Chemosphere 313 (2023) 137489

Contents lists available at ScienceDirect

Chemosphere

journal homepage: www.elsevier.com/locate/chemosphere

# Environmental and human health impacts of volatile organic compounds: A perspective review

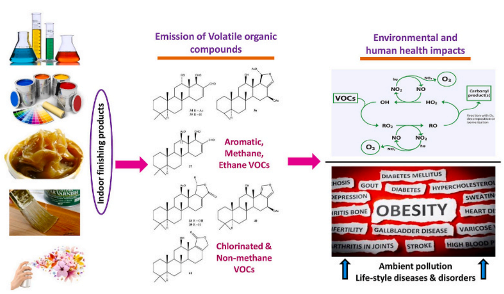
Xihe Zhou [a], Xiang Zhou [b], Chengming Wang [c], Handong Zhou [a,*]

[a] *Jiangsu Co-Innovation Center of Efficient Processing and Utilization of Forest Resources, International Innovation Center for Forest Chemicals and Materials, College of Materials Science and Engineering, Nanjing Forestry University, Nanjing, Jiangsu, 210037, China*
[b] *Sinomaple Furnishing (Jiangsu) Co., Ltd., 99 Fen an Dong Lu, Wujiang District, Suzhou, Jiangsu, 215200, China*
[c] *Holtrop & Jansma (Qingdao) Environmental Protection Equipment Co., Ltd., 8 Tongshun Road, High-tech District, Qingdao, Shandong, 266114, China*

## HIGHLIGHTS

- Volatile organic compounds (VOCs) are used in the production of day-to-day products.
- VOCs majorly accounts for the indoor and outdoor chemical pollution.
- Exposure of VOCs is mounting throughout the world.
- VOCs are widely assessed to promote ecological damage.
- VOCs are reported to influence lifestyle related diseases in human population.

## GRAPHICAL ABSTRACT




## ARTICLE INFO

*Keywords:*
VOCs
Environmental synthetic chemicals
Eco-toxicity
Global warming
Human-toxicity

## ABSTRACT

Volatile organic compounds (VOCs) are synthetic chemicals that are broadly used in the production of numerous day-to-day products for residential and commercial-based applications. VOCs are naturally occurring in the environment; however, average annual emissions of man-made volatile organic compounds may have increased dramatically in recent decades. Although many factors were attributed to influencing volatile compounds' emission, only mankind's activities are mainly proclaimed. Since vehicle and industrial pollution are mounting for years and years, urban areas are highly prone to the impacts of VOCs. Generally, volatile compounds are highly spontaneous and readily react with the particles of ambiance and produce a polluted atmosphere through several physical and chemical reactions. Though the volatile compounds play an indispensable role in the manufacture and maintaining the stability of many products, the health impacts associated with their prolonged exposure are gaining attention as recent research reports underline the influence of a wide range of diseases and disorders. Likewise, since the modern way of life applies a lot of day-to-day chemicals, it is imperative to spread a wide knowledge and safety aspects about these chemicals so that people of a wide category can implement preventive measures according to their exposure and living style. In this context, the review article attempts to shed light on past and current updates concerning the relationship between VOCs exposure and environmental and human health impacts.

* Corresponding author.
*E-mail address:* hdzhou@njfu.edu.cn (H. Zhou).

https://doi.org/10.1016/j.chemosphere.2022.137489
Received 23 October 2022; Received in revised form 28 November 2022; Accepted 3 December 2022
Available online 10 December 2022

## 1. Introduction

Volatile organic compounds (VOCs) are a type of chemical, typically found in a gaseous form and is consequently widely produced by humans as well as distributed throughout the environment for a variety of domestic and commercial purposes (Vereecken et al., 2018). VOCs occur in two forms in the environment: naturally occurring VOCs and anthropogenic VOCs (Michanowicz et al., 2022). Natural volatile organic compounds represent biogenic compounds that are produced and emitted by plants into the atmosphere. The worldwide data reveal tropical areas as the most prominent volatile organic compounds emitters followed by extra-tropical regions (Atkinson and Arey, 2003). In the last decade, it was ascertained that perhaps the annual emission of VOCs by tropical regions alone was over a thousand teragram of carbon, which attributed for substances such as isoprene, monoterpene, and other highly reactive hydrocarbons that contributed 44, 11, and 22.5%, respectively. Though there are numerous sources attributed to the emission of volatile organic compounds, human activities contribute most to the indoor and outdoor environments (Na et al., 2005; Zalel and Broday, 2008).

Mostly the urban areas are placed at the top of the trend since vehicle pollution as a result of largescale traffic, vehicle engine combustion, industrial processes, and exhausts, decomposition of biological and non-biological wastes, application of solvent varieties, etc. (Fig. 1) have been tremendously increased for past few decades (De Gouw and Warneke, 2007; Ho et al., 2009). Among the above, industrial activities are also vastly contributing to the release of volatile organic compounds in the atmosphere. Petrochemical manufacturing plants, coal-fired power plants, dry cleaning processes, large construction projects, and building painting activities all contribute significantly to VOC emissions in urban areas (Banaszkiewicz et al., 2022). Furthermore, the synthesis, manufacture, transportation, and use of fossil fuels emit significantly more volatile organic compounds (Atkinson and Arey, 2003).

