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Volatile Organic Compound in the Environment: Sources, Exposure and Mitigation

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Abstract

Volatile Organic Compounds (VOCs) constitute a diverse group of carbon-based chemicals that vaporize under normal environmental conditions. Their ubiquitous presence in the environment arises from both natural and anthropogenic sources, including industrial processes, vehicle emissions, and biological activities. This review explores the sources, exposure pathways, and mitigation strategies associated with VOCs in the environment. Anthropogenic activities such as transportation, manufacturing, and solvent use are significant contributors to VOC emissions, leading to concerns about their impact on air quality and human health. Exposure to VOCs occurs through inhalation, ingestion, and dermal contact, with potential health effects ranging from respiratory irritation to long-term risks such as cancer and neurological disorders. The application of nanomaterials in VOC reduction has encouraging opportunities to improve the effectiveness of environmental pollutant removal. Future research directions should focus on advancing monitoring technologies, assessing the efficacy of mitigation strategies, and understanding the complex interactions between VOCs and environmental factors.

Keywords: Volatile Organic Compounds, Environment, Sources, Exposure and Mitigation

Introduction

A significant amount of the pollutants found in a variety of items are volatile organic compounds (VOCs), which are organic molecules that evaporate quickly at ambient temperature. Their easy vaporization allows them to enter the environment under normal conditions, making them significant contributors to ground-level ozone formation. VOCs react with nitrogen oxides (NOx) in the atmosphere to produce ozone molecules. Once emitted, volatile organic compounds (VOCs) can travel great distances because of their high volatility, mobility, and resistance to degradation (Pandey and Yadav, 2018).

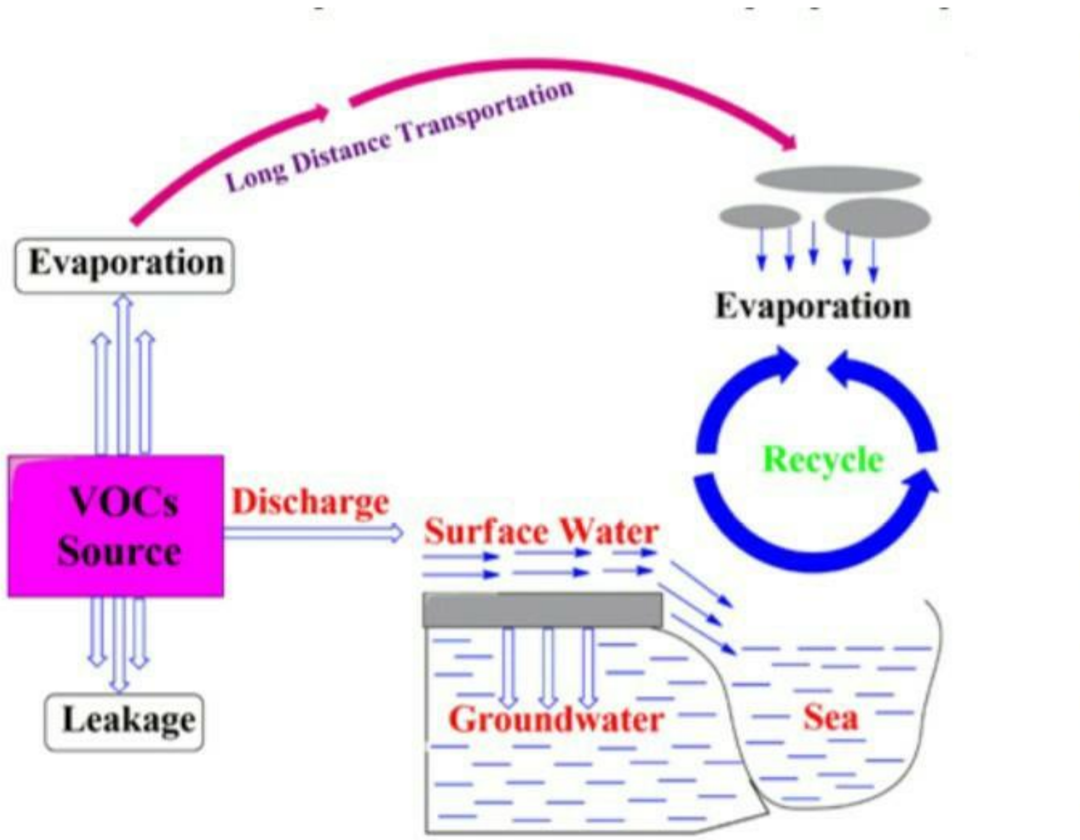
In addition to aromatic hydrocarbons like benzene, toluene, ethyl benzene, and xylene, halogenated hydrocarbons like trichloroethylene and chloroethylene are the most often seen volatile organic compounds (VOCs) (David and Niculescu, 2021). Being able to cause cancer in humans makes cancerous volatile organic compounds (cVOCs) unique among other volatile organic compounds (VOCs). People are most exposed to VOC-contaminated water by drinking, swimming, bathing, eating, taking showers, and doing laundry. Both cancer and non-cancer outcomes are risks associated with these practices. There might be hundreds of times more cancer risks associated with VOC-contaminated groundwater than are recommended by normal risk advice (Pandey and Yadav, 2018).

Airborne VOC exposure is almost inevitable due to the widespread use of VOCs in both home and occupational contexts. In addition, industrial discharge and disinfection procedures frequently expose people to drinking water (Khan et al., 2021). All living things are composed of organic substances, which are carbon-based and may release elements like oxygen, nitrogen, sulfur, fluorine, chlorine, bromine, and hydrogen. Some of the causes of VOC emissions include burning fuel (such as coal, oil, or gas), oil and gas fields, truck exhaust, paints, glues, and other products used in the house or workplace. VOCs represent a significant environmental concern due to their widespread presence and potential health impacts. Efforts to mitigate VOC emissions and minimize exposure are crucial for safeguarding human health and their environment.

