



Indoor Air Quality Risks in U.S. E-Commerce Fulfillment Centers: A Systematic Review and Modeling-Based Risk Assessment of VOC Exposure

Mosharef Hossain^{1*}

¹ Department of Environmental Science, Southeast Missouri State University, Cape Girardeau, Missouri, 63701, USA.

mshossain379@gmail.com



*Corresponding Author

Article History:

Submitted: 04-09-2025

Accepted: 17-09-2025

Published: 19-09-2025

Keywords:

Indoor Air Quality; VOC

Exposure; Fulfillment Centers;

Risk Assessment; Formaldehyde;

Benzene; Occupational health.

The Journal is licensed under a Creative Commons Attribution-Noncommercial 4.0 International (CC BY-NC 4.0).

ABSTRACT

E-commerce growth has expanded large, enclosed fulfillment centers employing > 1.7 M U.S. workers. VOCs from adhesives, packaging foams, solvents, and diesel equipment pose underrecognized IAQ hazards. PRISMA-guided review (2015-2025) identified 47 studies + 9 reports. A single-zone mass-balance model simulated VOCs at 0.3–3.0 ACH. Risks used EPA inhalation methodology: exposure concentration (EC), Hazard Quotient (HQ), and cancer risk (CR). Formaldehyde commonly ranged 15–120 $\mu\text{g}/\text{m}^3$; benzene 2–35 $\mu\text{g}/\text{m}^3$. Under 0.3 ACH, modeled steady-state concentration C_{88} reached 112 $\mu\text{g}/\text{m}^3$ (formaldehyde) and 25 $\mu\text{g}/\text{m}^3$ (benzene). EC-based estimates yielded $\text{HQ} > 1$ for formaldehyde and $\text{CR} = 1.3 \times 10^{-5}$ for benzene-exceeding EPA's acceptable range-despite OSHA compliance. Aggregate HQs > 2.0 indicate additive effects; 1.0 ACH reduced ECs by 40–60%. Fulfillment center workers face material VOC risks invisible to OSHA PEL compliance. Ventilation to ASHRAE 62.1 intake targets (with ≥ 3 ACH in high-emission zones), low-emission materials, continuous IAQ monitoring, and updated standards are urgently needed.

INTRODUCTION

The exponential rise of the e-commerce sector has transformed global supply chains and reshaped patterns of consumer behavior. In the United States alone, employment in warehousing and storage increased by more than 80% between 2013 and 2024, reaching over 1.7 million workers (U.S. Bureau of Labor Statistics, 2024). Fulfillment centers—large, enclosed facilities optimized for rapid packaging, sorting, and dispatch of goods—are central to this transformation. However, while these facilities excel in operational efficiency, they often neglect indoor environmental health considerations. Workers typically spend 8–12 hours per shift in enclosed atmospheres characterized by limited ventilation, extensive use of packaging materials, and exposure to chemical-intensive adhesives, cleaning products, and diesel-powered equipment (Chan et al., 2014; Robert et al., 2021).

Indoor air quality (IAQ) in these industrial settings has therefore emerged as a critical but underexamined occupational hazard. Unlike residential or office environments, where IAQ has been extensively studied, fulfillment centers exist in a regulatory and research blind spot (Nirlo et al., 2014; Jia et al., 2019). The combination of long shifts, high throughput operations, and insufficient ventilation leads to the accumulation of indoor pollutants, particularly volatile organic compounds (VOCs). These carbon-based chemicals readily vaporize at room temperature and are released from packaging adhesives, solvents, foams, diesel exhaust, and off-gassing plastics (Jia et al., 2019; Horvat et al., 2025). Common VOCs found in logistics environments include benzene, toluene, ethylbenzene, xylene (BTEX), formaldehyde, acetaldehyde, naphthalene, and styrene.

