F. Couvidat, "Benzo (a)pyrene in Europe: Ambient Air Concentrations, Population Exposure and Health Effects," *Environmental Pollution* 214 (2016): 657–667, https://doi.org/10.1016/j.envpol.2016.04.081.

[17] L. Yang, H. Zhang, X. Zhang, et al., "Exposure to Atmospheric Particulate Matter-Bound Polycyclic Aromatic Hydrocarbons and Their Health Effects: A Review," *International Journal of Environmental Research and Public Health* 18, no. 4 (2021): 2177, https://doi.org/10.3390/ijerph18042177.

[18] K. Peng, Z. Li, T.-R. Gao, et al., "Polycyclic Aromatic Hydrocarbon Exposure Burden: Individual and Mixture Analyses of Associations With Chronic Obstructive Pulmonary Disease Risk," *Environmental Research* 222 (2023): 115334, https://doi.org/10.1016/j.envres.2023.115334.

[19] Y. Xiao, L. Zhang, H. Liu, and W. Huang, "Systemic Inflammation Mediates Environmental Polycyclic Aromatic Hydrocarbons to Increase Chronic Obstructive Pulmonary Disease Risk in United States Adults: A Cross-Sectional NHANES Study," *Frontiers in Public Health* 11 (2023): 1248812, https://doi.org/10.3389/fpubh.2023.1248812.

[20] P. Boffetta, N. Jourenkova, and P. Gustavsson, "Cancer Risk From Occupational and Environmental Exposure to Polycyclic Aromatic Hydrocarbons," *Cancer Causes and Control* 8, no. 3 (1997): 444–472, https://doi.org/10.1023/A:1018465507029.

[21] N.-D. Dat and M. B. Chang, "Review on Characteristics of PAHs in Atmosphere, Anthropogenic Sources and Control Technologies," *Science of the Total Environment* 609 (2017): 682–693, https://doi.org/10.1016/j.scitotenv.2017.07.204.

[22] V. Kumar, N. C. Kothiyal, Saruchi, P. Vikas, and R. Sharma, "Sources, Distribution, and Health Effect of Carcinogenic Polycyclic Aromatic Hydrocarbons (PAHs) – Current Knowledge and Future Directions," *Journal of the Chinese Advanced Materials Society* 4, no. 4 (2016): 302–321, https://doi.org/10.1080/22243682.2016.1230475.

[23] N. Marchand, J. L. Besombes, N. Chevron, P. Masclet, G. Aymoz, and J. L. Jaffrezo, "Polycyclic Aromatic Hydrocarbons (PAHs) in the Atmospheres of Two French Alpine Valleys: Sources and Temporal Patterns," *Atmospheric Chemistry and Physics* 4, no. 5 (2004): 1167–1181, https://doi.org/10.5194/acp-4-1167-2004.

[24] A. B. Patel, S. Shaikh, K. R. Jain, C. Desai, and D. Madamwar, "Polycyclic Aromatic Hydrocarbons: Sources, Toxicity, and Remediation Approaches," *Frontiers in Microbiology* 11 (2020): 562813, https://doi.org/10.3389/fmicb.2020.562813.

[25] K. Ravindra, R. Sokhi, and R. Vangrieken, "Atmospheric Polycyclic Aromatic Hydrocarbons: Source Attribution, Emission Factors and Regulation," *Atmospheric Environment* 42, no. 13 (2008): 2895–2921, https://doi.org/10.1016/j.atmosenv.2007.12.010.

[26] L. Bai and C. Li, "Investigation of Indoor Polycyclic Aromatic Hydrocarbons (PAHs) in Rural Northeast China: Pollution Characteristics, Source Analysis, and Health Assessment," *Buildings* 12, no. 2 (2022): 153, https://doi.org/10.3390/buildings12020153.