Smog (ground-level ozone) is created when nitrogen oxides and volatile organic compounds (VOCs) react. One major factor contributing to climate change is this haze. Common sources of volatile organic compounds (VOCs) include benzene, formaldehyde, toluene, xylene, styrene, and perchloroethylene (or tetrachloroethylene used in dry cleaning) (Bari and Kindzierski, 2018). Exposure to volatile organic compounds (VOCs) has been associated with a number of health impacts, including as skin and eye irritation, sensitization, effects on the central nervous system, carcinogenicity, and effects on the liver and kidneys. Regulatory agencies use the findings of these health impact studies to establish safe exposure limits for each volatile organic compound (VOC) that is considered safe for human exposure.

Both indoor and outdoor environments are affected by VOCs. Outdoors, VOCs are primarily released during the manufacture or use of everyday products and materials. The usage of items and materials containing VOCs is the main source of indoor VOC emissions (Gallon et al., 2020). Indoor and outdoor settings raise different concerns about VOCs. The main worry when it comes to VOCs inside is their potential to be harmful to human health. On the other hand, outside, VOCs lead to the creation of ground-level ozone, which can cause a number of health issues, such as congestion, bronchitis, asthma, emphysema, and coughing (Ćurić et al., 2022). In addition to impairing lung function, ozone exposure can inflame the lining of the lungs, which may result in irreversible lung tissue damage. Because VOCs can contribute to photochemical smog when specific circumstances are met, the Environmental Protection Agency (EPA) primarily controls VOCs outside.

The colourless, extremely unpleasant gas known as ground-level ozone forms just above the surface of the Earth (Yang, 2020). It is categorized as a "secondary" pollutant because it arises from the interaction of two principal pollutants, namely volatile organic compounds (VOCs) and nitrogen oxides (NOx), in the presence of stagnant air and sunshine. Ground-level ozone is produced in the atmosphere by photochemical interactions between NOx and VOCs. This process commonly occurs in urban and industrial areas where emissions of NOx and VOCs are high. The resulting ozone pollution poses significant health risks, particularly to respiratory health, and contributes to environmental issues such as smog formation and climate change (Manisalidis et al., 2020). Therefore, reducing emissions of NOx and VOCs is crucial in mitigating ground-level ozone pollution and its associated impacts.



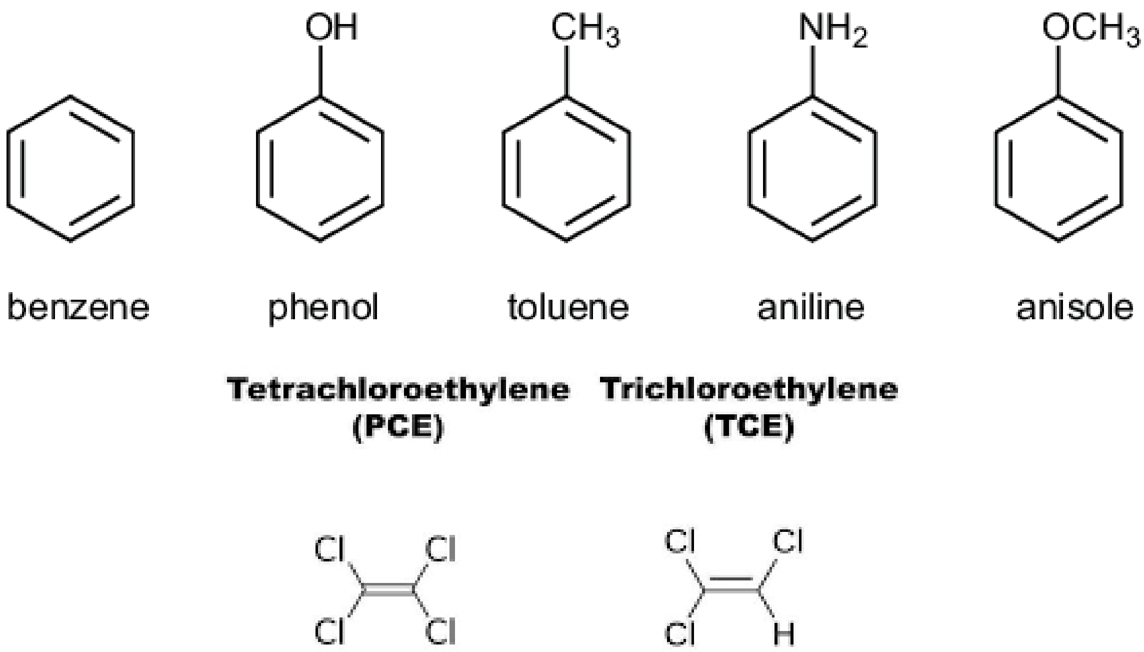
Process of VOCs transportation (Huang *et al.*, 2014).

Volatile Organic Compounds

Organic chemical substances found in a variety of goods that easily evaporate and spread into the environment under typical circumstances are known as volatile organic compounds, or VOCs. VOCs have increased volatility, mobility, and resistance to degradation, which allow them to travel long distances in the environment after discharge (Faroon et al., 2005). The most prevalent volatile organic compounds (VOCs) include aromatic hydrocarbons such as xylene, toluene, ethyl benzene, and halogenated hydrocarbons such as trichloroethylene and chloroethylene. VOCs that have the potential to cause cancer in humans are categorized as cancerous volatile organic compounds (cVOCs).

According to Bulatović et al. (2022), drinking, bathing, eating, swimming, and laundry are the main ways that people are exposed to volatile organic compounds (VOCs) from polluted water. Both natural and artificial processes can create volatile organic compounds

(VOCs). Natural sources comprise of plant emissions, anaerobic processes in wetlands, and naturally occurring forest fires. Anthropogenic sources of volatile organic compounds (VOCs) include domestic and industrial processes like food processing, spraying and fertilizing, running septic tanks, burning hydrocarbon fuels, distributing and storing petroleum, printing, and making pharmaceuticals (Pandey et al., 2018). A few instances of VOC chemical structures are shown below.