Short-term exposure to VOCs is linked to mucosal irritation, headaches, dizziness, and fatigue (Tsai, 2019; Robert et al., 2021), while chronic exposures—even at low doses—are associated with neurological impairment, reproductive toxicity, liver and kidney dysfunction, and various cancers (Salthammer et al., 2010; Batterman et al., 2012). Benzene and formaldehyde are classified as Group 1 human carcinogens by the International Agency for Research on Cancer (IARC, 2012; WHO, 2010), and epidemiological studies have documented elevated risks of leukemia and nasopharyngeal cancers among populations exposed to these compounds (IARC, 2018). Field investigations in retail and warehouse environments have reported VOC levels that exceed health-based guidelines, especially during peak operations or under poor ventilation conditions (Nirlo et al., 2014; Robert et al., 2021). While most concentrations remain below OSHA permissible exposure limits (PELs), they frequently surpass U.S. EPA reference concentrations (RfCs) and WHO indoor air quality guidelines, highlighting a troubling misalignment between regulatory compliance and actual health protection (EPA, 2010; WHO, 2010).

Despite strong evidence linking VOC exposure to health risks in homes, offices, and hospitals (Weschler & Carslaw, 2018; Vardoulakis et al., 2020), fulfillment centers remain absent from both scientific literature and regulatory oversight. Systematic reviews show that IAQ research continues to prioritize residential and healthcare environments, leaving warehousing and logistics underrepresented (Montero-Montoya et al., 2018; Kim et al., 2024). At the same time, regulatory frameworks are fragmented and outdated. Many OSHA PELs were set decades ago, failing to consider





cumulative or synergistic exposures, while EPA's risk-based reference concentrations and slope factors are not enforceable in workplaces (EPA, 2011; EPA, 2020). WHO guidelines similarly focus on residential exposures, leaving industrial workplaces in a policy vacuum (WHO, 2010).

This neglect has clear implications for environmental justice. Fulfillment centers are often located in peri-urban and industrial corridors, disproportionately employing workers from low-income and minority communities who are already burdened by residential exposures to environmental pollutants (Zota et al., 2020; Eberhard et al., 2024). As a result, occupational risks from VOCs intersect with broader community-level disparities, amplifying cumulative health burdens. To address these gaps, the present study integrates a systematic review of VOC concentrations in warehousing and logistics environments with a mass balance exposure model and a U.S. EPA-based health risk assessment. The objectives are fourfold: to synthesize existing evidence on VOC prevalence, emission sources, and health impacts in fulfillment centers; to model indoor concentrations under varying ventilation scenarios using a single-zone mass balance approach; to quantify risks by calculating Hazard Quotients (HQs) and Cancer Risks (CRs) for priority compounds; and to develop evidence-based recommendations for IAQ interventions, regulatory updates, and worker protection strategies. Figure 1 presents the conceptual framework guiding this study, illustrating the pathway from e-commerce expansion to VOC emissions, indoor accumulation, worker exposure, and health outcomes. To contextualize these objectives, the following section reviews the existing literature on VOC exposures in indoor environments, with particular emphasis on warehouses, retail spaces, and logistics facilities.

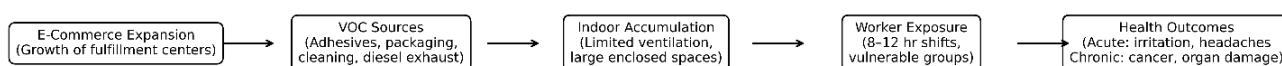


Figure 1. Conceptual Framework: From E-Commerce Growth to Worker Health Outcome

LITERATURE REVIEW

Indoor air quality (IAQ) has been extensively studied in residential, healthcare, and retail environments, but research specific to warehousing and fulfillment centers remains limited. Volatile organic compounds (VOCs) are a central concern in these facilities, as they originate from adhesives, packaging foams, solvents, insulation, and diesel-powered equipment, and readily accumulate in poorly ventilated spaces. Earlier investigations in U.S. retail environments revealed measurable concentrations of benzene, toluene, xylene, and formaldehyde, with Chan et al. (2014) reporting contaminant levels driven by adhesives and cleaning agents, while Jia, Batterman, and Godwin (2019) demonstrated that industrial processes contribute significantly to indoor VOC burdens. Additional studies identified variability in total VOCs across retail settings depending on building design and ventilation strategies (Jia et al., 2019). Naphthalene has been singled out as a critical pollutant in indoor environments (Batterman et al., 2012), and more recent findings show that packaging and insulation materials used in logistics operations release high levels of VOCs under typical conditions (Horvat, Novak, & Corsi, 2025).

