Chapter 16
Volatile Organic Compounds: The Concealed Depreciator of Indoor Air Quality

Nidhi Srivastava and Sushma Negi

Abstract Since the average time spent by the people at home and at work has increased significantly over the last few decades, the quality of the indoor environment is critical to their health. Indoor air contaminants come in many forms, with volatile organic compounds (VOCs) being one of the most common. These VOCs have been found to be present in higher amounts in the indoor environment than in open spaces. Indoor air quality is influenced by a number of elements, the most important of which are ventilation and anthropogenic activities. This chapter highlights the various prevalent sources of volatile organic compounds, their impact on human health and the controls that have been implemented to reduce exposure. Furthermore, VOCs are linked to indoor air quality and possible strategies for their improvements. This is accompanied by a brief description of the monitoring system used to detect VOC levels in indoor environments.

Keywords Indoor · Volatile organic compounds · Health effects · Sensors · Monitor

16.1 Introduction

A hasty improvement of the economic system and burgeoned population growth has led to an extensive requirement of energy, water and food in order to fulfil our requirements. This, in turn, produces an adverse variety of pollutants, among which air pollutants are the major ones. Air pollution has caused major challenges around the world because of its huge harm to our surroundings and capability fitness danger to humans [48]. It has a negative impact on both human health and the environment we live in [6]. Air pollution is currently listed fourth among the leading causes of worldwide disease and death [28, 70]. Pollution is evident in all realms of life and

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N. Srivastava (✉) · S. Negi
Department of Zoology and Environmental Sciences, Maharaja Agrasen University,
Baddi, Himachal Pradesh, India

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is not confined to those outside of our homes. Rather, it is more dangerous in an enclosed environment because hazardous pollutants can accumulate faster in closed areas as compared to the open ones. As per the Environment Protection Act of 1986, indoor air pollution levels are generally 2–5 times higher than outdoor levels. These levels can sometimes be 100 times higher than outdoor levels of the same contaminants. Indoor air may contain a variety of pollutants that are not visible to the naked eye. People spend more than 80% of their time indoors [36], which depends upon the season, age, gender, type of job, health status, etc.; adequate air quality can help in the better health of the individual [48]. It is expected that the shielding effect of buildings, the ventilation facilities and the air purification system may keep the indoor air quality better than the outdoors, but to our surprise, several reports are available which state that majority of human exposure to air pollutants occurs inside the closed areas [41, 59]. Chen and Zhao [13] reported that the concentration of indoor air pollutants is higher than outdoor air pollutant concentrations. The quality of the indoor environment in residential areas is influenced by three primary factors: (i) anthropogenic activities in the indoor spaces [11, 16, 17, 55], (ii) furniture and building materials [54, 86] and (iii) ambient air quality [12]. A majority of scientists reported that outdoor air has an impact on indoor air quality [8, 21, 38, 47, 53].

16.2 Sources of Indoor Air Pollution

According to the WHO [85], indoor air pollution is accountable for the fatalities of 3.8 million people per year. Approximately, three billion people continue to cook and heat their houses using polluting solid fuels which include waste wood, charcoal, manure, crop wastes, etc. If the inside air is not properly vented, these pollutants can build up in the indoor environment, posing a serious health danger to the residents. According to Wallace et al. [77], there are thousands of consumer products and building materials that contain hazardous organics that can be found inside. Asthmatic people and those with impaired immune systems are more vulnerable to these indoor air pollutants. Table 16.1 summarises the sources of many main indoor air contaminants [72].

Among all these indoor air pollutants, volatile organic compounds (VOCs) deserve special attention as they are carcinogenic and humans are easily exposed to them because they are found in all personal care products and are utilised as organic chemicals in a variety of household products. As a result, furniture and other household items, as well as building materials, may have an impact on indoor air quality [69]. Volatile organic compounds have been identified as one of the most significant types of interior air pollutants [82], and therefore, we are focussing only on these causes of indoor air quality degradation.