Sources of Volatile Organic Compounds

The following are thought to be the primary sources of VOCs (Ahmed *et al.,* 2017, Wang *et al.*, 2017):

i. The use and exploitation of fossil fuels, including partial combustion and evaporation, result in the release of VOCs. This includes processes like vehicle exhaust emissions, industrial combustion, and fugitive emissions from fuel storage and handling.

ii. Solvents commonly used in paints and inks also contribute significantly to VOC emissions. Paint production, which amounts to approximately 12 billion liters annually, typically involves the use of solvents such as aliphatic hydrocarbons, ethyl acetate, glycol ethers, and acetone. These solvents evaporate during painting and drying processes, releasing VOCs into the atmosphere.

iii. Additionally, compressed aerosol products, primarily containing butane and propane, contribute significantly to global VOC emissions. These aerosols are used in various applications such as aerosol sprays, air fresheners, and deodorants.

iv. The use of biofuels, including cooking oils, bioethanol, and other biofuels, also contributes to VOC emissions, particularly during combustion processes.

v. Burning biomass, particularly that from farms and forests, is another important way that greenhouse gas emissions are produced. Although partial combustion of biomass can produce a variety of volatile organic compounds (VOCs), full combustion of biomass should produce carbon dioxide and water.

vi. Metalworking fluids (MWFs), which are utilized in machining and metalworking operations, produce toxic volatile organic compounds, which contribute to VOC emissions.

vii. Furthermore, the incineration of household waste and other sources, such as industrial waste, contributes to VOC emissions, particularly when incomplete combustion occurs.

There are two types of sources for volatile organic compounds (VOCs): anthropogenic and natural. Anaerobic processes in marshy bogs, emissions from trees and other flora, and forest fires brought on by natural occurrences are examples of natural sources. Anthropogenic sources, originating from both domestic and industrial activities, encompass a wide range of processes. Fertilizer and pesticide usage, food extraction, textile washing, and metal surface degreasing are some of the household tasks that cause VOC emissions. Additionally, industrial processes such as fumigation, printing, building materials, hydrocarbon fuel evaporation, landfill operations, printing, and pharmaceutical manufacturing release significant amounts of volatile organic compounds (VOCs) into the environment (USEPA, 1994; Liu et al., 2013; Abdullahi et al., 2014).

Indoor sources of VOCs pose additional concerns, with various products and materials emitting these compounds indoors. A few examples include paint removers, kerosene heaters, adhesives, carpets, insulating foam, fragrances, tobacco smoke, and chlorinated water (Spengler and Chen, 2000). Composting, particularly during the aerobic decomposition process, is another significant source of VOC emissions (Komilis et al., 2004). Furthermore, it has been determined that using ionic liquids as solvents is a source of VOCs (Santa et al., 2000; Escudero et al., 2013).

Human activities such as dry cleaning can also contribute to VOC exposure, as evidenced by the detection of VOCs in human milk (LaKind et al., 2004). Even bottled water has been reported to contain VOCs (Diduch et al., 2011). The U.S. Environmental Protection Agency (USEPA) has identified around 189 air pollutants, 97 of which fall under the category of volatile organic compounds (VOCs). Fruits, flowers, leaves, stems, and roots are just a few of the organs from which plants can emit volatile organic compounds (VOCs). The production of microbial volatile organic compounds (mVOCs) from airborne microbial metabolites or fungal spores increases VOC emissions further (Fischer and Dott, 2003).

VOC emissions have adverse effect on both the environment and human health, and they provide serious epidemiological and environmental issues. Renal, hematological, neurological, hepatic, and mucosal irritation are among the health effects of VOCs exposure (Domingo and Nadal, 2009). Furthermore, VOCs have a role in both the photochemical creation of ozone on Earth and the decrease of stratospheric ozone. Furthermore, by effectively absorbing infrared radiation released by the Earth's surface, these compounds exacerbate global warming by increasing the concentration of these substances in the atmosphere (Hester et al., 1995; Change, 2006; Murrells and Derwent, 2007).

VOCs are released by plants in response to changes in light, temperature, floods, and drought. Furthermore, VOCs are necessary for many physiological and ecological functions of plants, including interactions with plant diseases, pollinator attraction, defensive mechanisms against insects, and plant-to-plant communication (Zhu et al., 2013). In terms of health, exposure to volatile organic compounds (VOCs) can result in fatigue and irritation of the throat, nose, and ocular mucous membranes. Even at quantities below the maximum concentration limit (MCL), volatile organic compounds (VOCs) may have detrimental long-term and cumulative effects on human health. For example, exposure to volatile organic compounds has been connected to spontaneous abortion, low birth weight, and birth defects (Squillace et al., 2002; Thiriat et al., 2009; Zeng et al., 2013).

A number of volatile organic compounds (VOCs) are regulated at the federal level; the US Environmental Protection Agency (USEPA, 2002) normally sets maximum contamination levels between 0.002 and 0.005 mg L-1. Carcinogenic volatile organic compounds (VOCs) including trichloroethylene, tetrachloroethylene, and carbon tetrachloride were routinely found in groundwater and drinking water supply wells across the country in a nationwide assessment carried out by the United States Geological assessment (Moran et al., 2006). Exposure to trichloroethylene has been connected to non-Hodgkin's lymphoma, liver cancer, and biliary cancer. Conversely, exposure to tetrachloroethylene has been related to an increased risk of non-Hodgkin's lymphoma, bladder, esophagus, cervical, rectal, and colon cancers. There is evidence that exposure to carbon tetrachloride can cause lymphohematopoietic cancers (Siegel and Jinot, 2011; Malaguarnera et al., 2012). These volatile organic compounds (VOCs) have been classified as priority pollutants by the USEPA and the European Commission (EC) due to their detrimental epidemiological impacts on human health.

Up to 95% of the freshwater accessible on Earth is found in groundwater, which is the primary source of drinking water for the great majority of people on the planet (Abakpa et al., 2023). As the world's biggest user of groundwater, India depends on groundwater sources for about 85% of its drinking water supply and 60% of its agricultural irrigation because it is thought to be safer and purer than surface water because of natural filtration processes that occur throughout the layers of the Earth (Suhag, 2016). However, the contamination of groundwater with VOCs poses significant health risks to human populations dependent on this vital resource, highlighting the importance of stringent regulatory measures and proactive management strategies to safeguard water quality and public health.