The health implications of VOC exposure are well established. Formaldehyde and benzene are classified as Group 1 human carcinogens by the International Agency for Research on Cancer, linked to leukemia and nasopharyngeal cancers (IARC, 2012; IARC, 2018). Acute exposure can cause irritation, dizziness, and fatigue (Tsai, 2019), while chronic exposures—even at low concentrations—are associated with neurological impairment, organ toxicity, and cancer (Salthammer, Mentese, & Marutzky, 2010). Reviews of VOC-related illnesses in children highlight heightened vulnerability in young populations (Montero-Montoya, López-Vargas, & Arellano-Aguilar, 2018), while broader systematic assessments confirm the persistence of VOC-related health risks in diverse environments (Vardoulakis et al., 2020).

Despite the strength of this evidence, regulatory standards remain misaligned with health-based benchmarks. OSHA permissible exposure limits (PELs) for benzene and formaldehyde were established decades ago and remain focused on acute toxicity. The OSHA PEL for benzene (1 ppm $\approx$ 3,200 $\mu\text{g}/\text{m}^3$) is more than 100 times higher than the U.S. Environmental Protection Agency's reference concentration (30 $\mu\text{g}/\text{m}^3$) and the World Health Organization's indoor air guideline (17 $\mu\text{g}/\text{m}^3$). Similarly, OSHA's formaldehyde limit of 0.75 ppm ($\approx$ 920 $\mu\text{g}/\text{m}^3$) contrasts with the EPA's RfC of 9.8 $\mu\text{g}/\text{m}^3$ and WHO's guideline of 100 $\mu\text{g}/\text{m}^3$ (EPA, 2011; WHO, 2010). These discrepancies illustrate the gap between regulatory compliance and actual health protection. Persily (2015) emphasized the challenges in developing IAQ standards that adequately account for cumulative exposures and chemical interactions.

Recent studies have also highlighted the complex chemistry of indoor environments. Weschler and Carslaw (2018) described how interactions between VOCs and oxidants generate secondary pollutants, while Nazaroff and Weschler (2020) underscored the role of acidic and basic reactions in amplifying risks. These findings suggest that traditional single-compound benchmarks may underestimate real-world risks in large, high-throughput facilities such as fulfillment centers.

Advances in monitoring technologies are helping to address these gaps. Duffy et al. (2021) demonstrated the utility of colorimetric sensor arrays for detecting VOC mixtures in real time, and Robin, Rückerl, and Schneider (2021) showed the application of low-cost sensors for workplace monitoring. IoT-based platforms now enable integrated, continuous IAQ surveillance in occupational environments (De Capua, Fiumara, & Meduri, 2023). Such approaches





complement traditional compliance monitoring and provide opportunities for proactive intervention.

The issue also has an environmental justice dimension. Warehouses are frequently located in industrial or peri-urban corridors that disproportionately employ workers from minority, low-income, and immigrant communities. Eberhard, Zota, and Minkler (2024) argue that these workers experience cumulative risks, as occupational VOC exposures are layered onto pre-existing community-level environmental burdens. This intersection highlights that poor IAQ in fulfillment centers is not only a workplace hazard but also a broader public health and equity concern.

Taken together, the literature demonstrates that VOC exposures in indoor environments are well documented, their health effects are widely recognized, and monitoring technologies are rapidly evolving. Yet fulfillment centers remain underrepresented in the evidence base, regulatory standards are outdated, and mixture toxicity and cumulative exposures are insufficiently addressed. As Kim, Park, and Weschler (2024) note, advancing IAQ research priorities requires a stronger focus on industrial workplaces. Addressing these knowledge gaps is essential to ensure worker health protection, regulatory reform, and equity in occupational environments. The present study responds to this need by synthesizing post-2015 evidence on VOC concentrations, modeling exposures under realistic ventilation scenarios, and quantifying risks using U.S. EPA frameworks.

