ISSN: 2586-6036
JWMAP website: http://accesson.kr/jwmap
doi: http://dx.doi.org/10.13106/jwmap.2025.Vol8.no3.17

A Study on Global Health Impacts of Volatile and Semi-Volatile Organic Compounds

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Received: June 01, 2025. Revised: June 18, 2025. Accepted: June 18, 2025.

Abstract

Purpose: This narrative review aims to synthesize global evidence on volatile organic compounds (VOCs) and semi-volatile organic compounds (SVOCs), evaluating their sources, distribution, and health impacts across urban, industrial, landfill, and indoor settings to inform mitigation strategies and public health policies. **Research design, data and methodology:** A comprehensive literature search was conducted in PubMed, Web of Science, Scopus, and Google Scholar for peer-reviewed studies (2010–2025), using keywords like "VOCs," "SVOCs," "health impacts," and "air pollution." From 1,800 articles, 120 were screened, and 35 were analyzed based on methodological quality. Data on emission sources, concentrations, exposure pathways, and health effects were extracted, categorized by setting and compound type, and synthesized narratively with tabular summaries. **Results:** VOCs (e.g., benzene, toluene) and SVOCs (e.g., phthalates, PAHs) from landfills, vehicles, industries, and household products pose significant carcinogenic (e.g., leukemia, cancer risks up to 1.67×10^{-3}) and non-carcinogenic risks (e.g., asthma, neurological disorders). Landfill emissions (18.1–806.3 mg/m³) and indoor concentrations (2–5 times higher than outdoors) disproportionately affect vulnerable populations like children and landfill workers. **Conclusions:** VOCs and SVOCs are critical global pollutants requiring urgent mitigation through biochar, ventilation, and regulatory reforms. Comprehensive monitoring and AI-based modeling are essential to protect public health.

Keywords : VOCs, SVOCs, Health Impact, Emission Sources

JEL Classification Code : K32, Q53, Q54, Q56

1. Introduction

Volatile Organic Compounds (VOCs) and Semi-Volatile Organic Compounds (SVOCs) are critical contributors to global air pollution, posing substantial risks to human health and environmental quality. VOCs, characterized by high vapor pressure, include compounds like benzene, toluene, and formaldehyde, which contribute to tropospheric ozone and particulate matter formation (Tanasorn et al., 2014; Wu et al., 2017). SVOCs, such as PAHs and phthalates, have lower volatility, persisting in soil, water, and indoor dust, leading to prolonged exposure (Guo et al., 2014; Shi & Zhao,

This work was supported by the research grant of the KODISA Scholarship Foundation in 2025.
This work is financially supported by Korea Ministry of Environment (MOE) as 「Graduate School specialized in Climate Change」

2014; Kim et al., 2022; Fromme et al., 2023). These compounds emanate from diverse sources: industrial processes (e.g., petrochemical manufacturing), vehicular exhaust, household products (e.g., paints, cleaners), and landfill decomposition. In urban environments, roadside locations typically demonstrate the highest concentrations of VOCs and associated ozone formation potential due to dense traffic emissions and limited dispersion (Tunsaringkarn et al., 2014). The prevalence of photochemical smog marked by elevated levels of ground-level ozone and fine particulate matter, has emerged as a significant environmental issue in China (Guo et al., 2017; U.S. Environmental Protection Agency [EPA], 2020). Their global ubiquity, chemical diversity, and ability to migrate across environmental compartments necessitate a comprehensive understanding of their health impacts.

The public health burden of VOCs and SVOCs is significant. Inhalation, the primary exposure pathway, is linked to acute effects like respiratory irritation and chronic conditions, including asthma, chronic obstructive pulmonary disease (COPD), neurological disorders, and cancer (Alford & Kumar, 2021; Sonne et al., 2022; Pan et al., 2023). Benzene and formaldehyde are classified as Group 1 carcinogens by the International Agency for Research on Cancer (IARC, 2018; Ataei et al., 2022), and PAHs are similarly carcinogenic (Kim et al., 2022). Indoor environments, where people spend over 90% of their time, often exhibit VOC concentrations 2–5 times higher than outdoors, amplifying risks, particularly for vulnerable populations like children and the elderly (EPA, 2024). The global economic cost of air pollution, partly driven by VOCs, is estimated at $4.6 trillion annually, underscoring the urgency of addressing these pollutants (World Health Organization [WHO], 2021).

Recent studies underscore the health risks posed by volatile organic compounds (VOCs) and semi-volatile organic compounds (SVOCs) in various environmental settings. Ran et al. (2018) reported elevated benzene levels in Hong Kong, an Asian megacity, correlating with increased cardiorespiratory hospitalizations due to traffic and industrial emissions. Bolden (2015) noted that occupational toluene exposure is correlated with neurological effects like slowed reaction times and short-term memory loss. Masekameni et al. (2019) conducted a health risk assessment of BTEX emissions in landfill environments and noted that PAHs in leachates contribute to health risks for nearby communities, including carcinogenic potential. Similarly, Ataei et al. (2022) found that phthalate accumulation in indoor environments from household products might cause respiratory disorders (asthma, allergies), which are linked to lung cancer. These studies, while insightful, are often limited to specific compounds, regions, or settings. A comprehensive global synthesis of VOC and SVOC sources, distribution, and health impacts is lacking, hindering evidence-based policy development. This review aims to address this gap by systematically synthesizing literature on VOCs and SVOCs across urban, industrial, and landfill environments. Objectives include evaluating emission sources, global distribution patterns, health risks (focusing on inhalation-related respiratory, neurological, and carcinogenic effects), and regulatory frameworks. By integrating findings from diverse regions and settings, this review seeks to inform global strategies for pollution control and public health protection.

2. Research Methods and Materials

This narrative review synthesized peer-reviewed literature on the health impacts of volatile organic compounds (VOCs) and semi-volatile organic compounds (SVOCs) across urban, industrial, landfill, and indoor settings. We searched PubMed, Web of Science, Scopus, and Google Scholar for studies published between January 2010 and May 2025, using keywords including “volatile organic compounds,” “semi-volatile organic compounds,” “health impacts,” “inhalation exposure,” “air pollution,” “urban air quality,” “landfill emissions,” and “indoor air.” Boolean operators (AND, OR) were used to refine searches. Inclusion criteria encompassed: (1) peer-reviewed original studies or reviews, (2) focus on human health outcomes (respiratory, neurological, or carcinogenic effects), (3) data from urban, industrial, or landfill environments, and (4) English-language publications. Exclusion criteria included non-English articles and studies lacking specific health or exposure data. From an initial pool of 1,800 articles identified, 120 were screened based on title and abstract relevance, and 35 were selected for analysis due to their methodological quality, sample size, and data clarity. Data were extracted on VOC/SVOC sources, concentrations, exposure pathways, health effects, and regional variations, then categorized by setting (urban, industrial, landfill) and compound type (VOCs, SVOCs). Findings were synthesized narratively and summarized in tables to provide a comprehensive overview of the literature, with no quantitative meta-analysis conducted due to variability in study designs and reported metrics.