In recent years, groundwater has increasingly often included organic pollutants, especially volatile organic compounds (VOCs). Major point sources of volatile organic compounds (VOCs) in groundwater include urban land use patterns, including waste disposal sites, detention basins, leaking USTs, septic tanks, landfills, and above-ground storage tanks (ASTs) (Baehr et al., 1999). Heating oil, gasoline, and diesel fuel are frequently stored in USTs and ASTs for usage in homes and farms. Council (1988) states that leaks from these residential USTs and ASTs are one of the primary reasons for VOC contamination in groundwater. Furthermore, septic tanks carry a significant danger of polluting groundwater if the organic matter in the effluent is not entirely broken down. VOCs have been found in septic tank fluid and groundwater close to these systems, according to many investigations (DeWalle et al., 1985a, 1985b; Viraraghavan and Hashem, 1986).

The first signs of VOC contamination of groundwater worldwide were seen in the mid-1970s, indicating leaks and emissions from improperly disposed of and inadequately treated industrial waste. These risks to human health and the environment are substantial (Guo et al., 2004; Malherbe and Mandin, 2007). VOCs deposited in the atmosphere can find their way into groundwater through processes including recharging, diffusive transport through the unsaturated zone, and precipitation. As a result, the atmosphere may be a non-point source of low-level VOC concentrations in groundwater. VOCs are resistant to degradation and have a modest sorption affinity, which allows them to travel quite far in groundwater (Barbash and Roberts, 1986). Since they are so volatile, VOCs are the most prevalent pollutant in groundwater when compared to surface water. High concentrations of vinyl chloride, trichloroethylene (TCE), tetrachloroethylene (PCE), and dichloroethylene (DCE) have been identified in groundwater aquifers, highlighting the widespread nature of VOC pollution (Chong and Mayer, 2017). This emphasizes how crucial it is to deal with the causes of VOC pollution and put into place efficient management techniques in order to safeguard human health and groundwater quality.

The presence of volatile organic compounds (VOCs) in groundwater has been the subject of several investigations (Squillace et al., 1999, 2002; Moran et al., 2007; Altalyan et al., 2016). Fan et al. (2009) evaluated particular non-cancer and cancer risks at an exposure level of 1 μg L-1 of each volatile organic compound (VOC) in Taiwanese groundwater by utilizing the Multimedia Environmental Pollutant Assessment System (MEPAS) model. This study brought up questions regarding whether the present VOC standards are sufficient to protect public health when groundwater is the main source of drinking water. VOCs are recognized human carcinogens, mutagens, and teratogens, and as such, they pose a serious risk to public health together with their reactive intermediates and breakdown products (Pandey and Yadav, 2018; Sunguti et al., 2021).

The simulation of internal chemical doses linked to various exposure pathways is made possible by physiologically based pharmacokinetic modeling (PBPK) (Krishnan and Carrier, 2008; Valcke and Krishnan, 2014). Although the oral route of exposure is usually the focus of the health risk assessment process for drinking water pollution, new research has indicated that other routes of exposure, such as cutaneous exposure and inhalation, may be equally or more significant in some circumstances. The presence of VOCs in the environment poses significant health risks, and further research and regulatory efforts are needed to mitigate these risks and ensure the safety of drinking water sources (David and Niculescu, 2021).

Volatile Organic Compounds Classification

Volatile organic compounds (VOCs) have a big effect on the environment and people's health. These compounds can be found in a variety of settings, such as confined places and outside air, and they can evaporate easily at room temperature and normal pressure. Whereas indoor VOCs directly harm human health, outdoor VOCs can cause environmental problems and have an indirect impact on human health. Different VOCs have varying levels of volatility, with some evaporating more quickly than others. Those that evaporate rapidly tend to be more hazardous and pose greater risks to both the environment and human health. Organic pollutants are categorized based on their volatility into three groups, as outlined by various studies (Reimann and Lewis, 2007; Williams and Koppmann, 2007; Sindelarova et al., 2014). This classification is particularly relevant in indoor environments and is used as a basis for defining indoor volatile organic compounds (Heeley et al., 2020).

Table 1. Classification of VOCs pollutants

Class	Examples of Compounds)	Boiling Point Range (°C
Very volatile organic compounds (VVOCs)	propane, butane, methyl-chloride	0 to 50–100
Volatile organic compounds (VOCs)	formaldehyde, toluene, acetone, isopropyl alcohol	50–100 to 240–260
Semi volatile organic compounds (SVOCs)	pesticides (chlordane, DDT), plasticizers (phthalates), fire retardants (PCBs, PBB))	240–260 to 380–400

Very Volatile Organic Compounds (VVOCs)

Very Volatile Organic Compounds (VVOCs) comprise a highly hazardous class of pollutants, known to exhibit toxicity even at extremely low concentrations (Williams and Koppmann, 2007; Reimann and Lewis, 2007; Heeley et al., 2020; Wang et al., 2007). This category includes compounds such as propane, butane, and methyl chloride. Propane (C_3H_8) is particularly dangerous, often transported in its liquefied form under vapor pressure and commonly utilized for heating and cooking purposes. In a similar vein, butane

(C_4H_{10}) is one of the more dangerous volatile chemicals to breathe in and has uses comparable to those of propane. Chloromethane, another name for methyl chloride (CH_3Cl), is a poisonous, flammable gas that lacks color. Aside from its use as a refrigerant, methyl chloride is also used as a solvent in petroleum refining, a chlorinating agent in organic synthesis, a herbicide, and a propellant in the production of polystyrene foam. Depending on the concentration and duration of exposure, methyl chloride exposure can cause a variety of health effects, from sleepiness and dizziness to seizures and comas. Another important volatile volatile organic compound is chloroform, also known as trichloromethane ($CHCl_3$), a dense volatile organic compound that appears as a colorless liquid with a strong odor. Large-scale production of it precedes the production of PTFE and other refrigerants. Inhaled or consumed, chloroform has strong sedative and anesthetic effects. Studies have shown that chloroform can induce liver and kidney tumors in mice and rats, with its hepatotoxicity and nephrotoxicity attributed to phosgene (a degradation product).