They primarily emit aromatic, alkane, and alkene-based derivatives, aliphatic and aromatic hydrocarbon-based petrochemicals, and other volatile organic compounds that are widely detected in the atmosphere (Singh et al., 2022). These volatile compounds are extensively employed to manufacture several finishing products especially, color paints, primers, varnish varieties, waxes, cleaners, pastes, gums, glues, greases, etc. (Talapatra and Srivastava, 2011). Since the volatile organic compounds are highly radical, they can react to any particle or substance right from the moment they are released into the surface air. They were found to rapidly undergo many physical and chemical transformations and release organic and inorganic derivatives as unwanted products into the atmosphere (Singh et al., 2022; Talapatra and Srivastava, 2011). Moreover, the count of novel volatile compounds entering the markets is consistently increasing, and the essential for the government bodies, regulatory bodies, and also chemical and research societies to monitor their exposure and their associated toxic effects is highly emphasized (Hernández et al., 2019). Keeping this in mind, the review article discusses some important and recent updates revealed on the toxicological aspects of VOCs as novel combined information of VOCs toxicity.

### 1.1. VOCs impact on atmosphere

The chemical transformation of volatile organic compounds leads to the production of highly reactive volatile substances and plays a significant contribution to atmospheric ozone formation, acid deposition, organic aerosol formation, photochemical smog formation in the atmosphere and contributes to the increased pollution rate and even leads to climate change effects (Bauguitte et al., 2011). VOCs are classified based on how easily they can be emitted. The World Health Organization (WHO), classifies the indoor organic contaminants as follows (Montero-Montoya et al., 2018): Organic compounds that are extremely volatile (VVOCs: methyl chloride, propane, and butane), Organic compounds that are volatile (VOCs: hexanal, formaldehyde, ethyl alcohol, D-Limonene, isopropyl alcohol, toluene, and acetone), and Organic compounds that are semi-volatile (SVOCs: pesticides). The elevated the volatility, the further presumably the compound would be released into the environment from various products (Zareian et al., 2018). VVOCs