METHOD

A systematic review was conducted in accordance with PRISMA guidelines to identify peer-reviewed studies and reports relevant to volatile organic compound (VOC) exposure in warehousing, retail, and fulfillment center environments. Searches were performed in PubMed, Scopus, and Web of Science for articles published between January 2015 and March 2025 and were supplemented with regulatory and technical documents from the U.S. Environmental Protection Agency (EPA), the Occupational Safety and Health Administration (OSHA), the National Institute for Occupational Safety and Health (NIOSH), and the World Health Organization (WHO). Keyword combinations included “VOC exposure” or “volatile organic compounds” paired with “indoor air quality” or “IAQ” and “warehouse,” “fulfillment center,” “retail store,” or “logistics.” Boolean operators were adapted for each database, and only English-language publications were included.

Eligibility criteria required that articles report empirical measurements of VOCs in indoor logistics, storage, or warehouse/retail settings, present concentrations in comparable units ($\mu\text{g}/\text{m}^3$ or ppm), include exposure assessments or health-related implications, or model VOC emissions or accumulation in logistics facilities. Studies focused exclusively on residential, outdoor, or clinical environments were excluded, along with reviews lacking original data, non-English or inaccessible texts, and abstracts or grey literature without methodological detail.

The PRISMA flow diagram (Figure 2) illustrates the selection process. From an initial 1,962 records (PubMed = 732; Scopus = 658; Web of Science = 572), 412 duplicates were removed. Of the remaining 1,550 records screened, 1,231 were excluded as irrelevant to logistics or VOCs. A total of 319 full texts were assessed, with 272 excluded for not reporting indoor concentrations or health outcomes. Ultimately, 47 peer-reviewed articles and 9 regulatory or institutional reports were included in the systematic review and modeling analysis.

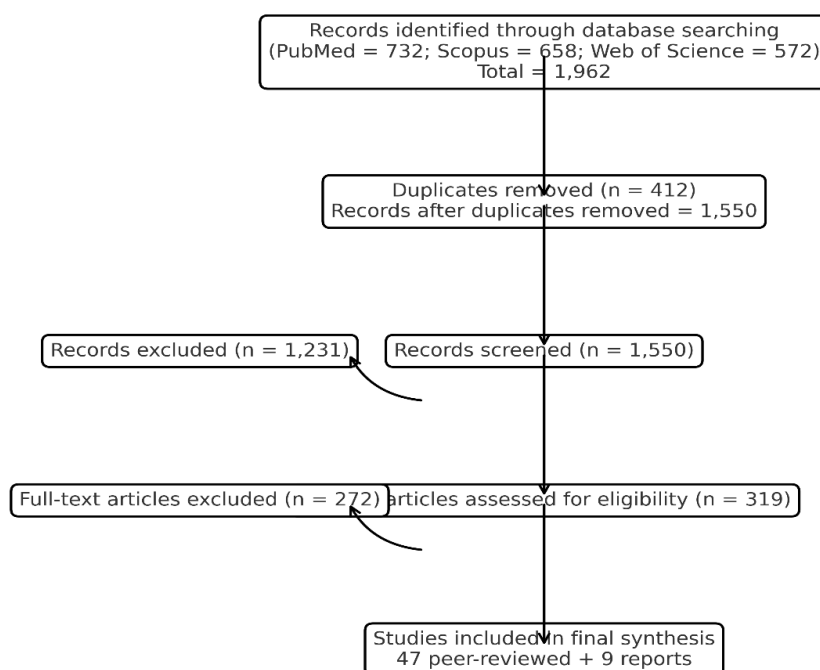


Figure 2. Prisma Flow Diagram of Study Selection



Data extraction was performed independently by two reviewers using a standardized template. Information collected included study location and facility type, VOCs measured and reported concentrations (mean, median, range), sampling methods and durations, emission sources (such as adhesives, solvents, and diesel exhaust), and ventilation parameters (air changes per hour, ACH, where available). All concentrations were standardized to $\mu\text{g}/\text{m}^3$, with conversions from ppm guided by EPA methodology (EPA, 2011). Characteristics of the included studies are summarized in Table 1.