Volatile organic compounds (VOCs)

Volatile organic compounds (VOCs) are present in the environment and household products and are equally toxic as volatile volatile organic compounds (VVOCs), according to research by Reimann and Lewis (2007), Williams and Koppmann (2007), Heeley et al. (2020), Wang et al. (2007), and others. This category includes, among other things, toluene, acetone, formaldehyde, vinyl chloride, carbon tetrachloride, isopropyl alcohol, hexanal, and carbon disulfide. For example, formaldehyde (CH_2O) is commonly utilized as a carcinogenic volatile organic compound (VOC) in the manufacturing of resins for building materials, paper, and textile fabrics. Particleboard, plywood, and other pressed wood products, as well as glues, varnishes, and insulating materials, are typical examples of items that include it. Also referred to as ethylene monochloride or chloroethene, vinyl chloride (C_2H_3Cl) is used in the production of consumer items, floor coverings, and polymers. It is considered "highly likely to be carcinogenic," with individuals residing near vinyl chloride production facilities facing exposure risks. Vinyl chloride primarily affects the liver, causing liver damage and affecting liver function upon exposure to air containing its vapors.

Trichloroethylene is a common industrial solvent that resembles chloroform and smells pleasant. The poisoning of drinking water and groundwater by industrial discharges presents serious health risks and has resulted in a number of accidents and lawsuits throughout the years. Tachypnea, adrenaline-accentuated cardiac rhythms, headaches, dizziness, disorientation, and even unconsciousness can be signs of trichloroethylene exposure, which is mostly caused by drinking water. Acute non-medical exposure to trichloroethylene might resemble alcohol intoxication, develop respiratory and circulatory depression, and even be fatal.

Toluene (C_7H_8) is an aromatic hydrocarbon that is a colorless liquid with a smell akin to paint thinners. Paint thinners, permanent markers, and some forms of glue are just a few of the products that employ it as an industrial feedstock and solvent. There is a chance that toluene will seriously damage your brain. Although its use has declined because of environmental concerns, carbon tetrachloride (CCl4) is an organic chemical with a pleasant scent that is used in fire extinguishers and as a precursor to refrigerants and cleaning agents.

Acetone ($(CH_3)_2CO$) is the most basic ketone. It is a colorless, flammable liquid with a pungent smell that may be miscible with water and used as an organic solvent. Acetone is a popular building block in organic chemistry and is also used to generate bisphenol A and methacrylate. Acetone is a VOC that can be harmful to people's health, particularly for diabetics. Colorless and flammable, isopropyl alcohol ($CH_3CHOHCH_3$) has a strong odor and is used in a variety of products including fragrances, antifreeze, soaps, cleansers, disinfectants, and cosmetics. As isopropyl alcohol is exposed to over time, respiratory problems may develop.

Hexanal ($C_6H_{12}O$), also called hexaldehyde, is a precursor to various compounds used in the manufacture of plastics, rubbers, and pesticides. It is also employed as a flavoring ingredient in food products and a scent in fragrances. Skin, eyes, nose, throat, and lungs might get irritated after brief exposure to moderate doses of hexanal. The symptoms of choking, coughing, and fast breathing may occur with extended or increased exposure. For the production of cellophane and viscose rayon, carbon disulfide, also known as carbon bisulfide (CS_2), is a very volatile chemical. Moreover, pesticides, solvents, and varnishes include it. When breathing in carbon disulfide, one may experience respiratory issues at work.

Semi volatile organic compounds (SVOCs)

Higher molecular weights and boiling points than volatile organic compounds (VOCs) give semi-volatile organic compounds (SVOCs) a lower propensity to evaporate at ambient temperature. Their potential threat to the environment and public health is not lessened by this trait, though. SVOCs usually boil between 240 and 260 °C and between 380 and 400 °C. The following are all examples of SVOCs:

1. Pesticides (DDT, Chlordane, Plasticizers (Phthalates)
2. Fire retardants (PCBs, PBB)

When choosing pollution control equipment, it's crucial for manufacturers to consider the specific type of volatile organic compound (VOC) being emitted. For instance, facilities with higher levels of very volatile organic compounds (VVOCs), which vaporize at lower temperatures, may experience elevated pollutant concentrations in the air. In such cases, a Regenerative Thermal Oxidizer (RTO) could be the optimal choice, as these systems are most effective with moderate to high concentrations of air pollution. On the other hand, facilities emitting semi-volatile organic compounds (SVOCs), which require higher temperatures to vaporize, may have lower pollutant concentrations in the air. Therefore, a Recuperative Thermal Oxidizer (TO) might be more suitable, as these units are designed to handle lower concentrations effectively.

Human Health Effects

Volatile organic compounds (VOCs) are thought to have a part in sick building syndrome (SBS), even if the precise reason or causes are yet unclear. Indoor levels of VOCs are frequently increased. Chronic effects like cancer, liver and kidney damage, and impairment of the central nervous system can result from prolonged exposure to volatile organic compounds. When volatile organic compounds (VOCs) are present at high concentrations (measured in parts per million, ppm), the acute effects might include irritation of the nose, eyes, and throat in addition to central nervous system reactions such headaches, dizziness, nausea, and vomiting, as well as short-term memory loss (Berglund et al., 1984). Laboratory studies have demonstrated that certain symptoms, such as headache and eye irritation, can occur in both sensitive and healthy individuals at total volatile organic compound (TVOC) levels ranging from 5 to 25 mg/m^3 (Otto et al., 1990).

VOCs Mitigation Measures

The most effective method to mitigate the presence of toxic volatile organic compound (VOC) pollutants in the environment is by reducing the use of products that emit them. VOC emissions persist even when products are not actively being used around the home. Indoor air quality monitors play a crucial role in monitoring concentrations of pollutants, including VOCs, particulate matter, and other contaminants in the air. By minimizing the use of hazardous products that emit VOCs, indoor air quality can be improved over time.

Proper Storage and Ventilation

Improving indoor air quality often involves enhancing ventilation to allow more fresh air into enclosed spaces, particularly in areas where VOC emissions are a concern. Indoor air quality typically deteriorates compared to outdoor air quality due to insufficient fresh air circulation. Simple measures such as opening windows or doors, utilizing ventilation systems, and other ventilation methods can help enhance indoor air quality in residential settings. If indoor storage spaces cannot be adequately ventilated, it's advisable to store off-gassing products, such as paint thinners containing toluene, outdoors in a shed or garage to minimize exposure risks. Prolonged exposure to gaseous pollutants in enclosed spaces can pose health risks, leading to adverse symptoms for individuals exposed to VOCs.