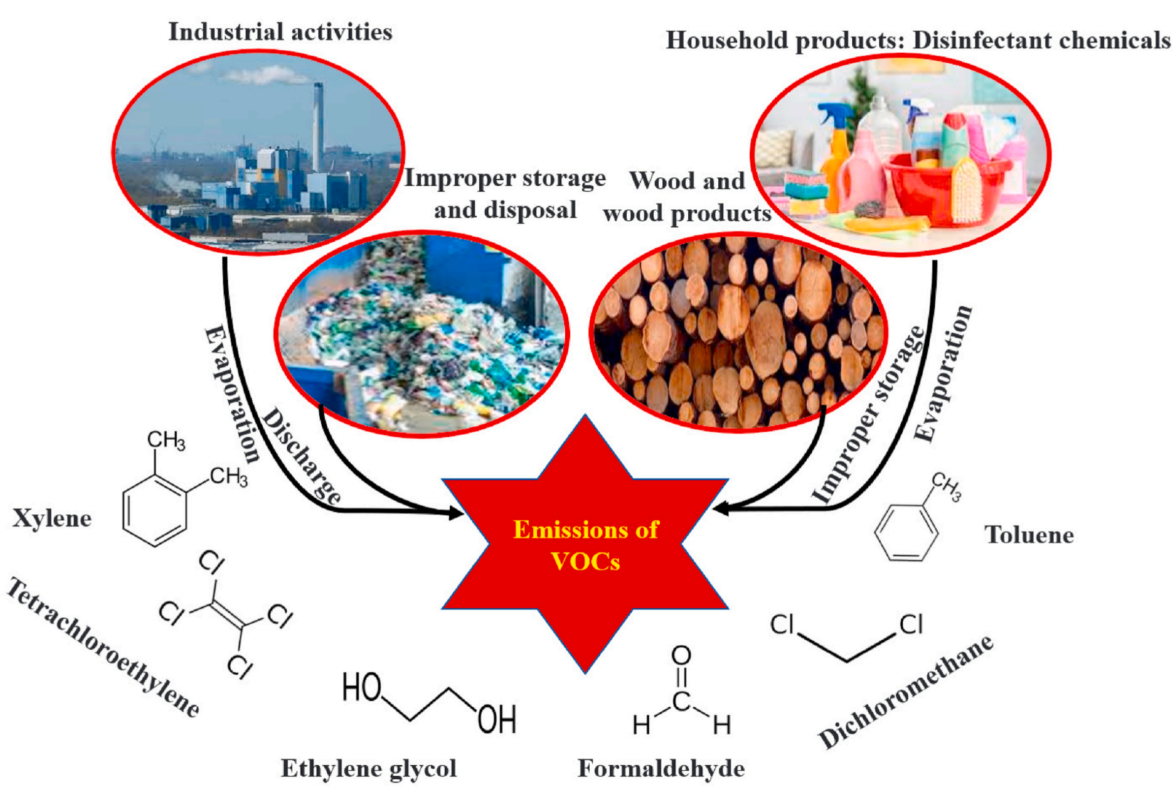



**Fig. 1.** Emission of most common problematic VOCs from various sources.

and hazardous air pollutants (HAPs) including some alkanes, alcohols, aromatics, ethers, aldehydes, ketones, esters, and amines are just so volatile that measuring them is challenging, while they are almost found as gases in the atmosphere instead of within components or just on surfaces. The least VCs found in air make up a much smaller percentage of the total observed indoors, with the significant proportion found in solids/liquids containing those or just on interfaces such as dust, construction materials, and furnishings (Zareian et al., 2018). Many volatile organic compounds are precursors for ozone production, they are more commonly claimed to expedite or further worse air pollution. In addition, ozone then becomes a secondary precursor that tends to induce a range of photochemical reactions between many primary oxidants and pollutant chemicals and ends up in the release of gaseous compounds with highly reactive nature (Swamy et al., 2012). This is highly complicating the ground-level atmosphere since the intense levels of ozone and their byproducts could seriously intervene with the fundamental physiology of vegetation. Forest VOCs are really the result of numerous metabolic processes in the plant system: isoprenoids are the largest significant class of metabolites (chemical compounds) in aspects of compound diversification and quantity of emissions of VOCs. Moreover, with not limiting to plants, the human exposure to such volatile derivatives also becomes a significant cause of concern as they are widely reported to pose a range of toxic outcomes more exclusively, including skin and lung-related illnesses (Jenkin and Clemitshaw, 2000).

The light-assisted chemical reaction by volatile organic compounds principally takes place with carbon dioxide, nitric oxide, and even with many volatile organic compounds which are mainly conducted in the presence of atmospheric radiation (Kroll and Seinfeld, 2008). Temperature-dependent release of VOCs from different biological and non biological sources is, accountable for ongoing climate warming at two times the rate of rising temperatures (Yáñez-Serrano et al., 2020). Furthermore, the arctic ecosystems have been expected to substantially enhance their VOCs releases. Researchers reported that the ongoing global warming has a significant and increasing impact on VOCs emissions (Ghirardo et al., 2020). Besides, that the influence of temperature as well as soil moisture into direct as well as indirect impacts via plant communities as well as biomass modifications process and other non-biological process. Another research report stated that the indirect effects of global warming by VOCs release were substantial but lesser than just the immediate impact. Besides that, variations through vegetation induce alterations in the chemical evolutionary change of VOCs emissions level. Depending on the regional vegetation as well as climate interactions, both direct as well as indirect consequences lead to significant geographic variations in VOCs emissions response in the global warming.

Furthermore, many primary and secondary organic aerosols are primarily produced by the oxidation of volatile organic compounds in a variety of environments, leads to release of several low and semi-volatile derivatives into the atmosphere. This chain process produces more novel volatile substances, many of which have been observed to potentially contribute to climate change, and changes in environmental health in a variety of ways. The increased concentration of carbon dioxide and halocarbons in combination with carbon monoxide stress was also found to play a huge role in accelerating the oxidation of volatile organic compounds. Similarly, an association of degradation of volatile organic compounds with incineration assisted by fossil fuel combustion is also nowadays highlighted the escalated global warming effects (Murrells and Derwent, 2007).

### *1.2. VOCs and human exposure*

According to multiple studies estimated data, human exposure to a variety of volatile organic compounds has substantially enhanced globally owing to enhanced time spent in major indoor environments such as offices, workstations, residences, and other similar places. Since the day-to-day life of a large ratio of people is more commonly running in these small environments, they are more prone to exposure as numerous volatile organic compounds are hidden in the household materials or finishing products. The exposure levels are also determined to be varied based on the routine activities, the intensity of routine activities, the season, etc., performed in the above-mentioned environments. Previously, it was discovered that VOCs cause an indoor chemical burden that appears to be greater in cold weather than in summer (Rehwagen et al., 2003).

Although in the context of toxicological research on routine chemicals continuously claim a diverse source cause potential health impacts to human and wildlife, the environmental exposure is the most pinpointed chemical source as a causative factor. While observing the health impacts of volatile organic compounds, though it is not covered completely, they were found to affect a wide range of populations with progressive exposure by every year (Franck et al., 2006). In addition, already several new classes of volatile organic compounds were consistently found in every new examination targeted by human observational and biomonitoring research. The significant finding has been that VOCs affected the young population irrespective of age, which was very concerning, and children faced the same health issues as adults. More particularly, children in kindergartens were found to face more impacts than the primary and secondary school kids (Adgate et al., 2004; Sonne et al., 2022). These observations have given some association for their susceptibility towards premature lung illnesses including bronchitis as their schooling environment is surrounded by a typically high pollution rate due to high traffic exhaust pollution and domestic heating activities, etc.