[27] M. Wang, S. Jia, S. H. Lee, A. Chow, and M. Fang, "Polycyclic Aromatic Hydrocarbons (PAHs) in Indoor Environments Are Still Imposing Carcinogenic Risk," *Journal of Hazardous Materials* 409 (2021): 124531, https://doi.org/10.1016/j.jhazmat.2020.124531.

[28] H. Kamani, M. Baniasadi, H. Abdipour, et al., "Health Risk Assessment of BTEX Compounds (Benzene, Toluene, Ethylbenzene and Xylene) in Different Indoor Air Using Monte Carlo Simulation in Zahedan City, Iran," *Heliyon* 9, no. 9 (2023): e20294, https://doi.org/10.1016/j.heliyon.2023.e20294.

[29] M. A. Zahed, S. Salehi, M. A. Khoei, P. Esmaeili, and L. Mohajeri, "Risk Assessment of Benzene, Toluene, Ethyl Benzene, and Xylene (BTEX) in the Atmospheric Air Around the World: A Review," *Toxicology In Vitro* 98 (2024): 105825, https://doi.org/10.1016/j.tiv.2024.105825.

[30] Y. Liu, L. Kong, X. Liu, et al., "Characteristics, Secondary Transformation, and Health Risk Assessment of Ambient Volatile Organic Compounds (VOCs) in Urban Beijing, China," *Atmospheric Pollution Research* 12, no. 3 (2021): 33–46, https://doi.org/10.1016/j.apr.2021.01.013.

[31] World Health Organization (WHO), *WHO Guidelines for Indoor Air Quality: Selected Pollutants* (WHO, 2010).

[32] C. Li, Q. Li, D. Tong, et al., "Environmental Impact and Health Risk Assessment of Volatile Organic Compound Emissions During Different Seasons in Beijing," *Journal of Environmental Sciences* 93 (2020): 1–12, https://doi.org/10.1016/j.jes.2019.11.006.

[33] S. Vardoulakis, E. Giagloglou, S. Steinle, et al., "Indoor Exposure to Selected Air Pollutants in the Home Environment: A Systematic Review," *International Journal of Environmental Research and Public Health* 17, no. 23 (2020): 8972, https://doi.org/10.3390/ijerph17238972.

[34] J. Zheng, Y. Pang, Y. Zhang, et al., "Indoor VOCs Exposure Induced Parkinson-Like Behaviors Through Autophagy Dysfunction and NLRP3 Inflammasome-Mediated Neuroinflammation," *Journal of Hazardous Materials* 440 (2022): 129818, https://doi.org/10.1016/j.jhazmat.2022.129818.

[35] C. J. Weschler and W. W. Nazaroff, "Semivolatile Organic Compounds in Indoor Environments," *Atmospheric Environment* 42, no. 40 (2008): 9018–9040, https://doi.org/10.1016/j.atmosenv.2008.09.052.

[36] Y. Xiong, J. Zhou, Z. Xing, and K. Du, "Cancer Risk Assessment for Exposure to Hazardous Volatile Organic Compounds in Calgary, Canada," *Chemosphere* 272 (2021): 129650, https://doi.org/10.1016/j.chemosphere.2021.129650.

[37] K. Harčárová, S. Vilčeková, and M. Balintova, "Building Materials as Potential Emission Sources of VOC in the Indoor Environment of Buildings," *Key Engineering Materials* 838 (2020): 74–80, https://doi.org/10.4028/www.scientific.net/KEM.838.74.

[38] H. Wang, J. Xiong, and W. Wei, "Measurement Methods and Impact Factors for the Key Parameters of VOC/SVOC Emissions From Materials in Indoor and Vehicular Environments: A Review," *Environment International* 168 (2022): 107451, https://doi.org/10.1016/j.envint.2022.107451.

[39] C. Duan, H. Liao, K. Wang, and Y. Ren, "The Research Hotspots and Trends of Volatile Organic Compound Emissions From Anthropogenic and Natural Sources: A Systematic Quantitative Review," *Environmental Research* 216, pt. 1 (2023): 114386, https://doi.org/10.1016/j.envres.2022.114386.