Table 16.1 List of major indoor air pollutants and the associated sources

Major indoor air pollutants	Sources
Particulate matter	Cooking stoves, fireplaces, candles and incense and outdoor air
Carbon monoxide	Gas stoves and appliances
Pesticides	Sprays used to kill insect pests in the house
Volatile organic compounds	Paints, stains, varnishes, solvents, pesticides, adhesives, wood preservatives, waxes, polishes, cleansers, lubricants, sealants, dyes, air fresheners, fuels, plastics, copy machines, printers, tobacco products, perfumes, dry-cleaned clothing, building materials and furnishings
Biological pollutants	Animal dander, dust mites, moulds, infectious agents and pollen

16.3 Volatile Organic Compounds (VOCs)

According to Tran et al. [72], volatile organic compounds are gases that contain a variety of chemicals and are emitted by liquids or solids. These VOCs have a chemical make-up that permits them to evaporate at room temperature and pressure. Irrespective of building location, indoor VOC concentrations are approximately ten times higher than the outdoor ones [76]. VOCs can be produced in various levels by anthropogenic sources such as wood construction materials, oil-based paints, fragrant decorations and indoor plants. Some of them may cause cancer, while others may react with ozone to produce secondary small suspended indoor particles [81]. Because of limited ventilation rates, VOC level indoors are often higher than those outdoors [15]. Sack and Steele [60] and Lim et al. [51] reported that sources of VOC among household products include automotive products, household cleaners, paint-related products, fabric and leather treatments, oils, greases, lubricants, glue-related products and miscellaneous other products. In short, indoor VOCs are produced by four primary sources: (i) human activities such as the use of housekeeping and personal care products, (ii) indoor chemical interactions, (iii) outside air infiltration through ventilation systems and (iv) building materials. The efficiency through which VOCs can be emitted is often used to categorise them. For example, WHO [83] has classified VOCs as follows and are represented in Table 16.2:

1. Very volatile organic compounds (VVOCs) – VVOCs have the boiling point in the range of <0–50/100 °C and are the most harmful type of pollutant. These can be very toxic even in extremely low quantities.
2. Volatile organic compounds (VOCs) – VOCs have a boiling point range of 50/100–240/260 °C. Though these are less dangerous than VVOCs, they are still harmful to human health.
3. Semi-volatile organic compounds (SVOCs) – SVOCs tend to have a higher boiling point range between 240/260 and 380/400 °C.

Table 16.2 Sorting of indoor organic pollutants

Types of VOCs	Boiling point (Tb)	Example	References
Very volatile organic compounds (VVOCs)	50–100 °C	Propane and butane acetone	Schieweck [63]
Volatile organic compounds (VOCs)	100 °C < Tb < 240 °C	Formaldehyde, benzene, toluene, xylene, etc.	Rashnuodi et al. [58]
Semi-volatile organic compounds (SVOCs)	240 °C < Tb< 380 °C	Pesticides, plasticisers, polychlorinated biphenyls, etc.	Lucattini et al. [52]

Adapted from WHO [83]

The lower the boiling point, the higher the volatility, which means the compound is more likely to be expelled into the air from a product or surface. The least volatile compounds found in air make up a far lower proportion of the total present indoors, with the bulk found in solids or liquids containing them or on surfaces like dust, furniture and construction materials [74, 75].

According to EPA [18], the major causes of VOC in indoor air are the following:

1. Household and cleaning products that include cleaners, disinfectants, furniture and wood polishes, air fresheners, dry-cleaned clothing, etc.
2. Pesticides
3. Products used during relaxation and creativity activities such as Glue 7 adhesives, permanent markers, copiers and printers, correction fluids, repair, maintenance and furnishing products, photofinishing chemicals, swimming pool chemicals, etc.

The sources and health hazards of six commonly occurring VOCs in the indoor environment are explained below.

16.3.1 Formaldehyde

Due to its widespread dispersion in interior air and highly hazardous properties, formaldehyde is considered as a priority indoor air pollutant [61].

16.3.1.1 Sources

Combustion operations such as smoking, heating, cooking and candle or incense burning can all produce formaldehyde indoors [61]. Building materials and consumer products that generate formaldehyde are the other primary sources of formaldehyde in indoor environments [43]. They can last for several months, even when applied to new materials and products [27]. This is especially true in settings with high relative humidity and high indoor temperatures [24]. Furthermore, furniture and wooden products containing formaldehyde-based resins, insulating materials and textiles, activity products, cleaning products, electronic equipment and paper products are some other major sources of formaldehyde pollution in the indoor environment.

Due to the slow removal rate of formaldehyde in the indoor environment, its levels are usually high as compared to that in the outdoor environment, ranging from 10 to 4000 μg/m^3 [31, 83].

