Managing VOC Hazards Proactively for a Safer, Healthier Workplace

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Introduction

Volatile Organic Compounds (VOCs) are carbon-containing chemicals that have a tendency to easily evaporate or "volatilize" at normal room temperature. They are present in natural products like plants, wetlands, and microorganisms, and in several man-made common products including paints, solvents, fuels, cleaning agents, building materials, etc. The VOCs can impact both environment and human health. Many VOCs react with nitrogen oxides in the presence of sunlight to produce ground-level ozone which is deleterious to crops and ecosystems. Some VOCs also act as greenhouse gases, contributing to climate change. Harmful effects of VOCs exposure on human health include short-term effects like eye and throat irritation, nausea, headaches, skin allergies, vertigo and severe long-term impacts like tissue damage, nervous system impairment, and even cancer (some are known carcinogens).

Monitoring of VOCs is crucial to understand and quantify their levels in the ambient air and indoor environments, and helps in assessment of their potential health risks. It is also needed for ensuring compliance with environmental regulations, and developing strategies to mitigate release of VOCs into the environment. Early detection of VOCs is useful in identifying sources, and preventing larger environmental impact or health related exigencies.

VOCs present a significant occupational hazard in workplace settings, particularly in the industries like manufacturing, painting, chemical processing, printing, and dry cleaning, where workers can be exposed to high levels of certain VOCs. If there is direct and chronic exposure, then it may cause respiratory irritation, nausea or chronic health problems over a period of time. This necessitates implementation of strong monitoring, and control measures, such as ventilation, and use of personal protective equipment (PPE) etc., to safeguard worker health and safety.

Workplace Sources of VOCs and Health Implications

Volatile organic compounds (VOCs) are released from a wide range of both natural and anthropogenic sources, making them inescapable in many environments. Common indoor sources such as building materials, pressed wood products (e.g., particleboard, MDF) known to emit formaldehyde, paints, varnishes, adhesives, and floor coverings, etc., contribute substantially to occupants' exposure (Salthammer et al., 2010; Yu & Crump, 1998). Common day to day use products like cleaning agents, personal care products, and electronic equipments like printers also contribute to the indoor VOC burden (Wolkoff & Nielsen, 2001). In industrial and occupational environments, VOCs emanate from solvents used in degreasing (e.g., trichloroethylene), paints and coatings (e.g., toluene, xylenes, ethylbenzene, styrene), fuels (notably benzene from gasoline), and chemical intermediates in manufacturing processes (Brugnone et al., 1994; ATSDR, 2019a). Specific industrial activities present unique VOC exposure profiles; for instance, dry cleaning industry has historically been significant sources of perchloroethylene (ATSDR, 2019b), while the automotive industry involved in the manufacture of motor vehicles, is vulnerable to exposure to a complex mixture of solvents and isocyanates (Sparer et al., 2004). Even natural sources, such as biogenic VOCs (BVOCs) like isoprene and terpenes released by vegetation contribute to atmospheric VOCs (Guenther et al., 2012). Coal mining has been identified as a significant source of anthropogenic volatile organic compound emissions with persistent health hazards and fire risks to the workers working in underground mines. The major source of these VOCs, especially methane, is the coal seam. Additionally, the hydraulic oils, fuels, and lubricants used in mining equipment often contain substances like glycol ethers, benzene, ethylbenzene, toluene, and other hydrocarbons, which also contribute to VOC emissions (Weiss et al., 2016).

The adverse health effects of occupational exposure to volatile organic compounds (VOCs) can vary in severity and nature depending on the nature of specific chemicals involved, the duration and intensity of exposure, and individual vulnerability. Prolonged or high dose exposure can manifest into more serious long-term health issues, and can damage nervous system, liver, and kidneys. Certain VOCs are known or suspected carcinogens, increasing the risk of developing cancers like leukaemia. Respiratory problems, including asthma and other chronic lung diseases, can also be exacerbated or induced by VOC exposure. Moreover, some VOCs can affect cognitive functions, coordination, and memory, while others may have reproductive or developmental