[40] X.-B. Li, B. Yuan, S. Wang, et al., "Variations and Sources of Volatile Organic Compounds (VOCs) in Urban Region: Insights From Measurements on a Tall Tower," *Atmospheric Chemistry and Physics* 22, no. 16 (2022): 10567–10587, https://doi.org/10.5194/acp-22-10567-2022.

[41] N. Mohd Hanif, N. S. S. Limi Hawari, M. Othman, et al., "Ambient Volatile Organic Compounds in Tropical Environments: Potential Sources, Composition and Impacts – A Review," *Chemosphere* 285 (2021): 131355, https://doi.org/10.1016/j.chemosphere.2021.131355.

[42] J. P. D. Abbatt and C. Wang, "The Atmospheric Chemistry of Indoor Environments," *Environmental Science: Processes & Impacts* 22, no. 1 (2020): 25–48, https://doi.org/10.1039/C9EM00386J.

[43] M. Lovrić, G. Gajski, J. Fernández-Agüera, et al., "Evidence Driven Indoor Air Quality Improvement: An Innovative and Interdisciplinary Approach to Improving Indoor Air Quality," *BioFactors* 51, no. 1 (2025): e2126, https://doi.org/10.1002/biof.2126.

[44] D. Moher, A. Liberati, J. Tetzlaff, and D. G. Altman, "Preferred Reporting Items for Systematic Reviews and Meta-Analyses: The PRISMA Statement," *Journal of Clinical Epidemiology* 62, no. 10 (2009): 1006–1012, https://doi.org/10.1016/j.jclinepi.2009.06.005.

[45] L. Malinverno, V. Barros, F. Ghisoni, et al., "A Historical Perspective of Biomedical Explainable AI Research," *Patterns* 4, no. 9 (2023): 100830, https://doi.org/10.1016/j.patter.2023.100830.

[46] J. Horálek, L. Vlasáková, M. Schreiberová, et al., *European Air Quality Maps for 2020. PM10, PM2.5, Ozone, NO2, NOx and Benzo(a)pyrene Spatial Estimates and Their Uncertainties* (ETC HE Report 2022/12. Zenodo, 2023), https://doi.org/10.5281/ZENODO.7657072.

[47] V. Gallon, P. Le Cann, M. Sanchez, C. Dematteo, and B. Le Bot, "Emissions of VOCs, SVOCs, and Mold During the Construction Process: Contribution to Indoor Air Quality and Future Occupants' Exposure," *Indoor Air* 30, no. 4 (2020): 691–710, https://doi.org/10.1111/ina.12647.

[48] B. Kozielska, E. Brągoszewska, and D. Kaleta, "Investigation of Indoor Air Quality in Offices and Residential Homes in an Urban Area of Poland," *Air Quality, Atmosphere & Health* 13, no. 1 (2020): 131–141, https://doi.org/10.1007/s11869-019-00777-7.

[49] S. Fuselli, M. De Felice, R. Morlino, and L. Turrio-Baldassarri, "A Three Year Study on 14 VOCs at One Site in Rome: Levels, Seasonal Variations, Indoor/Outdoor Ratio and Temporal Trends," *International Journal of Environmental Research and Public Health* 7, no. 10 (2010): 3792–3803, https://doi.org/10.3390/ijerph7103792.

[50] W. Liang, C. Wang, C. Yang, and X. Yang, "Volatile Organic Compounds in Different Interior Construction Stages of an Apartment," *Building and Environment* 81 (2014): 380–387, https://doi.org/10.1016/j.buildenv.2014.07.015.

[51] C. Mandin, M. Trantallidi, A. Cattaneo, et al., "Assessment of Indoor Air Quality in Office Buildings Across Europe–The OFFICAIR Study," *Science of the Total Environment* 579 (2017): 169–178, https://doi.org/10.1016/j.scitotenv.2016.10.238.