## 2. Significant remarks of VOCs exposure and measurement at indoor and outdoor levels

For the last few decades, there were some significant efforts have been conducted to observe the exposure of volatile organic compounds and for the same, standard protocols and statistical methods also have been developed to measure the exposure levels. Many studies have been conducted to monitor volatile organic compounds as well as other pollutants such as nitrogen-based contaminants, carbon-based contaminants, suspended particulate matter, and so on. In the late 1990s, studies concluded that volatile organic compounds contributed significantly to exposure in the majority of tested indoor and outdoor environments. Moreover, this significant outcome was mainly attributed to the cooling and heating practice and road traffic pollution in indoor and outdoor circumstances, respectively. Poor ventilation condition is generally claimed as contributing factor to the above exposure whereas, ventilated areas with the same pollution conditions were comparatively recorded with a minimal level of volatile organic compounds exposure. Meanwhile, it was discovered that the release of volatile organic compounds from smoking at different sites, including domestic activities and tobacco smoking, was comparatively minimal, emphasising the association of high volatile organic compound exposure with vehicle pollution and indoor temperature controlling practice (Baek et al., 1997).

Another group of researchers matched the indoor and outdoor levels of volatile organic compounds between houseworkers to those of their neighbours who were occupationally exposed to nearby road stations. It was shown that the indoor level concentration of volatile organic compounds was higher than that of people working outside in heavily trafficked areas (Jo and Moon, 1999). Similarly, studies also attempted to ascertain whether the outdoor environment contributes to indoor air quality. They also hypothesized that in terms of volatile organic compounds, either the air quality of the indoor or outdoor environment was not alone contributed by the outcome of activities performed in the respective environment (either indoor or outdoor) thereby, they targeted to detect of about thirty different volatile organic compounds that were most commonly present in the house finishing indoor products include, paints, waxes, cleaners, and personal care products. The study discovered that the concentration of volatile organic compounds in outdoor residential areas was dominated by roadside pollution caused by extensive transportation, indoor cleaning products, vehicle emissions, and personal care products all contributed to increased exposure to volatile organic compounds in the indoor environment. Similarly, VOC emissions from product finishes were found to have a greater indoor concentration in the working environment (Edwards et al., 2001). These data from the study collectively implied that activities at both indoor and outdoor levels can contribute to each other with their VOCs exposure.

Researchers also compared the human exposure to volatile organic compounds in different microenvironments to check whether there is a positive association with exposure duration. They examined people who were living or working in indoor work stations, home indoor, and outdoor areas over a duration of 2 days and found that those who spent about 90% of the time in indoor environments showed 20% more exposure to volatile organic compounds than in outdoor microenvironment. Therefore, routine indoor activities are significantly associated with a higher chance of exposure (Lai et al., 2004). Another similar study found that among people who had regular or more often spent in stores, malls, and restaurants about 25% of their regular time were found significantly exposed to volatile organic compounds compared to the control population (Loh et al., 2006). These observations imply that working in these non-residential indoor microenvironments on a long-term basis could pose potential health outcomes.

### 2.1. Importance of identifying VOCs in the microenvironments

Worldwide, when it comes to either living or working scenarios, the choice for many people has now become microenvironment rather than other types of workspaces and living spaces (Rhodes et al., 2012). Especially, after the raise of the covid pandemic, almost the living and working style also had a great format shift so that for many people, the comfort of residing or working also been adjusted to indoor environments. It is also known very well that the construction of the indoor modern houses, work stations, commercial malls, restaurants, corporate sites, etc. involves applying a wide variety of chemical-based finishing products including, color paints, primers, varnish varieties, waxes, cleaners, pastes, gums, glues, etc. in fact, the human health effects of several synthetic or environmental chemicals are revealed and it is continuously progressing. Moreover, the individual health effects of thousands of the chemicals hidden in these products are not completely addressed (Bourguet and Guillemaud, 2016). Compared to other chemicals, volatile organic compounds are highly comprised in the above products and moreover, they are highly reactive when exposed to the environment and humans (Montero-Montoya et al., 2018). Moreover, the impacts of exposure to these volatile organic compounds also depend on the time elapse, type of particular class, type of working environment, indoor and outdoor environment, and type of construction finishing materials employed in the indoor or outdoor surroundings, etc (Shrubsole et al., 2019). Since many studies have related the allergic, carcinogenic, mutagenic, and toxic properties of these volatile organic compounds, it is imperative to monitor the exposure, exposure levels, and also their health outcomes which would hopefully provide minimal knowledge to the general population about the safety of such products (Carocho et al., 2014; Vardoulakis et al., 2015).