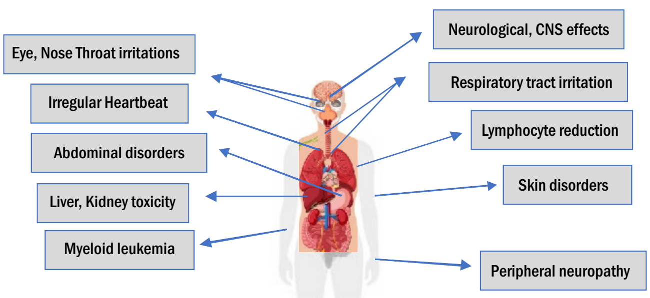

Fig.1: *Possible health implications of VOC exposure.*

***Table 1:** Workplace Sources, applications and potential health impacts of common VOCs.*

VOC Name	Common Workplace Sources	Primary Short - Term Health Effects (General) [a]	Primary Long - Term Health Effects (General & Specific) [b]	Key Industry / Application Examples [c]
Formaldehyde	Pressed wood products (particleboard, MDF), some paints, adhesives, building materials	Eye, nose, & throat irritation; headache; dizziness; respiratory distress	Known Carcinogen; organ damage; nervous system impairment; respiratory issues	Construction; Furniture manufacturing; Building materials
Benzene	Fuels (gasoline); industrial solvent	Eye, nose, & throat irritation; headache; dizziness; nausea	Known Carcinogen (leukemia); organ damage (bone marrow); nervous system impairment	Petrochemical industry; Fuel handling; Manufacturing (e.g., rubber, plastics)
Toluene	Paints, coatings, solvents, adhesives	Eye, nose, & throat irritation; headache; dizziness; confusion; nausea	Nervous system impairment (e.g., cognitive, coordination); organ damage (liver, kidney)	Painting; Printing; Manufacturing; Automotive refinishing
Xylenes (mixed)	Paints, coatings, solvents, adhesives	Eye, nose, & throat irritation; headache; dizziness; lack of coordination	Nervous system impairment; respiratory effects; potential organ damage	Painting; Printing; Manufacturing; Laboratories
Ethylbenzene	Paints, coatings, solvents; component of xylenes	Eye & throat irritation; dizziness	Possible Carcinogen; nervous system impairment; hearing damage	Manufacturing (e.g., styrene); Paints & coatings
Styrene	Paints, coatings (especially resins); manufacturing of plastics & rubber	Eye, nose, & throat irritation; headache; fatigue; dizziness	Possible Carcinogen; nervous system impairment; hearing damage	Plastics & resin manufacturing; Boat building; Paints
Trichloroethylene (TCE)	Solvents for degreasing; equipment cleaning	Headache; dizziness; confusion; nausea; facial numbness	Known Carcinogen; liver & kidney damage; nervous system impairment; immune system effects	Metal degreasing; Chemical manufacturing; Nuclear industry (cleaning)
Perchloroethylene (PCE)	Dry cleaning solvent; degreasing agent	Dizziness; headache; nausea; incoordination; eye & respiratory irritation	Probable Carcinogen; nervous system impairment; liver & kidney damage	Dry cleaning; Metal degreasing; Nuclear industry (cleaning)
Tributyl Phosphate (TBP)	Extractant in spent nuclear fuel reprocessing (PUREX process)	Eye & skin irritation; respiratory irritation	Potential for organ damage (liver, kidney); nervous system effects (less characterized in text)	Nuclear fuel reprocessing
n-Dodecane	Diluent for TBP in PUREX process; component of kerosene mixtures	Skin and respiratory irritation; dizziness;nausea (if high conc.)	Potential for organ damage; aspiration hazard (liquid)	Nuclear fuel reprocessing; Solvent manufacturing
Acetonitrile	Solvent for chromatography, sample preparation, quality control assays	Eye & respiratory irritation; headache; dizziness; nausea	Can metabolize to cyanide (high exposure); potential organ/nervous system effects	Analytical laboratories; Pharmaceutical manufacturing
Methanol	Solvent for chromatography, sample preparation; chemical intermediate	Headache; dizziness; nausea; blurred vision	Vision damage (optic nerve); nervous system damage; severe poisoning can be fatal	Analytical laboratories; Chemical manufacturing; Fuel component
Hexane (n- Hexane)	Solvent for chromatography, sample preparation; cleaning agent	Dizziness; headache; nausea; eye & throat irritation	Neurotoxicity (peripheral neuropathy-"Hexane neuropathy"); skin irritation	Analytical laboratories; Industrial cleaning; Food oil extraction
Dichloromethane (Methylene Chloride)	Solvent for chromatography, sample preparation; degreasing; paint stripping	Dizziness; fatigue; headache; nausea; eye & skin irritation	Probable Carcinogen; nervous system effects (can metabolize to carbon monoxide); liver effects	Analytical laboratories; Paint stripping; Degreasing; Pharmaceutical manufacturing
Isocyanates [3]	Automotive refinishing (paints, coatings); polyurethane manufacturing	Severe eye & respiratory irritation; chest tightness; asthmalike symptoms	Potent respiratory sensitizer (occupational asthma); skin sensitization	Automotive refinishing; Spray foam insulation; Polyurethane products mfg.