3. Sources and Distribution of VOCs and SVOCs

VOCs and SVOCs originate from anthropogenic and natural sources, with anthropogenic emissions dominating global burdens. The major sources of VOCs are shown in

Figure 3.

3.1. Sources of VOCs/SVOCs

3.1.1 Industrial Processes

Industrial emissions are one of the principal anthropogenic sources of volatile organic compounds (VOCs) and semi-volatile organic compounds (SVOCs), contributing significantly to urban air pollution, photochemical smog formation, and human health risks. These emissions originate from a wide range of industrial activities, including solvent use, manufacturing processes, surface coating, petrochemical production, and metal treatment. The chemical composition and concentration of VOCs emitted from industrial sources vary considerably depending on the type of industry, the processes involved, and the materials used. A recent study by Kim et al. (2024), conducted in an industrial complex in South Korea, employed proton-transfer-reaction time-of-flight mass spectrometry (PTR-ToF-MS) to characterize VOC emission profiles across 12 industrial sectors, including printing, synthetic leather production, metal plating, and industrial laundry services. Among the industries evaluated, the gravure printing sector exhibited the highest total VOC emissions, reaching daily concentrations up to 5934 mg day^{-1}. This industry predominantly released oxygenated VOCs (OVOCs) such as ethyl acetate and butyl acetate, as well as aromatic hydrocarbons like toluene and propene. Similarly, the plastic synthetic leather industry was characterized by high emissions of toluene and xylene isomers, both of which have strong photochemical reactivity and contribute substantially to ground-level ozone formation (Kim et al., 2024). The emission patterns varied across sectors. For example, chlorinated VOCs such as trichloroethylene and tetrachloroethane were especially prevalent in the metal plating industry, reflecting the use of solvent-based degreasing agents and chemical etchants. These compounds, often persistent in the environment, are recognized for their carcinogenic potential and were present at significantly higher levels in metal treatment facilities than in other sectors. In contrast, nitrogen-containing VOCs (N-VOCs) such as nitromethane and various amines were dominant in facilities involved in the production of general paints and coatings, and in industrial laundry services, where solvent-based detergents and stabilizers are used. Another study conducted in the Map Ta Phut industrial complex in Thailand by Pinthong et al. (2022) provides further insights into the VOC concentrations surrounding petrochemical zones. The researchers reported that aromatic hydrocarbons such as toluene, benzene, and 1,3-butadiene dominated the VOC profiles in both industrial and community zones near the complex. The average concentration of toluene was the highest among all measured species, and the diagnostic T/B (toluene/benzene) ratios ranged between 3.54 and 5.15, which clearly indicated vehicular and industrial emissions as dominant sources. Furthermore, health risk assessments revealed significant non-carcinogenic and carcinogenic risks, particularly due to 1,3-butadiene and 1,2-dichloroethane, which exceeded acceptable thresholds in multiple monitoring zones (Pinthong et al., 2022). Wang et al. (2023) similarly emphasized the critical role of industrial sources, including both production processes and solvent use, in contributing to ambient VOCs. In their study, the mass concentration of total VOCs was reported to be 34.10 ± 35.46 mg m^{-3} for emissions from general industrial processes and 25.39 ± 16.88 mg m^{-3} for those associated with solvent usage. Notably, they found distinct differences in VOC profiles between these two categories. Industrial processes emitted significantly higher levels of halocarbons, while solvent-related emissions were richer in alkanes. Additionally, the relative proportions of BTEX compounds (benzene, toluene, ethylbenzene, and xylene) were similar in both groups, highlighting their ubiquity across industrial sectors. However, the ratios of formaldehyde/acetaldehyde and acetaldehyde/propionaldehyde differed between the two sources, suggesting that these could serve as diagnostic indicators for source apportionment (Wang et al., 2023).

Crucially, the oxygenated VOCs (OVOCs) emerged as the most abundant VOC class across nearly all studied industries. These compounds not only contribute to tropospheric ozone formation but also play a central role in the generation of secondary organic aerosols (SOAs). Wang et al. noted that OVOCs accounted for the highest ozone formation potential among the studied VOC classes, surpassing even aromatics in some cases. Despite their importance, OVOCs have often been underrepresented in source inventories, underscoring the need for updated monitoring protocols and policy interventions. Together, these findings highlight the complexity of industrial VOC emissions and the importance of high-resolution chemical characterization in understanding source-specific risks. They also point to the urgent need for regulatory frameworks that address the full spectrum of emitted compounds, especially OVOCs and chlorinated VOCs, which have historically been underestimated in air quality management strategies. More comprehensive source profiling, combined with real-time monitoring technologies like PTR-ToF-MS, will be essential in devising effective emission control measures and protecting public health in industrially impacted regions.

3.1.2. Vehicular Emissions

Vehicular emissions constitute a dominant source of volatile organic compounds (VOCs) and semi-volatile organic compounds (SVOCs) in urban environments, significantly impacting air quality, human health, and atmospheric chemistry. These emissions arise from both

exhaust and evaporative processes, and their chemical composition is influenced by fuel type, engine condition, emission control technology, and vehicle usage patterns. Recent studies have advanced the understanding of these emissions by integrating high-resolution instrumentation and real-world traffic behavior data.

According to Wang et al. (2022), vehicular VOCs originate predominantly from fuel combustion and include hydrocarbons such as benzene, toluene, ethylbenzene, xylenes (BTEX), as well as oxygenated VOCs (OVOCs) such as acetaldehyde and acetone. The study used a chassis dynamometer and proton-transfer-reaction time-of-flight mass spectrometry (PTR-ToF-MS) to measure real-time VOC emissions from gasoline, diesel, and liquefied petroleum gas (LPG) vehicles under both cold and hot start conditions. Gasoline vehicles primarily emitted aromatic hydrocarbons, especially during cold starts, where VOC emissions could be up to 40 times higher than during stabilized driving. In contrast, diesel vehicles emitted significantly higher proportions of OVOCs (52%–71% of total VOC emissions), including organic acids such as formic acid and acetic acid, due to the fuel-lean combustion environment and less complete oxidation (Wang et al., 2022). The emission factors varied notably across fuel types and emission standards. For example, the emission factors of benzene from gasoline vehicles ranged from 0.8 to 7.4 mg/km, while those of acetaldehyde in diesel vehicles could reach 27.9 mg/km—several times higher than in gasoline vehicles (Wang et al., 2022). Furthermore, the emission reduction due to newer emission standards was significant, with a tenfold decrease in VOC emissions for China VI gasoline vehicles compared to China I vehicles. However, diesel vehicles, even with newer emission standards, still exhibited higher emissions of OVOCs and SVOCs, partly due to the incomplete oxidation and lack of effective after-treatment devices specifically targeting VOCs. While tailpipe emissions have been the primary focus of vehicular VOC research, evaporative emissions are increasingly recognized as a major contributor to ambient VOC levels. Yang et al. (2025) developed a full-process vehicular VOC emission model that accounts for both exhaust and evaporative emissions using automated vehicle identification (AVI) data in Xuancheng, China. Their findings revealed that evaporative emissions, including diurnal losses, hot soak emissions, and running losses**,** now account for up to 40.8% of total vehicular VOC emissions**,** surpassing exhaust emissions in some scenarios. Notably, during public holidays like Labor Day, with decreased traffic flow and increased parking duration, parking-related evaporative emissions rose to 33.4% of daily VOC totals, underscoring the influence of behavioral factors in emissions inventories (Yang et al., 2025). The spatial and temporal variability of VOC emissions from vehicles is also critical. Sui et al. (2025) analyzed VOC distributions in a northern Chinese city across multiple years, showing a sharp reduction in traffic-related VOCs during the COVID-19 lockdowns. Following the resumption of economic activity, diesel vehicle emissions rebounded more strongly than gasoline emissions, emphasizing the ongoing challenge posed by heavy-duty fleets. Additionally, their findings highlighted seasonal peaks in autumn and winter, likely due to atmospheric stagnation and lower mixing heights, which exacerbate pollutant accumulation.