VOCs Mitigation by Nanomaterials Use

Numerous nanomaterials have demonstrated potential in reducing volatile organic compounds (VOCs); however, the effectiveness of these materials varies based on characteristics such size, porosity, surface functionality, and chemical composition. Studies have been conducted on the ability of carbon nanomaterials, polymer nanocomposites, and metallic and metal oxide nanoparticles to adsorb volatile organic compounds (VOCs) from water and the environment. For example, carbon nanotubes (CNTs) have been utilized to lessen the amount of BTEX (benzene, toluene, ethylbenzene, and p-xylene) in contaminated water. Multiwall carbon nanotubes (MWCNTs), produced by catalytic chemical vapour deposition and oxidized with sodium hypochlorite (NaOCl), efficiently adsorbed BTEX from water. P-xylene had the strongest affinity among the produced carbon nanotubes, with BTEX exhibiting a particular order of affinity. The BTEX adsorption of many CNTs that had been oxidized by various chemical agents was also assessed; MWCNTs that had been oxidized by NaOCl showed the greatest adsorption capability. The adsorption process was ascribed to a π–π electron donor–acceptor mechanism, in which the BTEX aromatic ring functioned as the electron acceptor and the carboxylic oxygen atom of the MWCNTs as the electron donor.

Additionally, MWCNTs have been used as solid-phase extraction (SPE) sorbents to remove chlorobenzenes from water; their adsorption capacities were on par with those of classical adsorbents like activated carbon and C18 silica, suggesting their potential for effective determination of chlorobenzenes and other VOCs in natural or polluted waters. These studies show the potential uses of nanomaterials in mitigating VOC pollution and emphasize their potential as efficient adsorbents for a variety of environmental contaminants. For example, carbon nanotubes were used in a study by Peng et al. (2003) to remove 1,2-dichlorobenzene from aqueous solutions, with a maximum sorption capacity of 30.8 mg/g in 40 minutes.

Additionally, a one-pot condensation method was used to create periodic mesoporous organosilica nanoparticles (MO SiNPs), which produced nanomaterials with large pore volumes (0.92 cm^3/g) and high surface areas (977 m^2/g) (Ateia et al., 2019). Even at modest adsorbent dosages, these MO SiNPs demonstrated a mitigation effectiveness of more than 99% for both butyric and hexanal vapors. The nanomaterials showed that they could be reused for several cycles. Furthermore, Li et al. (2020) reported the effective synthesis of v-SiO_2, an organic-inorganic hydrophobic mesoporous silica, by means of a co-condensation technique employing vinyltriethoxysilane (VTES) and tetraethoxysilane (TEOS) in an acidic environment. When compared to pure silica, this nanomaterial demonstrated enhanced hydrophobicity against p-xylene adsorption.

Improving the dispersion of noble metals on the surface of the substrate is essential to maximize the usage of noble metal catalysts for VOC oxidation. This can be accomplished by altering the catalysts' structure, morphology, or particle size. Furthermore, increasing the amount of oxygen adsorbed and expanding the lattice oxygen mobility by substrate doping with additional transition metals can both improve the activation of oxygen for noble metal catalysts supported on transition-metal oxides. Pt-based nanomaterials have drawn interest among noble metal catalysts for the oxidation of volatile organic compounds (VOCs), such as methane, formaldehyde, xylene, benzene, and toluene. For example, at normal temperature, mesoporous AlOOH nanoflakes with Pt deposition demonstrated great efficiency in breaking down formaldehyde. Numerous features were found by Xu et al. (2015) to be associated with the catalytic activity, such as the high dispersion of Pt nanoparticles, the abundance of surface hydroxyl groups, the strong adsorption property of the substrates, the high specific surface area, and the large pore volume.

Pt loading was achieved by impregnation or deposition-reduction of porous SBA-15 silica with a high specific surface area; the resultant catalysts were then used for benzene oxidation. Pt/SBA-15 catalysts' physicochemical characteristics and catalytic performances were strongly impacted by the synthesis process. Higher dispersion, smaller crystallite size, and a negatively charged surface from a strong metal-support interaction were some of the reasons why catalysts prepared by reduction with $NaBH_4$ and H_2 showed higher efficiency than those prepared by sodium citrate reduction (Tang et al., 2014).

The size of Pt particles has a major impact on the catalytic oxidation of volatile organic compounds (VOCs). For example, Pt-d/ZSM-5 nano-catalysts have been synthesized by researchers and loaded on ZSM-5 substrates with varying Pt nanoparticle sizes (ranging from 1.3 to 2.3 nm). With a toluene conversion rate of 98%, Pt-1.9/ZSM-5 showed the most efficiency in toluene oxidation among them all. Similarly, catalysts containing 1 weight percent Pt/TiO_2 were produced and evaluated for catalytic oxidation of gaseous formaldehyde at room temperature. The Pt particle sizes in these catalysts ranged from 1.54 to 22.3 nm. According to Huang et al. (2014), the findings demonstrated that the catalytic efficacy varied with Pt particle size, with different particle sizes demonstrating variable degrees of efficiency.

Pd noble metal is still utilized in many catalysts despite generally showing less activity than Pt in the catalytic oxidation of most pollutants. This is because it is highly effective in some processes, including the oxidation of halocarbons or toluene. Because of their promising catalytic capabilities, Pd-based catalysts, including Pd-TiO, have attracted a lot of attention in their development for VOC mitigation (Huang et al., 2011). Due to its chemical inertness toward molecules like oxygen or hydrogen, gold (Au) was formerly thought to be a poor catalyst; nonetheless, Au nanoparticles have demonstrated unanticipated and distinctive catalytic properties. Propene oxidation has been explored using Au-supported catalysts on mesoporous TiO_2 oxide; Au/TiO_2 catalysts show excellent activity because of strong interactions between well-dispersed Au nanoparticles and the mesoporous oxide.