16.3.1.2 Health Effects

Since formaldehyde is abrasive, it causes sensory irritation in the eyes and upper airways, as well as lung consequences (asthma and allergy) and finally eczema. Long- term use, however, may aggravate asthma symptoms. In 2006, the International Agency for Research on Cancer (IARC) has classified formaldehyde as "carcinogenic to humans". In humans, formaldehyde has been linked to nasopharyngeal cancer.

16.3.2 Benzene

Benzene has been detected at high levels in indoor air. In the air, benzene remains in the vapour phase and can remain in the air from a few hours to days, reliant on the environment and the presence of other contaminants [65].

16.3.2.1 Sources

Indoor air can contain benzene from both outside and inside sources, including building materials and furniture, adjacent garages, heating and cooking systems, stored solvents and a variety of human activities [84]. Indoor benzene concentrations are mostly influenced by materials used in building, remodelling and decorating [26]. Certain furnishing materials and polymeric materials, such as vinyl, PVC (polyvinyl chloride), rubber flooring, nylon carpets and SBR latex-backed carpets, may contain benzene in trace amounts [84].

16.3.2.2 Health Effects

Even at low concentrations, long-term exposure to benzene produces progressive deterioration in haematopoietic function, including bone marrow destruction, alterations in circulating blood cells and a weakened immunological response [35]. The health impacts of benzene include blood dyscrasias and leukaemia, particularly acute myeloid leukaemia [84].

16.3.3 Toluene

Toluene is a clear, transparent liquid with a distinct, pleasant odour. It is produced commercially, primarily as a by-product of the coke oven industry or as a by-product of petroleum catalytic transformation. It is an aromatic hydrocarbon that is often employed as a solvent in almost all homes.

16.3.3.1 Sources

Indoor sources of toluene include building materials (such as solvent- and water-based adhesives, floor coverings, paint and chipboard), consumer and automotive items (such as cleansers, polishes, adhesive products, oils, greases and lubricants) and ambient tobacco smoke. Toluene emitted by running engines or product storage in nearby garages can also enter the indoor environment [71].

16.3.3.2 Health Effects

For both acute (short-term) and chronic (long-term) toluene poisoning in humans and animals, the brain is the major target organ. Humans exposed to high levels of toluene in the air have experienced CNS dysfunction and narcosis, with symptoms such as lethargy, sleepiness, headaches and nausea. Chronic abusers exposed to high quantities of toluene have been observed to develop CNS depression. Inhaling toluene causes irritation of the upper respiratory tract and eyes in humans, as well as a sore throat, dizziness and headache. Human investigations have discovered CNS dysfunction, attention difficulties and moderate craniofacial and limb abnormalities in the offspring of pregnant women who inhaled high amounts of toluene or mixed solvents [19].

16.3.4 Xylene

Xylene is an aromatic hydrocarbon that is frequently utilised as a solvent in industry and medical technologies. It is a colourless, sweet smelling liquid or gas found in petroleum, coal and wood tar, and it gets its name from crude wood spirit (Gr. xy'lon wood) [40].

16.3.4.1 Sources

In the chemical industry, xylenes are commonly employed as solvents in inks, dyes, paints, adhesives and detergents [29]. Cigarette smoking introduces xylenes into the indoor environment as well [45, 46]. Xylenes have long been utilised in products for the home, such as synthetic scents and paints [2].

16.3.4.2 Health Effects

Inhaling xylene vapour causes central nervous system depression, resulting in symptoms such as headache, dizziness, nausea and vomiting. The skin's natural protective oils can be dissolved by xylene. Irritation and dermatitis, as well as skin dryness, peeling and cracking, can result from frequent or prolonged skin contact [40]. Headaches, a loss of muscle coordination, dizziness, disorientation and alterations in balance can all be symptoms of high levels from short- or long-term exposure. Acute exposures also cause eye, nose and throat irritation, as well as difficulty in breathing, lung problems, slow reaction time, memory problems, stomach pain and liver and kidney abnormalities.

16.3.5 Styrene

Styrene is a flammable, colourless liquid with a pleasant odour that is highly volatile.

16.3.5.1 Sources

Styrene levels in indoor air have been shown to range between 0.1 and 50 g/m^3 due to building materials, consumer products and tobacco smoking. High styrene concentrations can be detected in workplaces and home offices due to styrene emissions from laser printers and photocopiers [3].