Further complexity arises from the role of specific driving patterns and vehicle age. The study by Yang et al. (2025) used detailed traffic behavior chains to model the impacts of individual vehicle parking durations and trip frequencies, showing that 80% of vehicles remained parked for over 90% of the day. Despite relatively lower emission rates per unit time, the cumulative effect of long-duration parking made diurnal and hot-soak emissions substantial. These insights stress the need for emission inventories to integrate real-time behavioral data alongside vehicle specifications. In conclusion, vehicular sources of VOCs and SVOCs encompass a wide range of emission processes and chemical species. Gasoline vehicles emit large quantities of BTEX compounds during cold starts, while diesel vehicles release significant amounts of OVOCs under lean combustion. With the rise of parking-related evaporative emissions, particularly in urban environments with dense vehicle ownership and limited mobility during off-peak hours, future regulatory and mitigation strategies must address not only engine performance but also evaporative control technologies and vehicle usage patterns.

3.1.3. Landfills

Landfills are major sources of both volatile organic compounds (VOCs) and semi-volatile organic compounds (SVOCs), which are released into the atmosphere through a combination of biodegradation of organic waste**,** chemical volatilization, and thermal processes such as open burning. The emission profiles from landfills are highly complex, influenced by waste composition, climatic conditions, and waste management practices such as flaring or containment.

According to Pan et al. (2023), VOCs and SVOCs in landfill gas primarily originate from two dominant processes: (1) the biodegradation of natural organic waste, such as food scraps, yard trimmings, and paper products; and (2) the volatilization of synthetic and chemical materials in disposed consumer goods, solvents, disinfectants, and plastic packaging. Aromatic hydrocarbons (e.g., benzene, toluene, ethylbenzene, and xylenes—collectively known as BTEX) and halogenated compounds (e.g., trichloroethylene, tetrachloroethylene) were among the most frequently detected VOCs, while SVOCs included polycyclic aromatic hydrocarbons (PAHs) and plasticizers such as phthalates.

These compounds were consistently found across 72 landfill sites in 20 countries, with concentration ranges spanning 1×10^{-1} to 1×10^{6} μg/m³, indicating a massive spatial heterogeneity (Pan et al., 2023). The spatial and chemical diversity of landfill emissions was also highlighted by Liang et al. (2025), who analyzed 777 solid waste samples and 43 groundwater samples from 14 landfill sites across China. BTEX compounds were again dominant, with toluene detected at 147.6 mg/kg, ethylbenzene at 240.0 mg/kg, and m,p-xylene at 179.9 mg/kg in landfill waste layers. SVOCs such as bis(2-ethylhexyl) phthalate (DEHP) and 19 different PAHs were also identified, many of which pose risks due to their high migration potential into groundwater. VOCs were found to be more mobile than SVOCs, with leaching order observed as phenols > anilines > halogenated aromatics > MAHs > PAHs, directly linking landfill composition to surrounding aquifer pollution (Liang et al., 2025). Landfill fires represent a further intensification of emission pathways. During fire events, VOC and SVOC emissions spike due to the combustion of mixed municipal solid waste. Kannankai and Devipriya (2024), investigating three major landfill fire events at the Brahmapuram MSW Treatment Plant in Kochi, India, quantified the total emissions as 2665.1 metric tons of VOCs, alongside PM2.5, CO, CH_4, and CO_2. These emissions were found to be severely underreported in satellite-based methods. The authors used both ex-situ (remote sensing and FRP estimates) and in-situ methods (direct sampling and modeling) to conclude that waste fires emitted VOCs equivalent to those produced during 159 days of passive waste storage, and the global warming potential of fire-induced GHGs was estimated at 147.9 Gg CO_2-eq (Kannankai & Devipriya, 2024). The health risks associated with landfill emissions are well documented. At the closed Kuchino landfill near Moscow, VOCs were measured before and after flaring systems were installed. Risk assessments indicated high carcinogenic (1.7×10^{-1}) and non-carcinogenic (1.1×10^{3}) risk levels for landfill workers before flaring. While post-flaring emissions decreased substantially, carcinogenic risks for nearby residents still exceeded the USEPA acceptable threshold (1.13×10^{-4}). Chloroform and xylene were the most toxic contributors to the health risk burden (Kurbatova et al., 2024). These findings point to the limitations of flaring as a mitigation strategy, especially when it becomes a secondary source of harmful VOCs, including formaldehyde and carbon tetrachloride. Additionally, the migration of VOCs/SVOCs to groundwater has become a major concern. Liang et al. (2025) observed that concentrations were highest in the mid-layer of landfills, a zone characterized by chemical stability and moisture retention, which facilitates the slow leaching of pollutants. In this context, landfill design, local hydrogeology, and rainfall patterns play key roles in determining the extent of environmental damage.