Furthermore, the catalytic activity was positively impacted by Au+ species that were present at the titania-Au nanoparticle interface, indicating the potential of Au nanoparticles in VOC mitigation (Ousmane et al., 2011).

Despite having less activity than Pt, Pd, or Au, silver (Ag) has attracted a lot of attention in the field of VOC abatement, especially for the catalytic oxidation of formaldehyde. Formaldehyde oxidation tests have been conducted on a variety of Ag-based catalysts that have been created by impregnation and loaded on various supports, such as TiO_2 or CeO_2. At temperatures close to 95 °C, these catalysts showed full formaldehyde conversion, demonstrating their potential for VOC elimination (Zhang et al., 2015).

Catalytic nanoparticles can be used for VOC reduction in coatings, paints, air filters, construction materials, etc. to enhance indoor air quality. Because of their great chemical stability, cheap cost, and non-toxicity, metal oxides like ZnO and TiO_2 have been extensively researched and applied to VOC elimination applications in buildings. Other nanocatalysts have also shown excellent performance in theoretical assessments and laboratory research, making them viable options for use in environmentally friendly and healthful buildings in the future. The advancement of understanding and prospective applications of these catalytic nanomaterials for lowering or eliminating VOCs will be aided by further research, which will promote better indoor and outdoor environments in buildings.

TiO_2- or TiO_2-supported metal catalyst-based photocatalysis is a well-researched green environmental remediation method for the elimination of volatile organic compounds (VOCs). A few examples of the variables that affect photocatalyst efficiency include TiO2 particle treatments, morphology, and structure. Research has examined how synthesis factors affect the size and shape of TiO_2 nanoparticles; with a particle size of 7 nm, trichloroethylene degradation is most efficient (Maira et al., 2000). Furthermore, research has been done on the photocatalytic activity of TiO_2 nanotubes and nanoparticles on the breakdown of gaseous toluene and acetaldehyde. Because of its highly organized open channel structure, which avoided catalytic deactivation by quickly supplying O_2 molecules to active areas, TiO_2 nanotubes performed more steadily than nanoparticles (Weon and Choi, 2016).

TiO_2 nanotubes are more effective than TiO2 nanoparticles at removing volatile organic compounds (VOCs) after repeated cycles of photocatalytic degradation, according to comparative studies (Weon and Choi, 2016). Moreover, new atomic layer deposition (ALD)-based nanostructured gas filtration systems based on TiO_2 thin films have shown improved toluene adsorption efficiency (Lee et al., 2011). In comparison to standard TiO2 nanotubes, freestanding doubly open-ended TiO_2 nanotubes (DNT) films have been produced and have shown enhanced performance and durability for the photocatalytic degradation of acetaldehyde and toluene (Weon et al., 2017). Furthermore, the effectiveness of VOC degradation was further increased by adding TiO2 nanoparticles onto DNT films.

Apart from TiO_2, another nanomaterial utilized for the quick and effective chemical decontamination of volatile organic compounds is zinc oxide (ZnO) (Azzouz et al., 2018). ZnO has potential as a substitute photocatalyst for reducing volatile organic compounds (VOCs), broadening the selection of materials for use in environmental rehabilitation projects. For the photocatalytic degradation of toluene in the gaseous phase, the synthesis techniques for $ZnAl_2O_4$ (solvothermal, citrate precursor, and hydrothermal) were compared (Li et al., 2011). Among these techniques, the solvothermal approach produced $ZnAl_2O_4$ samples that showed the promise of UV-illuminated $ZnAl_2O_4$ for air cleaning applications, with photocatalytic performance for toluene removal reaching over 90%.

The oxidation activities of amorphous manganese oxide (AMO), mixed copper manganese oxide ($CuO/Mn2O_3$), and cryptomelane-type octahedral molecular sieve (OMS-2) nanomaterials were produced and compared with commercial MnO_2 (Li et al., 2011). Because of their distinct structures, hydrophobicity, shape, and redox characteristics, OMS-2, AMO, and CuO/Mn_2O_3 showed greater oxidation activity than commercial MnO_2. Manganese oxide (MnOx) catalysts were loaded onto a polyacrylonitrile-based activated carbon nanofiber (PAN-ACNF) substrate to create a new composite catalyst for the long-term elimination of formaldehyde (Miyawaki et al., 2012). When MnOx and PAN-ACNF were combined, their effects on formaldehyde elimination were synergistic, increasing PAN-ACNF's activity in both humid and dry environments without UV radiation.

Schick et al., (2019) investigated the complete oxidation of volatile organic compounds (VOCs) using alternative oxides, such as iridium oxide particles supported on SiO_2. The catalytic activity rose as the iridium particle size shrank, suggesting that particle size matters in the oxidation of volatile organic compounds. Pt-rGO-TiO_2 hybrid nanomaterials were created and evaluated for their ability to remove volatile organic compounds using photocatalysis (Li et al., 2018). Light intensity affected Pt-rGO-TiO_2's catalytic effectiveness for toluene conversion and CO_2 yield; for a certain infrared irradiation intensity, a maximum of 95% toluene conversion efficiency and 72% CO_2 yield were attained. These researches demonstrate the wide variety of composite catalysts and nanomaterials being produced for efficient photocatalytic oxidation-based VOC reduction.

Graphene oxide and TiO_2 were hydrothermally reacted to create nanocomposites of TiO_2/graphene, which showed greater photocatalytic stability and efficiency than TiO2 alone in the gas-phase degradation of benzene (Samaddas et al., 2018). Three graphene-based co-catalysts (graphene oxide, reduced graphene oxide, and few-layer graphene) were investigated for the gas-phase photocatalytic oxidation of methanol; reduced graphene oxide had the greatest performance and conversion rate (Zhang et al., 2010). With a high adsorption capacity of 251 mg/g, graphene oxide composite materials with metal-organic frameworks (MOF-5) were successful in eliminating gaseous benzene (Roso et al., 2017). The ideal graphene oxide/MOF-5 composite was 5.25 weight percent graphene oxide, which expanded MOF-5's pore volume and surface area and improved its adsorption ability (Japhet et al., 2023).