Notes:

[a,b]*Health effects listed here are generic and can vary significantly depending on the concentration, duration of exposure, individual sensitivity, and route of exposure (inhalation, skin contact).*

[c]*The "Key Industry / Application Examples" may not be exclusive.*

[d]*Isocyanates are generally considered separately from typical VOCs due to their strong sensitizing properties but are included here in the context of solvent mixtures.*

effects. The following Fig.1 illustrates the implications of VOC exposure on human health.

Within the nuclear fuel cycle, from uranium processing to spent fuel reprocessing and associated research activities, various VOCs are utilized. The most significant and well-documented use of VOCs takes place in spent nuclear fuel reprocessing, particularly in the PUREX (Plutonium Uranium Reduction Extraction) process, which employs tributyl phosphate (TBP) as an extractant, normally diluted in a hydrocarbon solvent such as n-dodecane or a refined kerosene mixture (Nash & Lumetta, 2011; IAEA, 2008). These solvents are essential for separating uranium and plutonium from fission products but can lead to worker exposure and atmospheric emissions if not meticulously managed. Beyond reprocessing, nuclear fuel production facilities and related research laboratories utilize a range of VOCs for auxiliary jobs such as equipment cleaning, degreasing, and maintenance, etc. The common examples include chlorinated solvents like trichloroethylene (TCE) or tetrachloroethylene and various alcohols or ketones. Analytical laboratories also extensively use VOCs, such as acetonitrile, methanol, hexane, and dichloromethane as solvents for chromatography, sample preparation, and quality control assays. Other VOCs, such as dioxane, formaldehyde, acetone, etc., are routinely used in radioanalytical laboratories. The presence of these compounds necessitates thorough monitoring and control, not only due to their intrinsic chemical toxicity but also because of the potential for influencing process chemistry or safety (e.g., formation of flammable gases or corrosive by-products). Table 1 lists some important VOCs, their sources at workplaces, main short-term and long-term health effects, and common industrial applications.

Challenges in the Detection and Monitoring of VOCs

Detecting and monitoring volatile organic compounds in occupational and environmental surroundings present significant analytical and logistical challenges, primarily due to their vast chemical diversity, wide, and fluctuating range of concentrations (from parts-per-trillion to percent levels), and often complex nature of their mixtures. First of all, the total number of individual VOCs (many coexisting at trace concentrations), necessitates use of highly sensitive and selective analytical techniques such as gas chromatography coupled with mass spectrometry (GC-MS) or flame ionization detection (GC-FID) for speciation and accurate quantification. However, these methods generally require discrete, and often time-consuming sampling (e.g., onto sorbent tubes followed by thermal desorption, or collection in summa canisters), and laboratory analysis (Demeestere et al., 2007; Woolfenden, 2010). Moreover, VOC concentrations display substantial spatiotemporal variability, influenced by recurrent and fluctuating source emissions, ventilation rates, and process cycles within a workplace, which make the representative sampling a difficult choice. Recording short-term peak exposures, crucial for highly toxic VOCs, generally requires real or near real-time monitoring, but many direct-reading instruments (e.g., those using photoionization detectors - PIDs, or metal-oxide sensors - MOS) may not be capable of differentiating between various VOCs or can be affected by interferences from environmental humidity or presence of other airborne compounds, providing only a total VOC (TVOC) reading, often insufficient from toxicological perspective (Fine et al., 2010). The selection of an appropriate sampling method (e.g., active vs. passive, whole air vs. sorbent-based) depends