To better contextualize the complexity of landfill-related VOC and SVOC emissions, Figure 1 presents a comparative overview of the primary emission pathways routine landfill emissions, landfill fires, and groundwater contamination. Landfill VOC and SVOC emissions arise through multiple physical, biological, and chemical processes and manifest as a diverse mixture of hydrocarbons, halogenated solvents, plasticizers, and combustion by-products. These compounds not only pollute ambient air and groundwater but also pose significant carcinogenic and non-carcinogenic risks. Effective control strategies must include: waste segregation, landfill gas recovery, controlled flaring with advanced scrubbing systems, and comprehensive health-based risk assessments that integrate real-time monitoring data across multiple environmental media

Characteristic	Landfill Emissions	Landfill Fires	Groundwater
Source	Biodegradation, volatilization	Combustion of waste materials	Leaching from landfill waste
Composition	VOCs, SVOCs (BTEX, PAHs)	High VOC emissions	VOCs, SVOCs
Health Risks	Carcinogenic, non-carcinogenic risks	Exacerbated exposure risks	Contamination poses health threats
Mitigation	Waste segregation, gas recovery	Controlled flaring, monitoring	Landfill design, hydrogeology control

Figure 1: Comparative Overview of VOC and SVOC Pathways and Health Risks from Landfill-Related Sources

3.1.4 Household Products

Household products are a major and often underappreciated source of volatile organic compounds (VOCs) and semi-volatile organic compounds (SVOCs) in indoor environments. Unlike outdoor sources such as vehicles and industry, indoor emissions stem from everyday items—ranging from cleaning agents and furnishings to electronics and cosmetics—resulting in prolonged exposure in enclosed spaces. The sources and health implications of VOCs and SVOCs from household products have been extensively characterized in recent literature.

As reported by Sonne et al. (2022), VOCs in indoor air arise from a broad array of sources, including paints, adhesives, cosmetics, disinfectants, wall coatings, photocopiers, printers, furniture, and flooring. Formaldehyde and benzene are two particularly toxic VOCs that are emitted in significant quantities from artificial boards (e.g., medium-density fiberboard, plywood) commonly used in furniture construction. These materials are typically bonded with urea- or phenol-formaldehyde adhesives, which volatilize over time and continuously release formaldehyde into the indoor air, sometimes for over a decade after installation (Sonne et al., 2022). SVOCs, on the other hand, include compounds

such as phthalates (from vinyl flooring and personal care products), flame retardants (used in electronics, upholstery, and textiles), polybrominated diphenyl ethers (PBDEs), perfluoroalkyl substances (PFASs), and pesticides. These substances, owing to their lower vapor pressure, partition between the gas phase and indoor dust or surfaces, persisting in the environment for long durations and re-emitting slowly over time. Studies have shown that brominated flame retardants and PCBs can accumulate in household dust and be ingested or inhaled, especially by children, leading to chronic exposure (Sonne et al., 2022; Lucattini et al., 2018). Real-time monitoring further reveals the dynamics of these emissions. According to a study by Kim et al. (2024), even in industrial settings, human presence and usage of cleaning agents or heating devices significantly contribute to elevated indoor VOC levels. Similarly, Wang et al. (2023) reported that office environments equipped with HVAC systems showed VOC concentrations that fluctuated with occupancy, with peaks correlating with cleaning activities and periods of high human activity. Terpenes and alcohols such as isopropanol and ethanol were frequently detected in elevated concentrations, originating from air fresheners and disinfectants. An important distinction of household VOC/SVOC emissions is their cumulative and chronic nature. Indoor VOC concentrations are often significantly higher than those measured outdoors—up to 20 times greater in some buildings—particularly in settings with poor ventilation (Sonne et al., 2022). This disparity was also noted in the review by Liang et al. (2025), who emphasized that indoor emissions, particularly from synthetic materials and electronics, contribute to long-term health risks, including asthma, cognitive impairments, and various cancers. Health risk assessments consistently identify formaldehyde, benzene, and phthalates as among the most hazardous indoor contaminants. Benzene has been linked to hematopoietic cancers, while formaldehyde exposure causes respiratory irritation, allergic reactions, and is classified as a human carcinogen (IARC Group 1). SVOCs such as DEHP (di-2-ethylhexyl phthalate) have been associated with endocrine disruption, obesity, and developmental toxicity (Lucattini et al., 2018; Sonne et al., 2022). The health impacts are particularly concerning for vulnerable populations such as children, pregnant women, and the elderly. Mitigation strategies for indoor VOC/SVOC pollution emphasize both source control and active removal technologies. Sonne et al. (2022) advocate for replacing formaldehyde-based adhesives with bio-based alternatives (e.g., lignin, tannin, soy protein) and improving building ventilation systems. Advanced removal technologies such as metal-organic frameworks (MOFs), photocatalytic oxidation, and phytoremediation have also shown promise. However, these interventions remain underutilized due to cost and limited public awareness.

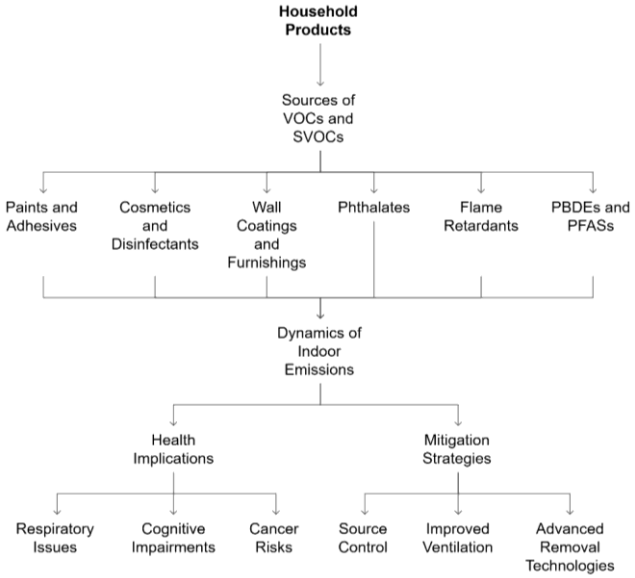

Figure 2 : Household Emission Sources and Their Role in Indoor VOC/SVOC Pollution

Figure 2 illustrates the multifaceted contribution of household products to indoor VOC and SVOC pollution, highlighting key emission sources, chemical components, and associated health and mitigation pathways. As shown, household products are a pervasive source of VOC and SVOC emissions, contributing significantly to indoor air pollution and long-term health risks. Formaldehyde, BTEX compounds, flame retardants, and phthalates are among the most critical pollutants, often emitted continuously from building materials, furnishings, electronics, and personal care items. Addressing indoor air quality requires comprehensive strategies encompassing material regulation, improved ventilation, public education, and adoption of low-emission alternatives.

3.1.5. Natural Sources of VOCs

Natural sources contribute the majority of global volatile organic compound (VOC) emissions, accounting for approximately 70–90% of total non-methane VOC outputs. These emissions stem from a range of biogenic and geogenic processes, including vegetative metabolism, microbial activity in soils, marine-atmosphere interactions, wildfires, and volcanic activity. Although historically considered less harmful than anthropogenic emissions, natural VOCs play a critical role in atmospheric chemistry, particularly in the formation of tropospheric ozone and secondary organic aerosols (SOAs), thereby impacting climate and human health.