16.3.5.2 Health Effects

The International Agency for Research on Cancer has classified styrene as providing Group 2A carcinogenic risks to humans [32–34]. Occupational exposure to styrene has been shown to reduce visuomotor accuracy and verbal learning skills and subclinical colour vision effects [25, 56].

16.3.6 Naphthalene

Naphthalene is a common contaminant, and extremely high concentrations can be found indoors when this chemical is used as a pest repellent or deodorant [7].

16.3.6.1 Sources

According to WHO [84], indoors, naphthalene can be found in air fresheners, paints, stains, floors and carpeting, as well as some pest control treatments. Cooking and combustion sources in the house, such as woodstoves and fireplaces, can both generate naphthalene. It is found in cigarette smoke and can enter the home via exhaust from vehicles and gas-powered equipment in adjacent garages.

16.3.6.2 Health Effects

The International Agency for Research on Cancer (IARC) classified naphthalene in Group 2B as “probably carcinogenic to humans” based on significant evidence of carcinogenicity in experimental animals and insufficient evidence of carcinogenicity in humans [84]. Naphthalene exposure has been related to a range of negative health impacts. Nasal tumours are the cancer endpoints of concern, while hyperplasia and metaplasia in respiratory and olfactory epithelium are the key non-cancer endpoints [37].

16.4 Control of Indoor VOC Exposure

We have covered the sources of VOCs, their detrimental effects and how to monitor them so far. Now, we need to figure out how to shield ourselves against these detrimental consequences in the most effective way possible. The following are a few key suggestions for doing so:

1. Increase ventilation when using VOC-emitting goods.
2. Comply with or exceed any label warnings.
3. Do not store unsealed containers of unused paints or similar products.
4. To limit the use of pesticides, use integrated pest management strategies.
5. Follow the manufacturer’s instructions while using household items.
6. Safely dispose of unwanted or infrequently used containers; purchase in quantities that you will utilise fast.
7. Keep children and pets out of reach.
8. Only use household cleaning products as directed on the label.

16.5 Volatile Organic Compounds and Indoor Air Quality

Indoor air quality (IAQ) denotes the quality of the air in a closed area and around buildings and structures, with a focus on occupant comfort and health. Because of their ubiquity, VOCs are frequently more relevant in analysing IAQ; VOCs can be utilised as "descriptors" to better characterise anthropogenic pollution. Indoor air quality monitors with VOC sensors can help us in keeping track of the amount of VOCs in the air. There are five main types of sensors used to detect VOC levels in the air [66]:

1. *A photoionisation detector (PID).* A photoionisation detector (PID) detects the presence of VOCs and other gases such as methane and benzene in a workplace by using ultraviolet (UV) rays. Unfortunately, none of these sensors are specific to a single VOC, and even with a 9.6 eV xenon lamp, benzene, toluene and xylene cannot be discriminated because their ionisation potentials are lower than the light's energy [50].
2. *Electrochemical sensors* are one of the most well-known and extensively utilised technologies for concentration measurements [23]. Electrochemical sensors can be potentiometric or amperometric, depending on whether a difference in potentials is recorded or the current of a redox reaction is measured [68]. All of these sensors' detection limits (for ethylene oxide) are far too high for air quality monitoring, with the best number reaching 50 ppb.
3. *Resistive sensor*. This sensor transducing mechanism is made up of a metal oxide that alters its electrical characteristics when exposed to different gases in the environment. The resistance or conductivity of metal oxide (MOx) sensors is mainly evaluated in commercial sensors. Tin oxide (SnO_2) is the most frequently employed because of its extensive reactivity and rapid resistance shifts. Resistive sensors are often smaller and require a high temperature for reactions to occur quickly; hence, a heater is frequently built within the sensor. They respond to a wide range of gas concentrations, ranging from a few parts per billion (ppb) for gases like NO_2 [44] to thousands of ppm for other gases [42].
4. *4. Spectroscopic sensors* are a valuable addition to the detection of VOCs. The IR spectral areas are used extensively in many of these standard approaches. Non-dispersive infrared (NDIR), differential absorption lidar (DIAL), differential optical absorption spectroscopy (DOAS), tunable diode laser absorption spectroscopy (TDLAS), Fourier transform infrared (FTIR) spectroscopy, open-path FTIR (OPFTIR) useful for measuring atmospheric gas species and dual-comb spectroscopy (DCS) are some of the spectroscopic methods [22].
5. *Micro-gas chromatograph sensors* combine micro-GC columns with either PID or MOx sensors [80].

