Indoor volatile and semi-volatile organic toxic compounds: Need for global action

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A B S T R A C T
Indoor air pollution results in mortalities worldwide, burdening especially the low- and middle-income countries. The volatile and semi-volatile organic compounds (VOCs and SVOCs) emitted from indoor structures and furniture materials are important sources of indoor air pollution. Exposure to VOCs, such as formaldehyde and benzene, has been associated with higher risk of reproductive problems, respiratory complications, immune suppression, cancers, and dementia. SVOCs are typically found in carpets, textiles, furniture, electronics and cosmetics. These chemicals are also neurotoxic, inducing a number of adverse health effects, behavioral changes, learning disability, and the impairment of locomotor activity. If not mitigated, indoor air pollution will continue to impose health and socioeconomic burden on both individuals and societies. Solutions to curb their environmental occurrences include those that reduce/eliminate the material sources of indoor VOCs/SVOCs and those that increase their removal, including phytoremediation and metal-organic frameworks to reduce their indoor concentrations. As such, there is an urgent need to tackle this problem by better regulating the indoor concentrations of these chemicals and developing and upscaling solutions to mitigate their health effects, using advanced, accessible, and environmentally sustainable materials, electronics and technologies.

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1. Indoor air pollution

Indoor air pollution is a worldwide problem occurring both in households and in workplaces, such as schools, offices, laboratory spaces, toll stations, shoe repair shops and beauty salons [1]. An estimated 45 million of disability-adjusted life years (DALYs) were attributed to household air pollution worldwide in 2019 [2]. Moreover, an estimated 2.3 million mortalities were attributed to this exposure, accounting for around 4% of all 2019 deaths [2]. The majority of the burden of disease due to indoor air pollution is related to particulate matter, occurring mostly in low- and middle-income countries, particularly in sub-Saharan Africa and South Asia, where the main source of indoor air pollution is the use of biomass for cooking and heating [2]. In high-income countries, the primary source of indoor air pollution is the continuous replacement of novel fixtures, electronics, and building materials in offices as well as private homes (Fig. 1) [2]. These products are usually manufactured by bonding the pieces using urea- and phenol-formaldehyde-
based adhesives, which volatilize with time as toxic chemicals, deteriorating the indoor air quality and inducing adverse health effects [3–5].

2. Volatile organic compounds (VOCs) and semi-volatile compounds (SVOCs)

VOCs are chemical species of particular concern due to their high volatility (in the range 50–240 °C, at standard atmospheric pressure) [6]. Their physico-chemical properties and high volatility make them difficult to be managed in individual's microclimate [7]. Factors and effects that exacerbate personal exposure to VOCs include air-conditioning, limited exchange with fresh outdoor air, and transport of polluted outdoor air to indoor environments [8]. This large group of chemicals includes, for example, benzene, toluene, and formaldehyde. Semi-volatile compounds are a subgroup of VOCs with lower volatility (in the range 260–400 °C). These chemicals partition between the gas and particulate fractions, with the latter occurring not only as airborne particles but also as dust and bulk deposition on surfaces and ventilation systems [9,10]. Hence, human exposure to these species occurs both via inhalation and ingestion of the settled indoor dust. They include brominated flame-retardants (BFR), polychlorinated biphenyls (PCBs), perfluorinated substances (PFAS) and phthalates that constitute a group of toxic contaminants that can affect indoor air quality (Table 1) [11–13]. Because their chemical and biological degradation is slow and due to their deposition onto indoor surfaces, they could persist in indoor environments for an extended period of time due to their lifetimes being tens of hours making them almost inert [5,10].

3. Sources

VOCs are emitted as gases from paints, cleaning chemicals, cosmetics, degreasing, wall joints, furniture, photocopiers, printers and other widely used materials in buildings, offices and private households [14]. Formaldehyde and benzene are two toxic VOCs contributing to occupational and personal exposure in closed buildings and environments [15]. VOCs are used in furniture and carpets, laptops, wall joints, and artificial boards, among the most frequently used materials. Artificial boards, for example, consist of medium-density fiber (MDF) boards and plywood glued together by applying an abundance of adhesives, resin glue and coatings derived from these chemicals [3]. SVOC chemicals originate from not only building materials, wall joints, paint and furniture but also from personal equipment, including electronics and clothing. SVOCs are found in consumer products, flame retardants, plasticizers, pesticides and coatings, which volatilize over time and release to indoor air and as dust (Table 1) [5]. Pesticides, such as pyrethroids,
are widely used to fight vectors of endemic diseases, sanitary and health purposes e.g., to fight insect-borne diseases, lice and scabies, and as household insecticide. In Brazil, for example, the latter is sold by the retail sector for the general public and applied as residual spraying (indoor) and tissue (nets and clothes) impregnation [16]. Other polycyclic aromatic hydrocarbons (PAHs), including polychlorinated dibenzo-p-dioxins/furans (PCDD/F), are emitted from combustion processes being a major source of indoor SVOCs in households reliant on wood burning for cooking and/or heating. This is particularly relevant in regions where people use wood waste treated with PVC, which can emit large amounts of PCDD/F [17].