### 2.2. The global exposure of VOCs, its environmental impacts, and regulations

As discussed earlier, vehicle pollution is one of the foremost human activities which is highly associated with the release of volatile organic compounds into the atmosphere. Researchers thereby have hypothesized how the emission standards, vehicle type, driving mode, conditions, and cumulative mileage contribute to different emission levels of volatile organic compounds (Wang et al., 2020). They have analyzed 25 compounds mostly of alkanes, aromatics, and halocarbon-based VOCs including, hexene, pentene, butene, butadiene, dodecane, undecane, decane, nonane, octane, methyl-cyclohexane, methyl-cyclopentene, diethyl-benzene, propylbenzene, trimethylbenzene, ethylbenzene, xylene, styrene, benzene, toluene, tetrachloroethylene, dichlorobenzene, trichloroethane, chlorobenzene, dichloropropene, and dichloroethane (Fig. 2). All these compounds were detected using the time-of-flight mass spectrometer analysis and found that the concentration of above volatile compounds released from a range of vehicles was significantly influenced by the different levels of individual parameters tested (Li et al., 2021). This indicated that vehicle emission could be a major influencer of volatile organic compounds released into the atmosphere.

Although vegetation-based release accounts for a certain ratio of volatile organic compounds, human activities are estimated to cause more impacts on the environment. Especially, extensive industrial based activities regularly produce numerous volatile organic compounds but, when either road traffic or operations in industries are limited or shut over a period of time, the condition of the atmosphere is getting improved in terms of not only overall pollution rate but also the concentration of various volatile organic compounds. Recently in China during early 2020, there were many restrictions executed to mitigate the Covid exposure so that public gathering was significantly limited due to which traffic on roads and functioning of hundreds of industrial units were temporarily halted. During this season, the assessment of the concentration of various volatile organic compounds and their environmental impacts was carried out based on online measurements using GC-MS and GC-FID methods. The study team addressed that the VOCs concentration of over thirty different volatile compounds was reduced to half during the lockdown period than the concentration levels recorded previously (Wang et al., 2021).

A similar exposure was also observed by another study conducted in tourist places where the lockdown activities were implemented due to the Covid surge. In Italy, the Lagoon of Venice, a global familiar heritage attracts the global population throughout the year (Cristiano and Gonella, 2020). However, in recent years, tourism in this city also impacted negatively by causing a series of pollution, including ambient air quality, sewage contamination in seawater, and many more. A local research team attempted to find out whether the imposition of lockdown resulted in the improvement of seawater quality of the Lagoon of Venice (Manoiu et al., 2022). Interestingly, there were about 40 volatile compounds were detected in seawater samples before the lockdown whereas, the analysis of the samples collected after the lockdown revealed only the presence of 17 volatile compounds. Also, their concentration was found to drop compared to the earlier levels (Cecchi, 2021).

The increased air pollution in the metro and cosmopolitan cities has become a serious environmental issue due to which population of all ages is developing deleterious health outcomes (Martinez et al., 2018). Therefore, observation of various classes of pollutants or contaminants responsible for the worst air quality is continuously carried out. A group of researchers in China attempted to monitor the contribution of volatile organic compounds to the heavy air pollution in Beijing city and also assessed its associated environmental impact and health risk (Mozaffar and Zhang, 2020). During the winter season, they measured the concentration of about 99 VOCs at 10 a.m. at every morning for 35 days and the same during in summer season for about 35 days. The results showed that the levels of volatile organic compounds during winter were significantly higher compared to the summer season contributed by aromatic-based volatile organic compounds. Moreover, they observed VOCs also significantly influenced secondary organic aerosol and ozone formation in the polluted environments so that they potentially contribute to the ecological impacts (Li et al., 2020a).

Similarly, a detailed study has revealed the potential of volatile organic compounds in the formation of ozone and secondary organic aerosol in the asphalt pavement construction where the emission of