Apart from these conventional sensors, some sophisticated sensor networks and communication technologies are also used for monitoring the indoor air quality. As automatic alert systems are need of the hour, we picked monitoring systems that propose online access to recorded environmental factors or generate SMS-based alerts. It could be divided into following two groups:

1. Wireless sensor network (WSN) – WSN provide autonomous monitoring of physical phenomena in crucial environments where human presence is undesirable or impracticable [49]. This technology has been well embraced in different areas such as military applications, homeland and border security, crisis management, habitat monitoring, traffic surveillance, industrial monitoring, checking the safety of buildings and facilities, environmental monitoring and health-care applications [5, 14, 67, 78]. In general, a WSN is made up of a dispersed network of small, low-cost and low-power sensor nodes that work together to build a network. Each node communicates with nearby nodes via wireless networks to monitor physical phenomena such as temperature, humidity, pressure, radiation and so on [9, 39, 57].
2. Internet of things (IoT) – An IoT-based indoor air monitoring system is used to record the air quality data and send it to the webserver for visualisation and classification purposes. IoT brings together a wide range of smart systems, frameworks and intelligent objects and sensors [87].

16.6 Strategies for Improving Indoor Air Quality

Three key ways for increasing IAQ are addressing emission sources, adopting air purification technologies and upgrading ventilation systems [30].

Minimising the use of VOC emission sources: According to the US Consumer Product Safety Commission [73], this is the most effective way to improve the indoor air quality. To implement this, the United States Environmental Protection Agency (USEPA) has issued a few guidelines, including the following:

(a) Replace VOCs with water-based degreasing baths, and utilise paints, inks, glues or adhesives that contain no or very little VOCs.
(b) Adopt excellent management practices like implementation of closed systems while using it.
(c) VOC recycling via control techniques such as adsorption, absorption, condensation and membrane processes; organic compounds should be utilised on-site whenever possible.
(d) Use procedures such as thermal or catalytic incineration or biological treatment to destroy efficiently collected VOCs.

Adopting air purification technologies: The use of air purification methods plays a critical role in protecting human health by removing indoor air pollutants. Ahn et al. [4] and Schroth [64] described four types of air filters based on particle filtration efficiency and are named as prefilters, medium filters, high-efficiency particulate air (HEPA) filters and ultra-low particulate air (ULPA). HEPA filters are utilised in theatres, hospitals, respirators, cars and other places where high efficiency is required [10]. Nonwoven nanofibre material is a new filtration method that has a very high filtration efficiency. At smaller particle sizes, they are comparable to HEPA filters or even better [79]. For the elimination of VOCs from indoor air, several non-thermal discharge plasma procedures have also been developed [62].

Upgrading ventilation systems: Increasing the amount of outdoor air that enters the house is another way to reduce the concentrations of indoor air pollutants. Since the majority of home heating and cooling systems, including forced air heating systems, do not provide fresh air mechanically, therefore, open windows and doors, operate window or attic fans or run a window air conditioner with the vent control open to boost the outdoor ventilation rate. Local bathroom or kitchen fans that exhaust outside eliminate impurities from the room where they are installed while simultaneously increasing the pace of outdoor air circulation [73].

Apart from the above-mentioned methods, several other strategies are employed to decrease indoor air pollution due to VOCs. Because of the low creation of secondary pollutants, advanced oxidation process (AOP)-based technologies have drawn a lot of interest in the development of indoor air pollution control techniques. Photocatalysis has been identified as a promising method since it degrades VOCs directly into CO_2 and H_2O in ambient circumstances [20].

16.7 Conclusion

Pollutants in the indoor environment degrade air quality, which has a negative impact on human health. This problem needs to be concentrated on to get a long-term solution. Among all pollutants, VOCs require special attention because they include all of the components that are an essential part of our daily lives. Although evidence exists for an increase in indoor air pollution in India, as well as its association with increased morbidity and mortality, more research is needed to assess the levels of exposure to indoor pollutants and to strengthen the evidence for their association with various diseases. This study will, therefore, help the researchers as a baseline for introducing advanced technologies associated with indoor VOC pollutions. Effective interventions ranging from education to changes in fuel patterns and proper design of stoves and houses, as well as a dedicated cross-sectoral coordination towards public health promotion at the social, economic and environmental level are some of the steps required to prepare a healthy and sustainable environment. This study will therefore be an eye-opener for the youth today.

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