A systematic review looking into the indoor concentrations of multiple VOCs on a global scale shows that the indoor:outdoor VOCs ratio depends on compounds, cold and warm seasons, as well as the type of indoor environment (e.g., private homes, offices, hotels, shopping centres and schools) [18]. The results of the meta-study clearly showed that indoor VOCs concentrations were up to 20-fold higher compared to the outdoor values in, for example, schools. Furthermore, surprisingly, the greatest differences were not found during warm seasons when evaporation is higher. This highlights the urgent need for remediation to safeguard health and to reduce exposure to these chemicals [19].

Other studies show that diesel, gasoline and compressed natural gas (CNG) are also significant sources to VOCs in indoor environments. For example, passengers’ exposure to BTEX (Benzene, Toluene, Ethylbenzene and Xylene) levels when using buses powered by CNG or by diesel is significantly higher compared to indoor environments [20]. Likewise, truck terminals and cabs are hotspots for exposure to BTEX and particulate matter exceeding the US EPA screening values [21]. VOCs may be present in the air of garages as a result of fugitive emissions from lawnmowers, fuels, solvents, paints, and cleaner storage containers [22], as well as direct emissions from the cars' tailpipes at start and drive. If the garage is connected to a house, the VOCs will eventually infiltrate into the adjacent living areas, depending on parameters such as the location of the air ducts in the garage, duct leakage, pressure and temperature differences between the garage and adjacent spaces, and quality of the door seals [22,23]. In the study by Batterman et al. [24], benzene concentrations in 15 houses connected to garages were almost exclusively caused by the infiltration of polluted air from the garage, accounting for the majority of an individual's cumulative dose. Although most studies focused on VOCs leaking into residential living areas from attached garages, the issue also exists in busy commercial buildings that must satisfy the ever-increasing parking demands of customers [25]. The ubiquity of VOCs in indoor environments may result in long-term cumulative hazards, such as sneezing, coughing, dizziness, and other physical discomforts known as “sick building syndrome” [26]. This emphasizes the need to minimize human exposure to BTEX in order to ensure indoor health.

4. Health effects

Some species from the SVOC group are endocrine-disrupting chemicals, e.g. PAHs and phthalates [14]. Once inhaled, VOCs could pass the air-blood barrier and enter the bloodstream causing a number of acute health outcomes such as eye, nose and throat irritation and headaches [14,27]. Long-term exposure to high concentrations may induce reproductive problems (e.g. abortion and infertility), respiratory conditions (e.g. asthma and chronic obstructive pulmonary disease, COPD), cardiovascular problems, immune suppression, allergic conditions, cancers and dementia [14,27]. The diseases induced by toxic indoor VOCs pose socio-economic burdens in developing countries as trillions of US$ investments in the US show how much is needed to reduce exposure and costs related to medical treatment and hospitalizations [19]. As the majority of the chemicals are toxic to the immune system, they also could affect the ability to produce antibodies towards viral infections [28]. The lockdown imposed during COVID-19 caused by the SARS-CoV-2 viral pandemic further highlighted the need to improve indoor air quality, particularly in countries where the lockdown coincided with the cold season and thereby with the burning of wood and coal for indoor heating [29]. This requires a call for action to ensure healthy indoor environments and to reduce not only personal exposure to chemicals, but also the adoption of controlled air circulation to remove aerosols from the inside [30,31].