[52] Z. Soltanpour, Y. Mohammadian, and Y. Fakhri, "The Concentration of Benzene, Toluene, Ethylbenzene, and Xylene in Ambient Air of the Gas Stations in Iran: A Systematic Review and Probabilistic Health Risk Assessment," *Toxicology and Industrial Health* 37, no. 3 (2021): 134–141, https://doi.org/10.1177/0748233720981218.

[53] T. Salthammer, "TVOC - Revisited," *Environment International* 167 (2022): 107440, https://doi.org/10.1016/j.envint.2022.107440.

[54] R. Rodrigues Dos Santos, J. Gregório, L. Castanheira, and A. S. Fernandes, "Exploring Volatile Organic Compound Exposure and Its Association With Wheezing in Children Under 36 Months: A Cross-Sectional Study in South Lisbon, Portugal," *International Journal of Environmental Research and Public Health* 17, no. 18 (2020): 6929, https://doi.org/10.3390/ijerph17186929.

[55] P. Wallner, M. Kundi, M. Panny, P. Tappler, and H.-P. Hutter, "Exposure to Air Ions in Indoor Environments: Experimental Study With Healthy Adults," *International Journal of Environmental Research and Public Health* 12, no. 11 (2015): 14301–14311, https://doi.org/10.3390/ijerph121114301.

[56] Ľ. Mečiarová, S. Vilčeková, E. Krídlová Burdová, and J. Kiselák, "Factors Effecting the Total Volatile Organic Compound (TVOC) Concentrations in Slovak Households," *International Journal of Environmental Research and Public Health* 14, no. 12 (2017): 1443, https://doi.org/10.3390/ijerph14121443.

[57] M. C. Pietrogrande, L. Casari, G. Demaria, and M. Russo, "Indoor Air Quality in Domestic Environments During Periods Close to Italian COVID-19 Lockdown," *International Journal of Environmental Research and Public Health* 18, no. 8 (2021): 4060, https://doi.org/10.3390/ijerph18084060.

[58] P. C. Martins, J. Valente, A. L. Papoila, et al., "Airways Changes Related to Air Pollution Exposure in Wheezing Children," *European Respiratory Journal* 39, no. 2 (2012): 246–253, https://doi.org/10.1183/09031936.00025111.

[59] S. Yang, V. Perret, C. Hager Jörin, H. Niculita-Hirzel, J. Goyette Pernot, and D. Licina, "Volatile Organic Compounds in 169 Energy-Efficient Dwellings in Switzerland," *Indoor Air* 30, no. 3 (2020): 481–491, https://doi.org/10.1111/ina.12667.

[60] N. Ninyà, L. Vallecillos, R. M. Marcé, and F. Borrull, "Evaluation of Air Quality in Indoor and Outdoor Environments: Impact of Anti-COVID-19 Measures," *Science of the Total Environment* 836 (2022): 155611, https://doi.org/10.1016/j.scitotenv.2022.155611.

[61] C. Rösch, T. Kohajda, S. Röder, M. V. Bergen, and U. Schlink, "Relationship Between Sources and Patterns of VOCs in Indoor Air," *Atmospheric Pollution Research* 5, no. 1 (2014): 129–137, https://doi.org/10.5094/APR.2014.016.

[62] C. Alves, A. Vicente, A. R. Oliveira, et al., "Fine Particulate Matter and Gaseous Compounds in Kitchens and Outdoor Air of Different Dwellings," *International Journal of Environmental Research and Public Health* 17, no. 14 (2020): 5256, https://doi.org/10.3390/ijerph17145256.

[63] D. Alvarez-Vaca, R. C. Duca, A. Borras-Santos, et al., "Surveillance of Indoor Air Concentration of Volatile Organic Compounds in Luxembourgish Households," *International Journal of Environmental Research and Public Health* 19, no. 9 (2022): 5467, https://doi.org/10.3390/ijerph19095467.