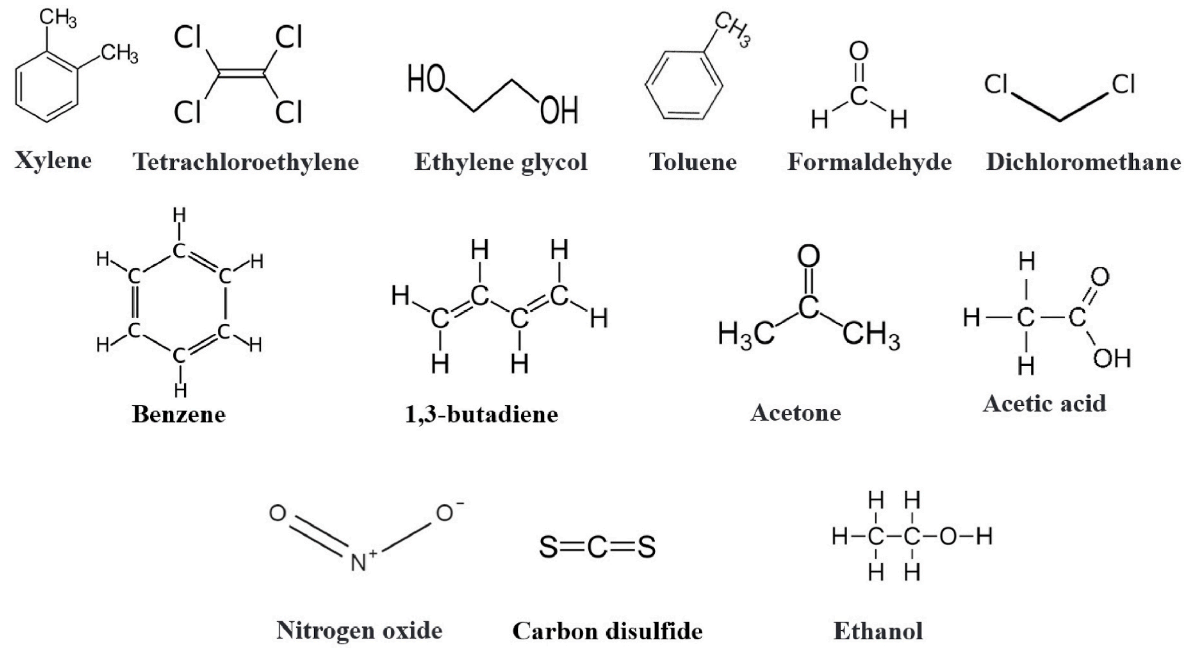



**Fig. 2.** Molecular structure of most common list of VOCs.

different classes of volatile compounds including, alkenes, alkanes, aldehydes, and alkylbenzenes was tested. During asphalt pavement construction, the above environmental impacts were assessed throughout various scenarios such as production, transportation, paving process, etc. They observed that the selected class of volatile compounds contributed about 62% and 97%, respectively the ozone and secondary organic aerosol formation potential that indicating that VOCs can effectively impact the environment (Li et al., 2020b).

The EPA regulates VOCs emissions to the environment primarily to avoid the creation of ozone, a component of photochemical pollution (smog) (Zhang et al., 2019). Numerous VOCs produce floor-level ozone through responding with $O_2$ molecules with in surrounding air, including NOx and CO, in the occurrence of sunlight. Moreover, only a few VOCs are deemed "reactive" sufficient warrant issue (Massetti et al., 2017). VOCs that seem to be non-reactive and have minimal sensitivity to establish ozone under such circumstances are excluded first from EPA's description about VOCs (Borbon et al., 2013). Since its first establishment the collection of excluded substances in the year 1977, the EPA had already introduced numerous substances to the lineup as well as commonly does have several pleas for additional substances pending review. Furthermore, each state has its own classifications and regulations lists of specifically excluded compounds like VOCs (Burghardt and Pashkevich, 2021). Hence, for regulatory/control purposes, whatever is exempted from the description of VOCs at indoors and outdoors can alter. For instance EPA guidelines, the formaldehyde, among the most prevalent VOCs, can indeed be released into the atmosphere from a variety of sources, including home furnishings, incense incinerating, as well as constructing materials (Huangfu et al., 2020). It's indeed worth noting that the threshold limit value seems to be 0.1 ppm of TLV-TWA (Threshold Limit Value - Time Weighted Average: 8 h) and 0.3 ppm TLV-STEL (Short Term Exposure Limit: 15 min). There are no federally properly enforced standards for VOCs in the aspect of non-industrial environments (Cravero et al., 2017).

Only, ambient air pollution is mostly recognized to comprise volatile organic compounds, however, these compounds are also found substantially present in other environmental sources including soil and water. Several reports from the toxicological society are concerned about the toxic levels of volatile organic compounds in drinking water, river water, etc. This type of contamination by different volatile compounds not only impacts ecological sources but also affects humans when frequently are exposed. Recently, in China, the concentration of about 54 volatile organic compounds in water samples was analyzed in a delta region covering about five rivers located in urban, semi-urban, and rural stretches (Anifowose et al., 2022). The study collected the water sample from 58 different locations in the selected delta region based on several industrial and domestic activities being performed. Among them, 31 volatile compounds were detected in the range of 0.5–46.82 μg per litter from all the locations. In addition, styrene and toluene detected among them found to pose a significant ecological risk in a few locations (Li et al., 2021). The WHO suggests that to address healthcare disparities, achieve by 2030 Agenda for Sustainable Development, as well as reduce climate change, meaningful policy modifications are required to faster boost the number of individuals with access to environmentally friendly technologies and fuels by 2030.

### 2.3. Effect of VOCs exposure on human health

Not limited to the environment, the impacts of volatile organic compounds are also extended to humans irrespective of age population, and the living standard. Different types of industries such as organic solvents, lacquers, paints, pesticides, cleaning supplies, furnishings, cosmetic products, building materials, printers, photocopiers, correction fluids, glues, graphics, adhesives, photographic solutions, permanent markers, and so on are all discharge VOCs (Table 1), which can cause air pollution and health effects (Soni et al., 2018). Acknowledging how detrimental chemicals' amounts have been evaluated is critical to comprehension at which prescribed dosages they are becoming lethal. Flame Ionisation Detection, metal oxide semiconductors sensors as well as Photo Ionisation Detection seem to be the 2 different greatest frequently used techniques for VOC descriptive statistics (Lough et al., 2017). All these techniques measure the amount of VOCs in the air upon that presumption. Since air pollution has become a very common issue even in small and mini towns nowadays, almost everybody in the world including wildlife also become prone to pollution and susceptible to developing a number of degenerative diseases (Fig. 3). The route of exposure of volatile organic compounds to humans principally occurs in different ways including inhalation, ingestion, and skin contact (Fig. 4). However, the inhalation route is significantly attributed to the exposure