Vegetation is the most significant natural source of VOCs. Through metabolic pathways such as the methylerythritol phosphate (MEP) and mevalonate (MVA) cycles, plants

release hydrocarbons including isoprene, monoterpenes, and sesquiterpenes. Isoprene alone constitutes over 50% of all biogenic VOCs (BVOCs), predominantly emitted by broadleaf species like oaks, poplars, and eucalyptus. Emissions are strongly influenced by temperature and solar radiation, typically peaking during warm, sunny conditions. Monoterpenes (e.g., α-pinene, limonene) are mainly emitted by conifers and citrus trees, while sesquiterpenes like β-caryophyllene, although less abundant, exhibit higher atmospheric reactivity and contribute substantially to SOA formation. These emissions are most concentrated in tropical rainforests, such as those in the Amazon Basin, Central Africa, and Southeast Asia (Duan et al., 2023). Wildfires (Figure 3) and biomass burning release large pulses of VOCs, including both BVOCs and combustion-related species like benzene, formaldehyde, and acrolein. The frequency and intensity of wildfires are increasing due to climate change, especially in boreal and Mediterranean regions. These events overwhelm atmospheric oxidative capacity and lead to elevated ground-level ozone and particulate matter. Unlike the continuous emissions from vegetation, wildfire VOCs are episodic but chemically complex and capable of long-range atmospheric transport (Duan et al., 2023). Soil microbial activity is another contributor to natural VOC emissions. Microorganisms emit compounds such as methanol, ethanol, acetone, and sulfur-containing gases during organic matter decomposition and nitrogen cycling. These emissions intensify after precipitation events and vary by soil type, moisture, and organic content. Though often excluded from emission inventories, microbial VOCs can meaningfully influence regional air chemistry in forested and agricultural areas. Marine ecosystems also emit VOCs through phytoplankton activity and sea-air gas exchange. Key compounds include isoprene, dimethyl sulfide (DMS), and halogenated organics like methyl iodide and bromoform. While marine VOC fluxes are generally lower than terrestrial sources, they play essential roles in cloud condensation processes and coastal atmospheric chemistry. Volcanic activity and geothermal vents are localized but potent sources of VOCs. Volcanic gases may contain hydrogen sulfide (H_2S), sulfur dioxide (SO_2), and organic species released during eruptions or passive degassing. Although spatially limited to tectonic zones, these emissions significantly contribute to local air pollution and acid deposition.

Global VOC emission estimates from natural sources range from 424 to 591 teragrams of carbon per year (TgC/year), far exceeding the ~160 TgC/year from anthropogenic sources (Duan et al., 2023). The spatial distribution of these emissions correlates with vegetation density, land-use patterns, solar radiation, and climatic factors. Tropical and subtropical forests show the highest emission densities due to abundant biomass and favorable environmental conditions. Climate change is expected to amplify natural VOC emissions via two key mechanisms: (1) rising temperatures, which enhance enzymatic VOC production in plants, and (2) expansion of vegetative biomass in certain regions. However, elevated CO_2 may suppress isoprene synthesis, and drought conditions could shift emission profiles by reducing isoprene but maintaining monoterpene outputs. This dynamic interplay among plant physiology, environmental stressors, and atmospheric processes underscores the need for continued research into VOC–climate feedbacks.

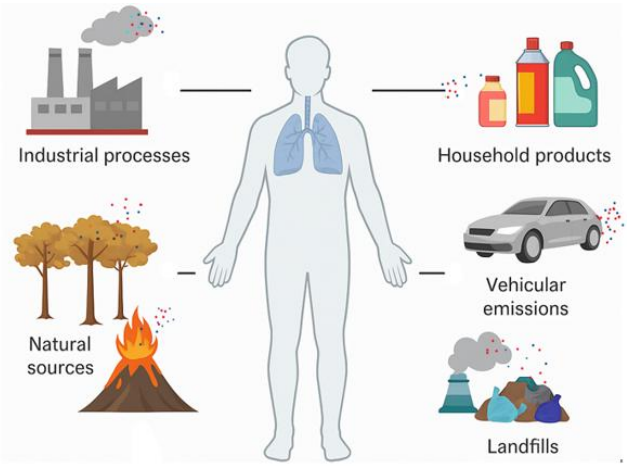

Figure 3 : Sources of VOCs exposure to humans

3.2. Global Distribution

Concentrations vary by setting and region:

3.2.1. Urban Areas

Urban environments typically exhibit high VOC and SVOC concentrations due to traffic congestion, residential fuel use, solvent-containing products, and commercial activities. In northern Chinese cities such as Beijing and Tianjin, daily mean concentrations of total VOCs often exceeded 60 ppbv, with significant contributions from BTEX compounds—benzene, toluene, ethylbenzene, and xylenes—particularly in winter months when atmospheric dispersion is limited (Wu et al., 2020; Sui et al., 2025). The study by Siu et al. (2025) in a northern provincial capital city highlighted that traffic-influenced sites and central business districts exhibited consistently higher concentrations compared to suburban or rural edges. Notably, the COVID-19 lockdown led to a temporary reduction in vehicle-related VOCs, although aldehydes and oxygenated VOCs (OVOCs) remained prominent due to indoor and residual emissions (Siu et al., 2025).

3.2.2. Industrial Zones

Industrial zones are major point sources of both VOCs

and SVOCs, with significant variability based on sector and emission control practices. A multi-sectoral study in China reported that petrochemical, pharmaceutical, and plastic manufacturing facilities emitted compounds such as ethyl acetate, butyl acetate, isopropanol, and methyl ethyl ketone at stack concentrations often exceeding 1000 μg/m³ (Wang et al., 2023). Oxygenated VOCs, which are especially potent ozone precursors, were found in higher proportions in pharmaceutical and painting industries. Wang et al. (2023) also noted that VOC speciation in these zones affects ozone formation potential (OFP), with some industrial facilities contributing OFP values up to 3000 μg/m³. Facilities with advanced control systems, such as catalytic oxidizers or flaring units, exhibited significantly lower fugitive emissions compared to those with limited abatement infrastructure.

3.2.3. Landfills

Landfills are significant and heterogeneous sources of volatile and semi-volatile organic compounds (VOCs and SVOCs), with emission concentrations largely influenced by operational practices, waste composition, and climatic conditions. Active landfills, especially those without advanced gas recovery systems, exhibit elevated surface-level concentrations of aromatic hydrocarbons due to ongoing microbial degradation and volatilization from leachate. A dispersion modeling study from a large municipal landfill in China quantified benzene, toluene, and xylene concentrations near working surfaces at 7.39 μg/m³, 21.34 μg/m³, and 18.85 μg/m³, respectively—exceeding several health-based exposure thresholds, particularly within a 200-meter radius (Li et al., 2023). Similarly, episodic open burning at the Brahmapuram landfill in Kochi, India, led to ambient benzene and toluene concentrations spiking above 300 μg/m³, significantly increasing acute exposure risks for nearby populations (Kannankai et al., 2024). A global synthesis of landfill gas emissions further confirmed the presence of trace aromatic and halogenated VOCs—such as benzene, chlorobenzene, and trichloroethylene, concentration depending on waste age and composition (Duan et al., 2022). Despite technological interventions, legacy emissions can persist for decades, underscoring the necessity for long-term surveillance and site-specific risk assessments.