[64] C. Konstantinou, A. Constantinou, E. G. Kleovoulou, et al., "Assessment of Indoor and Outdoor Air Quality in Primary Schools of Cyprus During the COVID–19 Pandemic Measures in May–July 2021," *Heliyon* 8, no. 5 (2022): e09354, https://doi.org/10.1016/j.heliyon.2022.e09354.

[65] J. C. Rufo, J. Madureira, I. Paciência, et al., "Indoor Air Quality and Atopic Sensitization in Primary Schools: A Follow-Up Study," *Porto Biomedical Journal* 1, no. 4 (2016): 142–146, https://doi.org/10.1016/j.pbj.2016.07.003.

[66] E. Fuentes-Ferragud, A. López, J. M. Piera, et al., "Indoor Air Quality and Bioaerosols in Spanish University Classrooms," *Toxics* 12, no. 3 (2024): 227, https://doi.org/10.3390/toxics12030227.

[67] A. M. C. Ferreira and S. M. Cardoso, "Estudo exploratorio da qualidade do ar em escolas de educacao basica, Coimbra, Portugal," *Revista de Saúde Pública* 47, no. 6 (2013): 1059–1068, https://doi.org/10.1590/S0034-89102013000901059.

[68] J. Madureira, I. Paciência, E. Ramos, et al., "Children's Health and Indoor Air Quality in Primary Schools and Homes in Portugal—Study Design," *Journal of Toxicology and Environmental Health, Part A* 78, no. 13–14 (2015): 915–930, https://doi.org/10.1080/15287394.2015.1048926.

[69] G. Settimo, L. Indinnimeo, M. Inglessis, et al., "Indoor Air Quality Levels in Schools: Role of Student Activities and No Activities," *International Journal of Environmental Research and Public Health* 17, no. 18 (2020): 6695, https://doi.org/10.3390/ijerph17186695.

[70] C. Vornanen-Winqvist, H. Salonen, K. Järvi, et al., "Effects of Ventilation Improvement on Measured and Perceived Indoor Air Quality in a School Building With a Hybrid Ventilation System," *International Journal of Environmental Research and Public Health* 15, no. 7 (2018): 1414, https://doi.org/10.3390/ijerph15071414.

[71] A. Marzocca, A. Di Gilio, G. Farella, R. Giua, and G. De Gennaro, "Indoor Air Quality Assessment and Study of Different VOC Contributions Within a School in Taranto City, South of Italy," *Environments* 4, no. 1 (2017): 23, https://doi.org/10.3390/environments4010023.

[72] G. De Gennaro, G. Farella, A. Marzocca, A. Mazzone, and M. Tutino, "Indoor and Outdoor Monitoring of Volatile Organic Compounds in School Buildings: Indicators Based on Health Risk Assessment to Single Out Critical Issues," *International Journal of Environmental Research and Public Health* 10, no. 12 (2013): 6273–6291, https://doi.org/10.3390/ijerph10126273.

[73] L. T. Gibson, A. Ewlad-Ahmed, B. Knight, V. Horie, G. Mitchell, and C. J. Robertson, "Measurement of Volatile Organic Compounds Emitted in Libraries and Archives: An Inferential Indicator of Paper Decay?," *Chemistry Central Journal* 6, no. 1 (2012): 42, https://doi.org/10.1186/1752-153X-6-42.

[74] G. Raffy, F. Mercier, O. Blanchard, et al., "Semi-Volatile Organic Compounds in the Air and Dust of 30 French Schools: A Pilot Study," *Indoor Air* 27, no. 1 (2017): 114–127, https://doi.org/10.1111/ina.12288.

[75] H. Lim, I. Sadiktsis, M. F. De Oliveira Galvão, R. Westerholm, and K. Dreij, "Polycyclic Aromatic Compounds in Particulate Matter and Indoor Dust at Preschools in Stockholm, Sweden: Occurrence, Sources and Genotoxic Potential In Vitro," *Science of the Total Environment* 755, pt. 1 (2021): 142709, https://doi.org/10.1016/j.scitotenv.2020.142709.