**Table 1**
Health impact assessment of some of well studied volatile organic compounds.

| VOCs | Class | Assessed health impacts | Location | Reference |
|---|---|---|---|---|
| Dichloroethane, bromodichlomethane, trichloroethane and toluene | Chlorinated VOCs and aromatic VOC | Carcinogenic<br>Non-carcinogenic | China<br>China | Huang et al. (2014)<br>(Li et al., 2020b) |
| Benzene, butadiene, chloroform, acrolein, and acetaldehyde | Aromatic VOC | Carcinogenic | China | Li et al. (2020a) |
| Polychloroethylene, polychloromethan, and polychloethane | Ethane-based VOCs | Cancer in bladder, rectum, esophagal, cervical, and colon | China | Jin et al. (2022) |
| Dichloroethane, bromodichlomethane, and trichloroethane | Chlorinated VOCs | Reproductive defects and frequent abortions | | (Lynge et al., 1997; Scott and Jinot, 2011) |
| 21 VOCs | Aromatic, chlorinated, ethane and non-methane VOCs | Carcinogenic | India | (Huang et al., 2014; Puttaswamy et al., 2021) |
| Toluene<br>Formaldehyde<br>Acetaldehyde | Aromatic VOC | Non-carcinogenic | China | Lin et al. (2019) |
| Acrolein<br>Crotanaldehyde and butadiene | Aromatic VOC | Altered systolic blood pressure, and endothelial dysfunction | USA | McGraw et al. (2021) |
| Dichloro-propane and dichloroethane | Aromatic VOC | Carcinogenic | UK | Chen et al. (2021) |
| Toluene and benzene derivatives | Aromatic VOC | Obesity and diabetes | Korea | Lee et al. (2022) |


**Fig. 3.** Exposure of VOCs and its impact on the environment and human health.

(Huang et al., 2014). And, as every day the rate of pollution mediated health impacts is mounting, researchers are in a continuous attempt to reveal the level of exposure and the impacts that are likely caused by the humans.

Recently, in China, the concentration of about 54 volatile organic compounds in water samples was analyzed in a delta region covering about five rivers located in urban, semiurban, and rural stretches. The study collected the water sample from 58 different locations in the selected delta region based on several industrial and domestic activities being performed. Among them, 31 volatile compounds were detected in the range of 0.5–46.82 μg per litter from all the locations. Based on the carcinogenic risk index, volatile compounds such as dichloroethane, bromodichloromethane, and trichloroethane were found to have high carcinogenic nature whereas, according to the non-carcinogenic risk index, volatile compounds such as toluene detected to pose another toxic risk. Moreover, many other volatile compounds were also found to pose olfactory risks but are available in meager concentrations (Li et al., 2020b). Another research in China attempted to monitor the contribution of volatile organic compounds to the heavy air pollution in Beijing city and also assessed its associated environmental impact and health risk. During the winter season, they measured the concentration of about 99 volatile organic compounds at 10 a.m. of every morning for 35 days and the same during in summer season for about 35 days. In addition to environmental impact, their carcinogenic risk was also measured with potential volatile compounds such as benzene, butadiene, chloroform, acrolein, and acetaldehyde and whose threshold values were found to exceed the USEPA and EPA standard for causing carcinogenic effects on human health (Li et al., 2020a).