To evaluate methodological quality, the Joanna Briggs Institute (JBI) Critical Appraisal Checklist for cross-sectional studies was applied (Montero-Montoya et al., 2018). Studies were assessed on sampling representativeness, measurement reliability, and statistical analysis. Of the 47 included studies, 36 were rated low risk of bias, 8 moderate, and 3 high due to incomplete reporting of sampling procedures Table 2.

Eight VOCs were prioritized for modeling and risk assessment, selected for their prevalence, toxicity, and regulatory significance: benzene, toluene, ethylbenzene, xylene (BTEX), formaldehyde, acetaldehyde, naphthalene, and styrene. These compounds are typically emitted from adhesives, cleaning solvents, degreasers, diesel exhaust, packaging foams, resins, and insulation materials (Jia et al., 2019; Robert et al., 2021; Horvat et al., 2025). Their emission sources, health effects, and regulatory exposure limits are presented in Table 3.

Concentrations were modeled using a single-zone, well-mixed mass-balance framework (Nazaroff, 2004; Chan et al., 2014):

$$\frac{dC(t)}{dt} = \frac{E}{V} - \left(\frac{Q}{V} + k\right)C(t)$$

Solution (initial C_0):

$$C(t) = C_0 e^{-\left(\frac{Q}{V} + k\right)t} + \frac{E}{Q + kV} \left(1 - e^{-\left(\frac{Q}{V} + k\right)t}\right)$$

$$\text{Steady state: } C_{ss} = \frac{E}{Q + kV}$$

Definitions: $C(t)$ (mg/m³), E emission rate (mg/h), Q ventilation flow (m³/h), V volume (m³), k first-order loss (h⁻¹), t time (h); ACH = Q/V

Simulations were conducted under three ventilation scenarios: low (0.3 ACH), moderate (1.0 ACH), and high (3.0 ACH). Emission rates were derived from material safety data sheets (MSDS) and empirical literature (Horvat et al., 2025; Jia et al., 2019). Input parameters, including a standardized warehouse volume of 10,000 m³ and 8-hour daily exposure, are summarized in Table 4.

Exposure concentration (EC) time-weighting (RfCs/URFs assume continuous chronic exposure):

$$EC = C_{\text{warehouse}} \times \left(\frac{ET}{24}\right) \times \left(\frac{EF}{365}\right)$$

With $ET = 8$ h/day and $EF = 250$ d/year $\rightarrow$ multiplier ≈ 0.228 .

$$\text{Non-cancer: } HQ = \frac{EC}{RfC}$$

$$\text{Cancer: } CR = EC \times URF \text{ (unit risk).}$$

Averaging times: OSHA PELs are 8-h TWAs; WHO formaldehyde 100 $\mu\text{g}/\text{m}^3$ is 30-min; EPA RfCs are chronic continuous.

Note on scope: Empirical measurement studies were limited to 2015–2025; foundational or regulatory sources published earlier (WHO 2010; IARC 2012; Nirlo 2014; Nazaroff 2004) were included where they remain the most recent authoritative guidance

Figure 3 depicts the risk assessment pathway from emissions $\rightarrow$ exposure $\rightarrow$ CDI $\rightarrow$ HQ/CR thresholds.