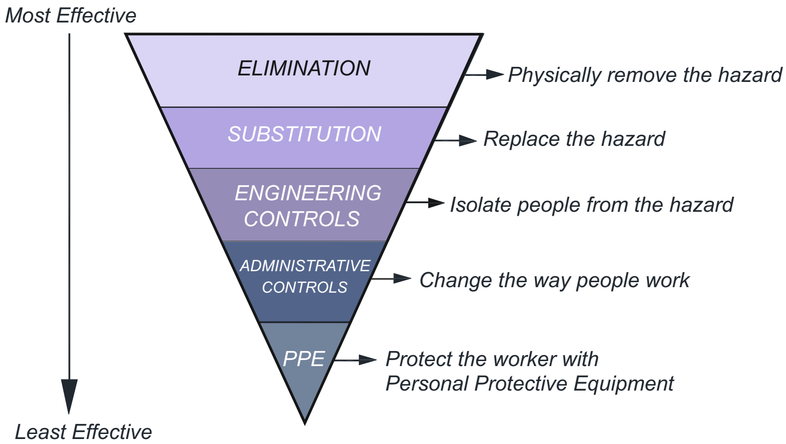

Fig.2: *Hierarchy of Controls.*

profoundly on the target VOCs' qualitative aspects (e.g., volatility, reactivity), the required detection limits, and the desired sampling duration, etc. (Brown, 2002; US EPA, 1999 - specifically Compendium Method TO-17 for sorbent tubes). Lastly, maintaining calibration accuracy for a wide range of VOCs and ensuring the integrity of samples during collection, storage, and transport can be challenging from quality assurance point of view.

Proactive management of VOC Hazards: The Hierarchy of Controls

Proactive management of the Volatile Organic Compound (VOC) hazards at workplace is vital for ensuring a healthy and safe environment for all occupants. An important and universally recognised concept in this regard is hierarchy of controls, which provides a rational framework in occupational health and safety (OHS) management to methodically eliminate or minimize workplace hazards by prioritizing control measures on the basis of their effectiveness and reliability. It outlines a categorization of desired actions, starting with the most effective and long-lasting protective measures those that remove the hazard entirely to less effective controls that depend more on human factors or provide a barrier or personal protection (Fig.1). Utilizing this hierarchy proactively for VOC management involves following and applying these principles from earliest stages of process design, material selection, and workplace layout. Instead of reacting to VOC exposures after they occur, a proactive approach uses the hierarchy as a decision-making tool to anticipate potential VOC hazards and implement the most feasible controls, ideally by designing out the need for hazardous VOCs or limiting them at their source, thereby preventing worker exposure and consequent health risks from materializing. At the most effective level, elimination involves completely removing the VOC source or process, such as by redesigning a product or not using VOC-containing adhesive/switching, or modifying a part of manufacturing technique (e.g., powder coating instead of solvent-based spraying, mechanical fastening instead of gluing) that obviates the need for VOC altogether. If elimination is not feasible, substitution is the next preferred step, which entails replacing hazardous VOCs with substances that are less volatile, less toxic, or non-hazardous while still performing the required function; examples include switching from high-VOC solvent-based paints to water-based or low-VOC formulations or replacing chlorinated solvents like trichloroethylene with less harmful aqueous cleaners or alternative organic solvents with lower toxicity (e.g., certain alcohols or esters, if suitable).

When elimination or substitution are not viable, engineering controls are implemented to isolate workers from the hazard or remove contaminants at the source. For VOCs, this often involves installing effective local exhaust ventilation (LEV) systems, such as fume hoods, paint booths with dedicated extraction, or capture hoods directly over vats of solvents, to draw vapours away from the workers' breathing zone before they can disperse into the general workplace air. Enclosing the processes that generate VOCs (e.g., closed-loop solvent recovery systems) or increasing general dilution ventilation can also decrease airborne concentrations, though LEV is generally more effective for point sources. Another engineering control measure involves the use of indoor VOC abatement technologies designed to efficiently reduce or even eliminate these airborne compounds. For example, air purifiers equipped with activated carbon filters play a crucial role in controlling VOC exposure by circulating indoor air and drawing VOC particles through the activated carbon, which then adsorbs or captures them, preventing their re-release. In addition to activated carbon systems, other progressive technologies like biofiltration, other adsorption methods, and catalytic oxidation can also be employed for comprehensive VOC removal. The deployment of these abatement systems yields significant benefits by considerably reducing VOC concentrations, thereby mitigating associated health risks for occupants. The major limitations of the adsorption process are the high cost of adsorbents and the necessity for their regeneration (Kamal et al., 2016).