5. Mitigation and solutions

Indoor exposure to VOCs and SVOCs could affect health in several ways [19] and therefore mitigation efforts are necessary to (i) reduce/eliminate the sources and (ii) increase their removal from indoor air using innovative technologies and materials. One of the challenges that has attracted greater attention is the development of advanced sustainable materials that reduce the use of VOC/SVOC-emitting indoor ornamentation. These include reducing the use of carpets and artificial boards that contain high concentrations of formaldehyde [14]. Replacing formaldehyde resins in artificial boards with, for instance, hot-pressed self-bonding boards made from abundantly available bio residues (e.g. sawdust and formaldehyde-free wood composites) is a promising alternative [14]. Part of this is taking advantage of the self-bonding ability of natural wood, which can create the required strong bonding from the naturally occurring compounds at proper pressure and temperature [32]. Such development of formaldehyde-free artificial boards is highly desired to ensure acceptable indoor air quality and human health, hence it calls for more significant research in this field. It is therefore highly recommended to increase the research efforts in developing renewable and ecofriendly adhesive alternatives possessing high bonding performance. In addition, there is a need for more research on material sciences in terms of developing non-formaldehyde-based resins/coatings for their application in furniture boards. A variety of biomass-derived polymers, such as lignin, tannin, protein, polysaccharides, and vegetable oils have already been analyzed as bio-based wood adhesives to replace the use of conventional resins [33]. For instance, plant-derived proteins with a variety of functional groups are promising sustainable and nontoxic alternatives to formaldehyde-based resins, which have already been used in making bio-based adhesives that does not leak toxic VOCs [33]. However, natural biopolymers suffer from a number of challenges, including high cost and poor performance in terms of durability and water resistance, limiting their competitiveness in the market.
Another important component in the solution of VOC/SVOC indoor air pollution is their removal using specific technologies and mechanisms to revitalize the air. These solutions include the use of smart chemical sensors that reflect exposure concentrations and mitigation as a novel warning system similar to smoke detectors. Advanced materials, such as metal-organic frameworks (MOFs), photocatalytic oxidation in combination with biological filters, biochar and activated carbon derived from renewable biomass can help reducing indoor VOCs/SVOCs [14,34]. Of these, MOFs generally possess large pore size and area compared to activated carbon and zeolite, granting ultra-high adsorption capacities towards both VOCs [14]. Currently, photocatalysts and UV radiation are used to remove VOCs/SVOCs; however, this only seems to be partly suitable [10]. Hence, so far these solutions are insufficient to meet exposure guidelines [14]. Studies of occupational microenvironments show that automatized surveillance of air pollution can aid in informing mitigation strategies and actions, such as a review of ventilation configurations and hazardous materials used in certain occupations [35]. Likewise, both indoor and outdoor automated surveillance systems that report air pollution at the building level would be another smart initiative to mitigate indoor air pollution through the activation and replacement of filters and automatic window shutters. This may be combined with phytoremediation using plants to remove air pollution [15]. Phytoremediation offers beneficial properties for VOCs removal in indoor environments due to the absorption capacity determined by their physiology [18]. This can be used to remove gaseous formaldehyde through microbial and plant decomposition, thus depending on rhizosphere, humidity, temperature and season. However, it is not only formaldehyde that undergoes phytoremediation. Recently, it was shown that botanical biofiltration may also remove other VOCs including acetone, benzene, cyclohexane, ethyl acetate, hexane, isopentane, isopropanol and toluene [36]. Of these, ethanol is the VOC that can be eliminated most effectively, while benzene is the least effective, as determined by the compound’s dipole moment (differences in electronegativity) and molecular mass. Thus, the VOCs chemical properties help to optimize the VOC partitioning into biofilter’s aqueous phase, and substrate development that enhances compound-specific adsorption. Therefore, using the right plant species and continuously changing species composition pave the road towards better indoor heath as warranted by the Global Goals.

6. Regulations and considerations

As an example, the maximum allowable indoor air formaldehyde concentration in China is surpassed by more than 10% in Beijing households, owing to the growth of industrial and economic development, population density and consumption of energy and raw materials [14]. The release of formaldehyde and benzene derivatives has forced several countries to impose mandatory standards for their use, including China (GB/T 39600-2021), Canada (SOR/2021-148) and the EU (EN 13986:2004). This helps to limit the use and subsequent release of formaldehyde vapors from indoor artificial boards and furniture, thereby relieving the negative effects. Despite the regulations and the positive effects on indoor air quality, the mitigation is unfortunately only temporary. One reason for this is the long-term release of harmful formaldehyde that can occur continuously for up to 15 years, due to leakage of non-bound free formaldehyde molecules during manufacturing that does not originate from formaldehyde-based resins [37]. For example, indoor formaldehyde concentration could be up to 134 µg/m³ in the first year for new homes [38]. After three years, the concentration might decrease by 50% and then could stay for several years at around 88–90 µg/m³ [38]. This calls for not only new regulations of currently regulated VOCs and SVOCs, but also of those that are currently not regulated in indoor environments.

Coordinated global action is required to reduce the highly underestimated problems of VOCs and SVOCs. So far, the World Health Organization has established guidelines of certain indoor VOCs, but more is required to mitigate emerging SVOCs and VOCs that are otherwise unregulated [39]. Such actions should include guidelines and legislations regarding filters, ventilation, absorbing materials, phytoremediation and photocatalysts following international guidelines, including the United National Sustainable Development Goals #3, Good health and wellbeing, and #11, Sustainable cities and communities. When it comes to SVOCs, there is a need to have a complete ban on the more toxic and persistent chemicals, such as PCBs, PFAS and brominated flame retardants. This action requires a multi-stakeholder collaboration among the chemical industry, academic disciplines, and national and international governance bodies. If not mitigated, indoor VOCs will continue to impose health and socioeconomic burden on both individuals and societies [19]. To tackle this problem, further studies on the health effects of VOCs (especially the emerging ones) will help to develop new accessible and environmentally sustainable solutions, evaluate the cost-effectiveness and potential health effects of these solutions, and develop national and international indoor air quality standards for better regulating VOC concentrations, especially those that are not regulated yet.

Author statement

Christian Sonne: Original draft preparation, writing, reviewing, editing, methodology, visualization and graphics, software, data curation.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

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