3.2.4 Regional Variations

VOC and SVOC concentrations vary significantly across geographic regions due to differences in land use, regulatory frameworks, meteorological conditions, and vegetation types. In China, southern provinces such as Yunnan and Hainan exhibit higher BVOC emissions due to dense vegetation and higher temperatures, with isoprene and monoterpenes contributing a large fraction to total VOC loads (Wu et al., 2020). In contrast, northern industrial provinces showed elevated anthropogenic VOCs, primarily from combustion and manufacturing. Duan et al. (2023) reported that tropical regions such as the Amazon, Southeast Asia, and Central Africa are major hotspots for natural VOC emissions, while also facing growing anthropogenic sources from expanding urbanization. In Europe, stricter emission regulations have led to lower urban VOC concentrations (generally <20 ppbv), though episodic spikes still occur in high-traffic or industrial zones (Duan et al., 2023). This contrast underscores the importance of localized emission inventories and regulatory action.

3.3. Environmental Fate of VOCs and SVOCs

The environmental fate of volatile organic compounds (VOCs) and semi-volatile organic compounds (SVOCs) is governed by their physicochemical properties, environmental conditions, and degradation mechanisms. After being emitted into the environment through various anthropogenic and natural sources such as industrial emissions, vehicle exhaust, household products, landfills, and vegetation, they undergo complex transport, transformation, and partitioning processes in air, soil, and water systems. Volatile organic compounds (VOCs) and semi-volatile organic compounds (SVOCs) undergo various transport, transformation, and degradation processes in the environment that determine their persistence and impact. In the atmosphere, many VOCs react rapidly with hydroxyl radicals (OH), ozone (O_3), or nitrate radicals (NO_3), resulting in the formation of secondary pollutants such as ozone and secondary organic aerosols (SOAs) (Atkinson et al., 2003, Hallquist et al., 2009, Guo et al., 2017; Kumari et al., 2023). Compounds like isoprene and monoterpenes have short atmospheric lifetimes (ranging from minutes to a few hours) due to their high reactivity, while other compounds like benzene and chlorinated aromatics are more stable and capable of long-range transport (Guenther et al., (2006; WHO. (2010)). In terrestrial environments, the fate of VOCs and SVOCs is influenced by their physicochemical properties (e.g., volatility, water solubility, partition coefficients) and soil characteristics such as organic carbon content and moisture. Some compounds, particularly chlorinated VOCs such as trichloroethylene and benzene, can leach into soil and groundwater due to their high mobility and moderate hydrophobicity, leading to contamination of subsurface aquifers. Conversely, soil systems can act as both sources and sinks: while microbial processes and desorption from waste can release VOCs, soil microbial uptake and sorption can mitigate VOC persistence in certain ecosystems (Rinnan et al., 2020, Queensland Government, 2023). In aquatic environments, VOCs and SVOCs may dissolve, volatilize, or adsorb to suspended particles. Compounds such as benzene, toluene, and xylene (BTX) exhibit significant

solubility and can be toxic to aquatic biota. Their environmental persistence is typically lower in water due to volatilization and photodegradation. However, SVOCs such as polycyclic aromatic hydrocarbons (PAHs) and phthalates are more persistent and tend to bind to sediments, posing long-term ecological risks and bioaccumulation in aquatic organisms (Pozzer et al., 2022). The overall source of VOCs and VOCs and their environmental behavior are summarized in Table 1. Collectively, the environmental fate of VOCs and SVOCs reflects a dynamic interplay of emission sources, environmental media, and degradation processes. Their persistence and transformation products necessitate long-term monitoring, especially near emission hotspots such as landfills and industrial zones. These processes are further modulated by seasonal changes, meteorological conditions, and the presence of co-contaminants, all of which influence exposure risk and regulatory approaches.

Table 1: Summary Table of Major VOCs and SVOCs and Their Environmental Behavior

Compound	Type	Primary Source	Typical Concentration	Environmental Fate	Reference
Toluene	VOC	Industrial processes, vehicular emissions, landfills	Up to 5934 mg/day (industrial), 21.34 µg/m³ (landfill)	Moderate volatility, photochemical reactivity, can leach into groundwater, contributes to ozone and SOA formation	Kim et al., 2024; Kannankai et al., 2024; Liang et al., 2025
Benzene	VOC	Vehicular emissions, landfills, wildfires	Up to 7.4 mg/km (vehicles), 7.39 µg/m³ (landfill)	High mobility, carcinogenic, long-range transport, leaches into groundwater	Wang et al., 2022; Kannankai et al., 2024; Liang et al., 2025
Formaldehyde	VOC	Household products, wildfires	Elevated indoor levels from MDF and adhesives	Reacts with OH, toxic, indoor air pollutant	Sonne et al., 2022; Duan et al., 2023
Isoprene	VOC (biogenic)	Vegetation	Over 50% of BVOC emissions globally	Short atmospheric lifetime, contributes to ozone and SOA formation	Duan et al., 2023; Wu et al., 2020
Ethyl acetate	VOC	Industrial processes (printing, painting)	>1000 µg/m³ (stack emissions)	Volatile, contributes to ozone formation	Kim et al., 2024; Wang et al., 2023
DEHP (Di(2-ethylhexyl) phthalate)	SVOC	Household products, landfills	Detected in landfill layers	Persistent, binds to dust/sediments, endocrine disruptor	Lucattini et al., 2018; Liang et al., 2025
1,3-Butadiene	VOC	Petrochemical industry, vehicles	Significant in community zones near industrial complexes	Carcinogenic, reacts with atmospheric radicals	Pinthong et al., 2022
Xylene	VOC	Industrial processes, landfills	179.9 mg/kg (landfill waste), vehicular emissions	Photochemical reactivity, possible groundwater contamination	Kim et al., 2024; Liang et al., 2025
Trichloro-ethylene	VOC	Metal plating, landfills	High in metal treatment facilities	Persistent, leaches into soil and water, carcinogenic	Kim et al., 2024; Pan et al., 2023
α-Pinene	VOC (biogenic)	Coniferous vegetation	Key monoterpene in natural emissions	Highly reactive, forms SOAs	Duan et al., 2023

Table 2: Comparative Summary of Study-Based Health Impacts and Protective Measures for VOC-Related Exposure