To remove toluene, graphene oxide and reduced graphene oxide have also been studied. Their π-π bonds, hydrophobicity, and electrostatic interactions with toluene molecules have all been taken advantage of (Kumur et al., 2020). Comparing several graphene nanomaterials to activated carbons, they demonstrated promising toluene adsorption capabilities. These nanomaterials included graphene platelets, reduced graphene oxide modified with KOH (rGOMW-KOH), and graphene oxide modified with KOH (rGOMW-KOH). The graphene platelets' particular surface areas and graphitic character, which affect the π-π interactions between the graphene materials and toluene molecules, correlate with the order of rGOMW-KOH > rGOMW > graphene platelets in terms of adsorption effectiveness. These investigations demonstrate the potential of graphene-based nanomaterials for the adsorption and elimination of airborne volatile organic chemicals.

Due to its greater specific surface area, rGOMWKOH had the maximum adsorption capacity for toluene and demonstrated efficiency for toluene removal that was equivalent to active carbons (Kim et al., 2018). Graphene materials were used to study the adsorption of ethanol, another volatile organic compound (VOC), especially in composites including metal-organic frameworks (MOFs) (Liu et al., 2015). The remarkable adsorption capacity of

158.2 mg/g for ethanol was achieved by these composites due to their large specific surface area, porous structure, and oxygen functionality.

According to Yan et al. (2016), a Cu-BTC/graphene oxide composite demonstrated an adsorption capacity of 635 mg/g for ethanol at room temperature in a separate research. Graphene nanoparticle removal of carbonyl volatile organic molecules has also been studied. Using amino-functionalized graphene sponge (G/S) and amino-functionalized graphene sponge embellished with graphene nanodots (G-GND/S), indoor formaldehyde was eliminated (Wu et al., 2015). The second substance interacted with formaldehyde more strongly than the former, and it was distinguished by having more amine groups on its surface. These investigations highlight the adaptability and potency of graphene-based nanomaterials in the adsorption of different volatile organic compounds (VOCs), advancing the creation of practical air filtration systems.

Methods and Models of Analysis of VOCs

Finding volatile organic compounds (VOCs) in water samples has grown in importance as a challenge for environmental monitoring in recent decades. For this goal, several technologies have been created, each with unique benefits and drawbacks. A well-liked method for examining volatile organic compounds (VOCs) in water is USEPA Method 524.2, which employs gas chromatography/mass spectrometry (GC/MS) after a purge and trap extraction apparatus (Eichelberger et al., 1989). This technique may be used to properly detect and identify the volatile organic compounds (VOCs) present in water samples.

Various other techniques have been employed for the analysis of VOCs, such as gas chromatography (GC), mass spectrometry, surface acoustic wave (SAW), ion mobility spectrometry (IMS), headspace solid-phase microextraction followed by gas chromatography (SPME/GC/HS) quantification, and photoionization detector (PID) (Mieure, 1980; Wylie, 1988; Ho et al., 2001). When it comes to VOC detection, GC and GC/MS are more sensitive and have detection limits in the parts per billion (ppb) range than other techniques (Archbold, 2005; Schellin and Popp, 2006).

Traditional methods such as GC/MS remain valuable despite requiring labor-intensive sample collection and off-site laboratory analysis that can be costly and time-consuming. However, new and enhanced technologies have emerged that eliminate the need for sample collection and off-site analysis, therefore reducing analytical errors. Graphene sensors have been developed to analyze the kind and amount of volatile organic compounds (VOCs) released by food packaging (Sundramoorthy and Gunasekaran, 2014). These sensors provide quick and on-site VOC detection, increasing efficiency and lowering the need for convoluted sample processing and transportation. They work in tandem with automated systems for sampling and analysis. As VOC detection technologies continue to progress, more effective and dependable techniques for environmental monitoring have been created, offering important new information on VOC pollution in water sources.

Conclusion

Reducing the concentration of volatile organic compounds (VOCs) both indoors and outdoors is crucial for maintaining human health and environmental quality. Elevated levels of VOCs can lead to adverse health effects and environmental pollution, making it essential to implement effective mitigation strategies. The application of nanomaterials in VOC reduction has encouraging opportunities to improve the effectiveness of environmental pollutant removal. More effective technological methods for the removal of volatile organic compounds (VOCs) can be created by utilizing the special qualities of nanomaterials, such as their large surface area, increased reactivity, and adjustable surface chemistry. To detect and reduce possible health concerns, it is important to conduct periodic screenings of the population for health risks related to volatile organic compounds (VOCs). Intentional or inadvertent VOC contamination can be decreased by raising public knowledge of proper waste disposal techniques and reducing indoor air pollution. By promoting education and implementing proactive measures, communities can work towards safeguarding human health and preserving environmental quality for future generations.

Recommendation

Some steps to reduce exposure to VOCs include:

i. Afforestation is indeed a collective responsibility that can significantly contribute to improving natural ventilation and environmental quality.

ii. Government funding for researchers to improve bioremediation techniques is essential for promoting environmental-friendly solutions to pollution. Bioremediation, which utilizes biological organisms to degrade or remove pollutants from contaminated sites, has the potential to be a cost-effective and sustainable method for cleaning up environmental hazards (Abakpa et al., 2023).

iii. Reducing the use of products that emit volatile organic compounds (VOCs) is crucial for minimizing indoor air pollution and protecting human health. Purchasing only necessary items such as paints, solvents, adhesives, and caulks can help reduce VOC emissions. Proper storage of unused chemicals in areas such as garages or sheds can prevent VOC leakage into indoor spaces.

iv. Proper waste disposal, including recycling and utilizing household hazardous waste collection sites, is essential for preventing environmental contamination.

v. When purchasing new items, opting for floor models that have been allowed to off-gas in the store can reduce indoor VOC exposure. Additionally, choosing solid wood items with low-emitting finishes over those made with composite wood can help minimize VOC emissions in indoor environments.

vi. Home renovations should ideally be conducted when the house is unoccupied or during seasons that allow for increased ventilation. Opening doors and windows to increase airflow can help dissipate indoor pollutants and improve indoor air quality before occupying the renovated space.

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