[76] H. Fromme, T. Lahrz, M. Piloty, H. Gebhardt, A. Oddoy, and H. Ruden, "Polycyclic Aromatic Hydrocarbons Inside and Outside of Apartments in an Urban Area," *Science of the Total Environment* 326, no. 1-3 (2004): 143–149, https://doi.org/10.1016/j.scitotenv.2004.02.002.

[77] I. Jakovljević, M. Dvoršćak, K. Jagić, and D. Klinčić, "Polycyclic Aromatic Hydrocarbons in Indoor Dust in Croatia: Levels, Sources, and Human Health Risks," *International Journal of Environmental Research and Public Health* 19, no. 19 (2022): 11848, https://doi.org/10.3390/ijerph191911848.

[78] A. Stamatelopoulou, M. Dasopoulou, K. Bairachtari, S. Karavoltsos, A. Sakellari, and T. Maggos, "Contamination and Potential Risk Assessment of Polycyclic Aromatic Hydrocarbons (PAHs) and Heavy Metals in House Settled Dust Collected From Residences of Young Children," *Applied Sciences* 11, no. 4 (2021): 1479, https://doi.org/10.3390/app11041479.

[79] M. R. Mannino and S. Orecchio, "Polycyclic Aromatic Hydrocarbons (PAHs) in Indoor Dust Matter of Palermo (Italy) Area: Extraction, GC–MS Analysis, Distribution and Sources," *Atmospheric Environment* 42, no. 8 (2008): 1801–1817, https://doi.org/10.1016/j.atmosenv.2007.11.031.

[80] L. Melymuk, P. Bohlin-Nizzetto, Š. Vojta, et al., "Distribution of Legacy and Emerging Semivolatile Organic Compounds in Five Indoor Matrices in a Residential Environment," *Chemosphere* 153 (2016): 179–186, https://doi.org/10.1016/j.chemosphere.2016.03.012.

[81] A. Besis, E. Botsaropoulou, D. Balla, D. Voutsa, and C. Samara, "Toxic Organic Pollutants in Greek House Dust: Implications for Human Exposure and Health Risk," *Chemosphere* 284 (2021): 131318, https://doi.org/10.1016/j.chemosphere.2021.131318.

[82] G. Simonetti, P. Di Filippo, C. Riccardi, D. Pomata, E. Sonego, and F. Buiarelli, "Occurrence of Halogenated Pollutants in Domestic and Occupational Indoor Dust," *International Journal of Environmental Research and Public Health* 17, no. 11 (2020): 3813, https://doi.org/10.3390/ijerph17113813.

[83] N. Pieters, G. Koppen, K. Smeets, et al., "Decreased Mitochondrial DNA Content in Association With Exposure to Polycyclic Aromatic Hydrocarbons in House Dust During Wintertime: From a Population Enquiry to Cell Culture," *PLoS One* 8, no. 5 (2013): e63208, https://doi.org/10.1371/journal.pone.0063208.

[84] H. Choi and J. Spengler, "Source Attribution of Personal Exposure to Airborne Polycyclic Aromatic Hydrocarbon Mixture Using Concurrent Personal, Indoor, and Outdoor Measurements," *Environment International* 63 (2014): 173–181, https://doi.org/10.1016/j.envint.2013.11.007.

[85] J. Rybak, W. Rogula-Kozłowska, I. Jureczko, and R. Rutkowski, "Monitoring of Indoor Polycyclic Aromatic Hydrocarbons Using Spider Webs," *Chemosphere* 218 (2019): 758–766, https://doi.org/10.1016/j.chemosphere.2018.11.174.

[86] P. Gustafson, C. Östman, and G. Sällsten, "Indoor Levels of Polycyclic Aromatic Hydrocarbons in Homes With or Without Wood Burning for Heating," *Environmental Science & Technology* 42, no. 14 (2008): 5074–5080, https://doi.org/10.1021/es800304y.