Authors	Health Risks Identified	Affected Populations	Avoidance Strategies
Yang et al. (2019)	Cancer risk (1.67×10^{-3}), chronic toxicity (514), olfactory effects from trichloroethylene, benzene	Pesticide plant workers	Enhanced ventilation, emission controls, personal protective equipment
Du et al. (2024)	Cancer risks ($2.27–2.93 \times 10^{-4}$) from formaldehyde, benzene, 1,4-dichlorobenzene	Urban working adults	Reduce indoor VOC sources, improve home ventilation, regulate outdoor emissions
Onyebuchi et al. (2025)	Reproductive hormonal disruptions in parents and offspring	General population, offspring	Limit exposure to automobile paint sprays, use safer alternatives
Hester et al.	Neurological effects (synaptic plasticity	General population	Minimize solvent use, enhance

(2011)	gene changes) from toluene		workplace ventilation
Montero-Montoya et al. (2018)	Developmental, respiratory issues from benzene, toluene, ethylbenzene, xylenes	Children in industrial/suburban areas	Environmental monitoring, restrict industrial emissions near schools
Li et al. (2024)	Cancer and chronic toxicity risks from trichloroethylene, toluene	Landfill workers	Use of biofilters, advanced emission controls, worker monitoring
Fini et al. (2025)	Neurological damage, increased toxicity with aging asphalt	General population, children	Use biochar in asphalt, reduce exposure in public spaces
Fan et al. (2012)	Cancer and neurological risks from TEX compounds	Socio-economically disadvantaged communities	Community air monitoring, reduce industrial emissions
Alford & Kumar (2021)	Asthma, wheezing from indoor VOCs	General population, children	Improve indoor ventilation, use low-VOC materials
Kurbatova et al. (2024)	Cancer (1.7×10^{-3}) and non-carcinogenic risks from carbon tetrachloride	Landfill workers, nearby residents	Avoid flaring, implement alternative gas treatment methods

Table 3: Health Impacts of Volatile Organic Compounds (VOCs)

Key Compounds	Primary Source	Exposure Route	Exposure level	Health Impact	Authors
Benzene	Gasoline, tobacco smoke, landfill gas	Inhalation	Chronic	Leukemia, anemia, immune suppression	Wang et al., 2021; Pan et al., 2023
Toluene	Paints, adhesives, landfill gases	Inhalation, Dermal	Acute/Chronic	CNS depression, reproductive toxicity, altered gene expression	Hester et al., 2011; Hemmativaghef, (2020)
Formaldehyde	Building materials, combustion	Inhalation	Chronic	Nasal cancer, asthma, oxidative stress	Alford & Kumar, 2021; Pan et al., 2023
Styrene	Plastics, rubber industries, landfills	Inhalation	Occupational	Hearing loss, neurotoxicity	Fuente et al., 2023
1,3-Butadiene	Vehicle exhaust, landfill emissions	Inhalation	Chronic	Leukemia, cardiovascular inflammation	Wang et al., 2021
Acrolein	Tobacco smoke, incomplete combustion	Inhalation	Acute/Chronic	Cardiovascular toxicity, systemic inflammation	Fu et al., 2024
Phthalates (DEP, DEHP)	Consumer products, indoor dust	Inhalation, Oral	Chronic	Asthma, endocrine disruption	Ataei et al., 2023
Trichloroethylene	Industrial solvent, landfill gas	Inhalation	Chronic	Liver/kidney cancer	Pan et al., 2023; Wang et al., 2021
Propylene oxide	Landfill emissions	Inhalation	Intermittent/Chronic	Sensory irritation, oxidative stress	Wang et al., 2021
Ethyl acetate, Acetone	Organic waste decomposition in landfill	Inhalation	Chronic	Headaches, respiratory irritation	Pan et al., 2023

4. Results and Discussion

4.1. Health Impacts of VOCs and SVOCs

The reviewed studies demonstrate the widespread prevalence of volatile organic compounds (VOCs) and semi-volatile organic compounds (SVOCs) across industrial, urban, rural, and indoor environments, with concentrations varying significantly by source and location, contributing to substantial carcinogenic and non-carcinogenic health risks (Table 2, 3). In a pesticide wastewater storage tank, 21 VOCs were identified, with concentrations ranging from 0.63 to 5023.83 μg/m³, dominated by chlorinated compounds such as trichloroethylene (mean = 2581.29 μg/m³) and dichloromethane (mean = 2309.55 μg/m³), contributing to a cumulative cancer risk of 1.67×10^{-3} (74.91% attributed to trichloroethylene, linked to liver/kidney cancer) and chronic toxicity levels reaching 514, exceeding occupational safety limits by three orders of magnitude (Yang et al., 2019; Pan et al., 2023). Benzene, primarily from gasoline and landfill gas, posed a cancer risk of 3.32×10^{-4}, associated with leukemia and immune

suppression, while triethylamine and diethylamine drove olfactory effects (39.93% and 34.26% relative perception importance, respectively) (Yang et al., 2019; Wang et al., 2021).

Landfill sites exhibited high VOC emissions (18.1–806.3 mg/m³), with oxygenated compounds (e.g., acetophenone, propionic acid), chlorinated compounds (e.g., 1-chlorobutane, trichloroethylene), and aromatics (e.g., benzene, m-xylene) predominant, resulting in elevated carcinogenic risks (1.7×10^{-3}) and non-carcinogenic risks (1.1×10^{3}) for landfill workers, primarily due to carbon tetrachloride (73.5% and 61% contributions, respectively) (Wang et al., 2021; Kurbatova et al., 2024; Li et al., 2023). In urban settings, benzene concentrations reached 33 µg/m³ at high-traffic sites in Delhi, with winter peaks due to reduced atmospheric dispersion, contributing to cancer risks of 1×10^{-6} to 3×10^{-6} and ozone formation potential (Kumari et al., 2023). Indoor environments showed elevated VOC levels, with formaldehyde (from building materials, linked to nasal cancer and asthma) and 1,2-dichloropropane contributing 13.169% and 14.779% to total anthropogenic emissions, respectively, and urban formaldehyde emissions 2.55 times higher than rural ones (Fan et al., 2025; Alford & Kumar, 2021). In urban China, average lifetime cancer risks for working adults were 2.27×10^{-4} (females) and 2.93×10^{-4} (males), driven by formaldehyde, 1,4-dichlorobenzene, benzene, and 1,3-butadiene (linked to leukemia and cardiovascular inflammation), with 70% of risk from indoor inhalation exposures (Du et al., 2014; Wang et al., 2021). Industrial activities, such as automobile paint spraying, released toluene (17.35%, linked to CNS depression and reproductive toxicity), xylene (21.98%), ethanol (34.61%), and benzene isomers (26.06%), causing reproductive hormonal disruptions in rats, including decreased progesterone, luteinizing hormone, follicle-stimulating hormone, estrogen, and testosterone levels in parents and offspring, with total VOC concentrations of 686.00–805.66 µg/m³ (Onyebuchi et al., 2025; Hester et al., 2011). Asphalt emissions, evolving from aliphatic to aromatic compounds with aging, increased toxicity and caused neurological damage in Drosophila, particularly in females, with compounds like toluene implicated (Fini et al., 2025; Hemmativaghef, 2020). Indoor VOC exposure was associated with respiratory effects, with a meta-analysis reporting medium-sized effects on asthma (Cohen's d = 0.37) and wheezing (Cohen's d = 0.26), driven by compounds like formaldehyde and phthalates (DEP, DEHP) from consumer products, which also cause endocrine disruption (Alford & Kumar, 2021; Ataei et al., 20222). Acute toluene exposure (1000 ppm for 6 hours) in rats altered synaptic plasticity gene expression, including long-term depression and GABA receptor signaling (Hester et al., 2011). Solid fuel combustion in rural homes yielded high VOC concentrations (median 671.8 ppbv for cooking), with vinyl chloride and 1,4-dioxane triggering immune and oxidative stress responses, correlating with elevated glutathione peroxidase and Clara cell secretory protein levels (Feng et al., 2025). Socio-economically disadvantaged communities in Camden, New Jersey, faced elevated TEX exposure (toluene, ethylbenzene, xylenes), with higher personal and ambient concentrations in industrial "hot spots," increasing cancer and neurological risks (Fan et al., 2025). At the Daegu dyeing industrial complex, VOCs like toluene, DMF, and chloroform resulted in hazard quotients exceeding 1 and cancer risks above 10^{-4}, with increased incidence of respiratory, immune, and allergic diseases (Shuai et al., 2018). Additional compounds, such as styrene (from plastics and landfills, linked to cancer risks and neurotoxicity), acrolein (from tobacco smoke, linked to cardiovascular toxicity), and propylene (from polypropylene, linked to cancer risk and personal exposure), further underscore the diverse health impacts of VOC exposure (See Table 1) These findings highlight the urgent need for targeted mitigation strategies to address the severe health implications of VOC and SVOC exposure across diverse settings.