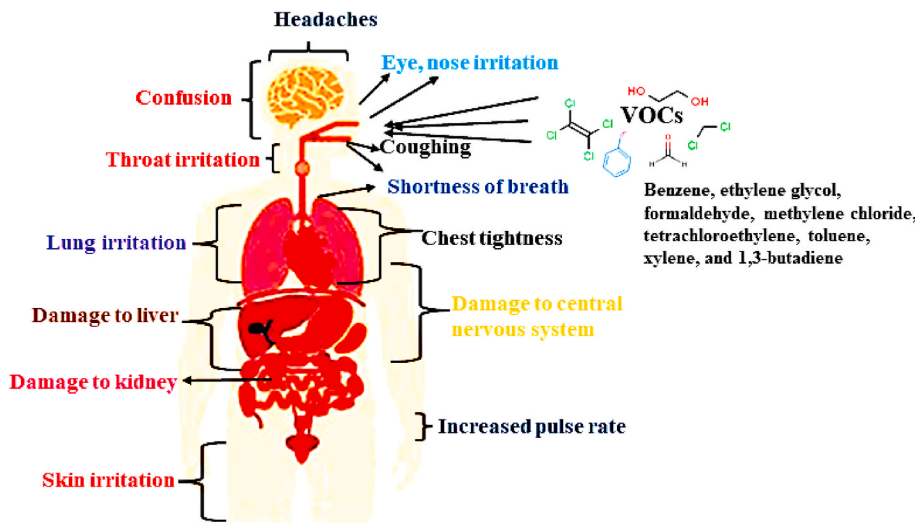



**Fig. 4.** Possible health impacts of VOCs on human when exposed.

Ethane-based chlorinated VOCs such as polychloroethylene, polychloromethane, and polychloethane are broadly used in construction finishing products including various solvents, varnishes, paints, and degreasing agents (Lough et al., 2017). These chemicals were widely noticed to contaminate soil, groundwater, and other local water bodies so their toxicity properties were assessed in recent studies conducted around the globe. Epidemiological studies proclaim that chlorinated volatile compounds are able to cause bladder cancer, rectum cancer, esophageal cancer, cervical cancer, and colon cancer (Jin et al., 2022). Other studies also demonstrated that exposure to chlorinated VOCs is associated with birth defects and frequent abortions thereby, they could also pose a reproductive risk. Due to their multiple cancer influencing properties, the ministry level environmental bodies of many world countries have enlisted a number of chlorinated volatile compounds in the priority category to have continuous monitoring (Huang et al., 2014; Lynge et al., 1997; Scott and Jinot, 2011).

In Southern India, health risks associated the household exposure to VOCs were assessed. In a study, authors targeted the women cooks to measure the exposure levels of different household cook fuels such as biomass, kerosene, and liquified petroleum gas. They have enrolled 112 women cooks and assessed the time-based exposure of 21 non-methane VOCs and found that women who were exposed for more duration in the combustion of liquified petroleum gas showed more folds of maximum cancer risk index compared to biomass and kerosene used women cooks (Puttaswamy et al., 2021). In 2019, a Chinese study was attempted to investigate whether how effectively exposure to VOCs affects asthmatic children. They estimated the exposure level during night sleep and compared the data with another group of asthmatic children who slept in rooms facilitated with indoor air cleaner systems. They found that study participant who slept without indoor air cleaners were significantly exposed and the measurement levels of toluene, formaldehyde, and acetaldehyde were showed exceeding the non-carcinogenic limit, compared to their counterparts. In addition, although the counterparts slept with air cleaners, they were also exposed to concerning levels (Fang et al., 2019) so that regardless of protective systems, it implied that VOCs are able to pose significant impacts. Similarly, VOCs were also investigated to whether they are able to promote cardiovascular risk. A study recruited 346 non-smoking individuals and examined their urinary samples for the presence of acrolein, crotanaldehyde, and butadiene metabolites and carefully measured the CVD (cardiovascular disease) risk.

Other than vehicle engine combustion, house construction finishing products, and other commercial products, VOCs are constantly released from electric and electronic products and their waste (e-waste) (Lough et al., 2017). The rate of release is high proportionally influenced when e-wastes are disposed of, dumped, and particularly at the time of the recycling process, VOCs comprised in e-wastes are reaching out to the surrounding ambiance and contribute significant environmental impacts and thereby also cause serious health impacts to humans. Recently in 2021, a study has monitored the association of cancer risk with the exposure of e-waste emitted volatile compounds in different seasons; winter, autumn, spring, and summer. Compounds such as dichloro-propane and dichloroethane were markedly emitted in the winter and autumn seasons shown to exceed cancer threshold values (Chen et al., 2021). Apart from this, volatile compounds such as toluene and benzene-based derivatives can pose obesity and diabetes risk factors thus, VOCs are not only concerned with carcinogenic, respiratory, and cardiovascular diseases but also cause metabolic risks. In Korea between 2015 and 2017, there was about 3787 adult population was participated in a national wide survey in which their urinary concentrations of VOCs metabolites were determined. The benzene-based volatile metabolites were found markedly exert both diabetes and obesity risks by exceeding the index values of non-alcoholic fatty liver disease (Lee et al., 2022).

## 3. Conclusion

Despite the fact that we humans choose our contemporary way of life, the use of a wide range of chemical-based products for residential, industrial, and commercial purposes has become unavoidable. Because urbanization and industrialization are increasing regardless of economic and developmental factors, the rate of pollution in public, residential, and workstations is expected to peak in the coming years almost in every country. Although biomonitoring, epidemiological, and toxicological studies reveal significant findings on other classes of environmental chemicals, awareness of VOCs remains low because the majority of these compounds are hidden in the respective synthetic products. Thus, more research focusing on exposure and specific impacts on both ecological and human life is expected, as the number of novel compounds entering the market continues to grow around the world.

## Credit author statement

Xihe Zhou: Investigation, Conceptualization, Validation, Data Curation, Writing - Original Draft. Xiang Zhou: Writing - Review & Editing. Chengming Wang: Writing - Review & Editing. Handong Zhou: Writing - Review & Editing, Investigation, Supervision, Project administration, Funding acquisition.

## 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.

## Acknowledgments

This work was financially supported by the National Key R&D Program of China (2022YFD2200705) and National Technology Innovation Alliance of Wood and Bamboo Industry Program of China (TIAWBI 202007).

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