[87] J. Loive, B. Strandberg, K. Christensen, and L. Hagvall, "Indoor Air Levels of Polycyclic Aromatic Compounds (PAC) in Public

Buildings With Creosote Impregnated Constructions – A Pilot Case Study Using Passive Samplers," *Chemosphere* 352 (2024): 141240, https://doi.org/10.1016/j.chemosphere.2024.141240.

[88] G. De Gennaro, P. Dambruoso, A. Di Gilio, V. Di Palma, A. Marzocca, and M. Tutino, "Discontinuous and Continuous Indoor Air Quality Monitoring in Homes With Fireplaces or Wood Stoves as Heating System," *International Journal of Environmental Research and Public Health* 13, no. 1 (2016): 78, https://doi.org/10.3390/ijerph13010078.

[89] W. Rogula-Kozłowska, B. Kozielska, G. Majewski, P. Rogula-Kopiec, W. Mucha, and K. Kociszewska, "Submicron Particle-Bound Polycyclic Aromatic Hydrocarbons in the Polish Teaching Rooms: Concentrations, Origin and Health Hazard," *Journal of Environmental Sciences* 64 (2018): 235–244, https://doi.org/10.1016/j.jes.2017.06.022.

[90] P. Romagnoli, C. Balducci, M. Perilli, F. Vichi, A. Imperiali, and A. Cecinato, "Indoor Air Quality at Life and Work Environments in Rome, Italy," *Environmental Science and Pollution Research* 23, no. 4 (2016): 3503–3516, https://doi.org/10.1007/s11356-015-5558-4.

[91] E. Błaszczyk, W. Rogula-Kozłowska, K. Klejnowski, P. Kubiesa, I. Fulara, and D. Mielżyńska-Švach, "Indoor Air Quality in Urban and Rural Kindergartens: Short-Term Studies in Silesia, Poland," *Air Quality, Atmosphere & Health* 10, no. 10 (2017): 1207–1220, https://doi.org/10.1007/s11869-017-0505-9.

[92] M. Oliveira, K. Slezakova, C. Delerue-Matos, M. C. Pereira, and S. Morais, "Polycyclic Aromatic Hydrocarbons: Levels and Phase Distributions in Preschool Microenvironment," *Indoor Air* 25, no. 5 (2015): 557–568, https://doi.org/10.1111/ina.12164.

[93] T. Cirillo, P. Montuori, P. Mainardi, I. Russo, M. Triassi, and R. Amodio-Cocchieri, "Multipathway Polycyclic Aromatic Hydrocarbon and Pyrene Exposure Among Children Living in Campania (Italy)," *Journal of Environmental Science and Health, Part a* 41, no. 10 (2006): 2089–2107, https://doi.org/10.1080/10934520600867854.

[94] Z. Fiala, A. Vyskocil, V. Krajak, et al., "Environmental Exposure of Small Children to Polycyclic Aromatic Hydrocarbons," *International Archives of Occupational and Environmental Health* 74, no. 6 (2001): 411–420, https://doi.org/10.1007/s004200100239.

[95] M. Mortamais, J. Pujol, B. L. Van Drooge, et al., "Effect of Exposure to Polycyclic Aromatic Hydrocarbons on Basal Ganglia and Attention-Deficit Hyperactivity Disorder Symptoms in Primary School Children," *Environment International* 105 (2017): 12–19, https://doi.org/10.1016/j.envint.2017.04.011.

[96] B. L. Van Drooge, I. Rivas, X. Querol, J. Sunyer, and J. O. Grimalt, "Organic Air Quality Markers of Indoor and Outdoor PM2.5 Aerosols in Primary Schools From Barcelona," *International Journal of Environmental Research and Public Health* 17, no. 10 (2020): 3685, https://doi.org/10.3390/ijerph17103685.