Unlike adsorption, which only transfers pollutants from one phase to another, catalytic decomposition can directly convert volatile organic compounds (VOCs) into carbon dioxide and water (Yibing Mu et al., 2022). Additionally, non-thermal plasma (NTP)-assisted catalysis has emerged as an attractive alternative to conventional thermally activated catalysis. Non-thermal plasma is a highly ionized gas composed of electrons, various ions, radicals, excited species, and neutral species. Its non-equilibrium nature, low energy costs, and unique ability to initiate both physical and chemical reactions at low temperatures make it particularly beneficial. Besides, the interaction between NTP and the catalyst can enhance the selectivity in the decomposition of highly stable and corrosive chlorine-containing VOCs (Cl–VOCs) when compared to using plasma alone or thermal activation systems. In addition to the engineering controls, administrative controls can be applied to modify work practices and policies to reduce exposure. This includes developing and implementing safe work procedures (e.g., keeping lids on solvent containers, using minimal quantities, proper spill clean-up), establishing restricted access zones, scheduling high-VOC tasks during periods of low

Table 2: *Key Regulatory Frameworks and Occupational Exposure Limits (OELs) for Selected VOCs.*

Regulatory Body / Region	Key Regulatory	Key Provisions / Requirements related to VOCs	Example VOC	Occupational Exposure Limit (OEL) & Type	Notes / Source for OEL Examples
International Labour Organization (ILO)	C155 - Occupational Safety and Health Convention, 1981; C170 - Chemicals Convention, 1990; ILO Code of Practice "Safety in the use of chemicals at work."	Provides foundational principles for national legislation. Emphasizes risk assessment, prevention, control of chemical hazards (including VOCs), right to information, training. Promotes hierarchy of controls.	N/A	ILO does not typically set internationally binding OELs but provides guidance, compiles international OEL lists, and promotes the establishment of national OELs.	ILO Conventions & Recommendations.
European Union (EU)	Chemical Agents Directive (98/24/EC) & subsequent amending Directives establishing OELs; REACH Regulation (EC No 1907/2006); CLP Regulation (EC No 1272/2008).	Employers must assess risks from hazardous chemical agents, implement preventive measures (hierarchy of controls), adhere to binding OELVs (BOELVs) and indicative OELVs (IOELVs). REACH: Registration, Evaluation, Authorisation & Restriction of Chemicals. CLP: Classification, Labelling and Packaging.	Benzene	0.2 ppm (0.66 mg/m³) (8-hr TWA) - BOELV (Directive (EU) 2022/431). Skin notation. Carcinogen Category 1A.	ECHA (European Chemicals Agency); Official Journal of the EU. OELs are subject to change.
			Toluene	50 ppm (192 mg/m³) (8-hr TWA); 100 ppm (384 mg/m³) (STEL) - IOELV. Skin notation.	ECHA; SCOEL (Scientific Committee on Occupational Exposure Limits) recommendations.
			Formaldehyde	0.3 ppm (0.37 mg/m³) (8-hr TWA); 0.6 ppm (0.74 mg/m³) (STEL) for healthcare, funeral, embalming sectors until July 2024, then general limit. Skin notation. Carcinogen Category 1B, Sensitizer. (Directive (EU) 2019/983).	ECHA; Official Journal of the EU.
United States (OSHA)	29 CFR 1910.1000 (Air Contaminants - Tables Z-1, Z-2); Specific substance standards (e.g., Benzene: 29 CFR 1910.1028, Formaldehyde: 29 CFR 1910.1048); 29 CFR 1910.1200 (Hazard Communication Standard - HCS).	Sets Permissible Exposure Limits (PELs). Mandates hazard communication (Safety Data Sheets, labels, training). Requires engineering controls, work practices, and PPE. Specific standards often include medical surveillance and exposure monitoring.	Benzene	1 ppm (8-hr TWA); 5 ppm (STEL) - OSHA PEL (29 CFR 1910.1028). Action Level: 0.5 ppm.	OSHA website (www.osha.gov). PELs may differ from other recommended limits (e.g., NIOSH RELs, ACGIH TLVs).
			Xylene (mixed isomers)	100 ppm (435 mg/m³) (8-hr TWA) - OSHA PEL (Table Z-1).	OSHA website.
			Trichloroethylene (TCE)	100 ppm (8-hr TWA); 200 ppm (Ceiling); 300 ppm (5-min Peak in any 2 hrs) - OSHA PEL (Table Z-2). OSHA is considering lowering this PEL.	OSHA website. Note: TCE is a known carcinogen.
India	The Factories Act, 1948 (and associated State Factories Rules). The Manufacture, Storage and Import of Hazardous Chemical Rules, 1989 (MSIHC Rules).	Sec 41F (general duties of occupier for health), Sch II of Factories Act (permissible levels of exposure), Sec 13 (ventilation), Sec 36 (dangerous fumes), Sec 35 (PPE). MSIHC rules mandate safety reports, on-site emergency plans.	Benzene	5 ppm (16 mg/m³) (8-hr TWA) - Schedule II, The Factories Act. Carcinogen.	The Factories Act, 1948,