4.2. Discussion

The pervasive global burden of volatile organic compounds (VOCs) and semi-volatile organic compounds (SVOCs) across urban, industrial, landfill, and indoor environments significantly contributes to air pollution and poses substantial public health risks (Duan et al., 2023; Wu et al., 2020). Emitted from diverse sources—including industrial processes, vehicular exhaust, household products, landfills, and natural sources, which dominate the global VOC budget—these compounds, such as benzene, toluene, formaldehyde, polycyclic aromatic hydrocarbons (PAHs), and phthalates, drive environmental and health challenges (Zhou et al., 2023). Landfill emissions, ranging from 18.1 to 806.3 mg/m³, are particularly concerning, with benzene, trichloroethylene, and toluene as dominant pollutants resulting from microbial decomposition and chemical volatilization (Wang et al., 2021; Li et al., 2023a). These compounds contribute significantly to ozone formation and secondary organic aerosol (SOA) production, exacerbating air quality deterioration in urban and industrial settings (Zhou et al., 2023).

Health impacts from VOC and SVOC exposure are a central concern, with inhalation as the primary exposure pathway leading to a spectrum of adverse effects (See Table 3). Benzene, a Group 1 carcinogen, is consistently linked to leukemia, with cancer risks ranging from 1×10^{-6} to 3×10^{-6} in urban areas like Delhi and up to 1.67×10^{-3} in industrial settings, such as pesticide wastewater storage tanks (Kumari

et al., 2023; Yang et al., 2019). Formaldehyde and 1,3-butadiene, prevalent in indoor and industrial environments, are associated with nasal cancer and cardiovascular inflammation, respectively, while toluene induces neurological impairments (e.g., synaptic plasticity alterations) (Alford & Kumar, 2021; Feng et al., 2024; Hester et al., 2011). Indoor SVOCs, such as phthalates and PAHs, present chronic risks, including asthma, endocrine disruption, and lung cancer, with concentrations 2–5 times higher indoors than outdoors, particularly affecting children due to hand-to-mouth behaviors (Ataei et al., 2022). Synergistic effects in mixed exposures, such as benzene and ethylbenzene, amplify health risks by 185%–284% compared to single exposures, underscoring the need for comprehensive risk assessments that account for compound interactions (Ma et al., 2025).

Vulnerable populations, including children, landfill workers, and socio-economically disadvantaged communities, face disproportionate exposure risks (See Table 2). Children in industrial and suburban areas are susceptible to developmental and respiratory issues from benzene, toluene, ethylbenzene, and xylenes (TEX), while socio-economically disadvantaged communities, such as those in Camden, New Jersey, experience elevated cancer and neurological risks from TEX exposure (Montero-Montoya et al., 2018). Landfill workers and residents within 1,000–3,000 meters of sites, such as the Kuchino landfill, face carcinogenic risks exceeding 1×10^{-4} due to carbon tetrachloride and trichloroethylene, with additional reproductive hormonal disruptions reported in exposed populations (Kurbatova et al., 2024; Li et al., 2024; Onyebuchi et al., 2025). In developing regions like Sub-Saharan Africa, inadequate waste management amplifies these risks, posing significant environmental justice concerns (Zahra et al., 2025).

Mitigation strategies are essential to reduce VOC and SVOC-related health risks (Table 2). Biochar integration in asphalt has demonstrated up to 76% reduction in VOC emissions, offering a sustainable source control method, while biofilters and advanced emission controls are effective for landfill management (Fini et al., 2025; Li et al., 2024). Indoor environments benefit from enhanced ventilation and low-VOC/SVOC materials, which are critical for protecting vulnerable populations like children (Alford & Kumar, 2021). However, ineffective practices, such as flaring in landfill gas management, generate harmful VOCs like chloroform and xylene, necessitating advanced filtration systems (Kurbatova et al., 2024). Community air monitoring and stricter emission regulations are vital, particularly in high-risk areas, to safeguard disadvantaged communities (Fan et al., 2012; Montero-Montoya et al., 2018). AI-based modeling and real-time monitoring, as proposed by Zahra et al. (2025), could enhance emission prediction and risk management, but regulatory gaps for ototoxic compounds like toluene and styrene hinder progress (Hemmativaghef, 2020). These findings highlight the need for integrated approaches combining source control, public education, and regulatory reform to address the global challenge of VOC and SVOC pollution.

5. Conclusions

This review establishes VOCs and SVOCs as critical global pollutants, with emissions from landfills, industry, vehicles, household products, and natural sources driving significant health risks, including cancer, respiratory, neurological, and reproductive effects. Benzene, trichloroethylene, and PAHs are priority compounds due to their toxicity and prevalence, with landfills and indoor environments as key exposure hotspots (Wang et al., 2021). Children, landfill workers, and residents in developing regions face disproportionate risks, necessitating urgent action (Zhou et al., 2023). Sustainable mitigation strategies, such as biochar and enhanced ventilation, offer solutions, but regulatory gaps must be addressed to ensure effective control (Fini et al., 2025; Kurbatova et al., 2024). Future efforts should focus on comprehensive exposure assessments and AI-based monitoring to inform robust policies, safeguarding public health worldwide.

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