occupancy or at the end of shifts, providing comprehensive worker training on VOC hazards and safe handling, and implementing job rotation to limit individual exposure durations. Finally, as the last line of defence, Personal Protective Equipment (PPE) is used when other controls cannot sufficiently reduce exposure. For VOCs, it is crucial to select appropriate respiratory protection, e.g., air-purifying respirators with organic vapor cartridges specific to the VOCs present or supplied-air respirators for high concentrations or oxygen-deficient environments. For selecting other PPEs such as chemical-resistant gloves, aprons, and eye protection (e.g., goggles, face shields) one must ensure that these are made from materials impervious to the specific VOCs being handled. The effectiveness of PPEs relies heavily on proper selection, fit, maintenance, and consistent, correct use by employees, underscoring why it is the last rung control measure in the hierarchy of control framework.

Legal and Regulatory Obligations Related to Occupational VOC Exposure

Internationally, organizations like the International Labour Organization (ILO) establish conventions (e.g., ILO, 1981, C155 -Occupational Safety and Health Convention) and recommendations outlining fundamental principles for national legislations, and emphasizing risk assessment, prevention, and control of chemical hazards, including VOCs. Highly industrialized countries, in general, have strong regulatory frameworks. European Union's Chemical Agents Directive (Council Directive 98/24/EC) mandates assessment of risks from hazardous chemical agents, implementation of preventive measures based on the hierarchy of controls, and compliance with obligatory occupational exposure limit values (OELVs) for specific VOCs. Similarly, the U.S. Occupational Safety and Health Administration (OSHA) provides Permissible Exposure Limits (PELs) for numerous airborne contaminants, many of which are VOCs (e.g., under 29 CFR 1910.1000), and mandates hazard communication (29 CFR 1910.1200). In India, the primary legislation governing OHS, including chemical exposure, is The Factories Act, 1948, along with the accompanying State Factories Rules, which may vary, to some extent, from state to state. Section 41F of the Factories Act outlines the general duties of the occupier to ensure the health of workers, which implicitly includes protection from harmful chemical exposures. More explicitly, Schedule II of The Factories Act, 1948 lists permissible levels of exposure for various toxic substances, many of which are common VOCs (e.g., benzene, toluene, xylene, trichloroethylene), serving as India's OELs. The Act also mandates provisions for effective ventilation measures for protection against dangerous fumes and gases (Section 13, Section 36), the supply of suitable personal protective equipment (Section 35) when hazards cannot be otherwise controlled, and administrative controls such as health monitoring of workers. Therefore, both globally and within India, the regulatory system expects the establishment to identify VOC hazards, assess risks, implement controls, monitor exposure levels, and train workers to ensure a safe working environment. The table 2 provides a summary of important regulatory frameworks and occupational exposure limits thereof.

Conclusion

Volatile Organic Compounds, emanating from diverse sources, ranging from industrial processes to everyday workplace products may present significant implications for both human health and the environment. Occupational exposure to VOCs can affect the health adversely and thus a comprehensive understanding and assessment of the potential VOC hazards is necessary for the implementation of proactive OHS management strategies. In accordance with the hierarchy of controls strategies, prioritizing elimination and substitution over other measures, wherever feasible, and diligently employing engineering and administrative measures can contribute to significant reduction in the workplace VOC exposure. Various national and international level legal and regulatory frameworks provide the standards and guidelines for monitoring, control, and worker protection vis-à-vis VOC exposure. Effective management of VOCs is not only a regulatory compliance but a commitment for workplace safety and well-being of occupational workers.

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