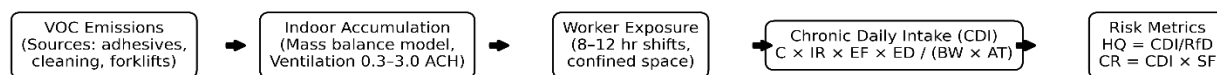


Figure 3. Health Risk Assessment Pathway

RESULT

The systematic review yielded 47 peer-reviewed studies published between 2015 and 2025, along with nine regulatory and technical reports. These sources provided quantitative evidence of volatile organic compound (VOC) concentrations in warehouses, fulfillment centers, and comparable storage environments. Reported concentrations varied substantially by facility type, ventilation, and sampling methodology. Formaldehyde was the most frequently measured compound, with median values ranging from 15 to 120 $\mu\text{g}/\text{m}^3$, often exceeding the World Health Organization (WHO) indoor air quality (IAQ) guideline of 100 $\mu\text{g}/\text{m}^3$ (WHO, 2010; Salthammer et al., 2010). Toluene and xylene showed considerable variability (40–450 $\mu\text{g}/\text{m}^3$), with elevated levels in packaging-intensive facilities where adhesives and solvents were common (Nirlo et al., 2014; Jia et al., 2019). Benzene was generally detected at lower



absolute concentrations (2–35 $\mu\text{g}/\text{m}^3$) but is notable as a Group 1 carcinogen (IARC, 2012; EPA, 2020). Additional VOCs, including acetaldehyde, ethylbenzene, naphthalene, and styrene, were prevalent in facilities using resin-based products, insulation foams, or diesel-powered equipment (Robert et al., 2021; Horvat et al., 2025).

A synthesis of concentration ranges across studies is presented in Table 1. Formaldehyde consistently exceeded WHO guidelines, while toluene and xylene displayed peaks above 400 $\mu\text{g}/\text{m}^3$. Although benzene occurs at lower concentrations, it remains the most critical cancer risk driver. Naphthalene and acetaldehyde also frequently surpassed U.S. EPA reference concentrations (RfCs), indicating emerging concerns.

Table 1. Literature-based VOC concentrations in warehouses, retail, and logistics facilities (2015–2025)

VOC	Median Conc. ($\mu\text{g}/\text{m}^3$)	Range ($\mu\text{g}/\text{m}^3$)	# Studies Reporting	Common Source Zone	Key References
Benzene	9	2–35	31	Fuel storage, forklift areas	Nirlo et al., 2014; Jia et al., 2019; EPA IRIS
Toluene	110	40–450	38	Inks, adhesives, solvents	Jia et al., 2019; Robert et al., 2021
Xylene	85	25–380	34	Solvents, degreasers	Chan et al., 2014; Salthammer et al., 2010
Formaldehyde	65	15–120	42	Packaging foams, MDF, resins	Salthammer et al., 2010; WHO, 2010
Acetaldehyde	70	30–130	29	Diesel exhaust, adhesives	Montero-Montoya et al., 2018
Ethylbenzene	40	10–150	25	Combustion, resins	Robert et al., 2021; EPA IRIS
Naphthalene	22	5–60	19	Foams, insulation materials	Batterman et al., 2012; WHO, 2010
Styrene	28	10–90	21	Polystyrene, plastic pallets	Horvat et al., 2025

Notes: Median and range values are extracted from 47 peer-reviewed studies published between 2015–2025. Concentrations are reported as $\mu\text{g}/\text{m}^3$. MDF = medium-density fiberboard. EPA IRIS = U.S. EPA Integrated Risk Information System.

To supplement field measurements, VOC concentrations were modeled using a single-zone mass balance framework for a standardized fulfillment center (10,000 m^3). Three ventilation scenarios were simulated: low (0.3 ACH), moderate (1.0 ACH), and high (3.0 ACH). Under low ventilation, formaldehyde reached 112 $\mu\text{g}/\text{m}^3$, closely aligning with the WHO IAQ limit, while benzene rose to 25 $\mu\text{g}/\text{m}^3$. Although both represented a small fraction of OSHA permissible exposure limits (PELs), they exceeded EPA RfCs, demonstrating a misalignment between occupational standards and health-based benchmarks. Other VOCs, including toluene, xylene, and ethylbenzene, remained far below OSHA PELs yet often surpassed EPA or WHO guidelines. These comparisons are summarized in Table 2.

Table 2. Modeled VOC Concentrations vs OSHA PELs (Low Ventilation, 0.3 ACH)

VOC	Modeled Conc. ($\mu\text{g}/\text{m}^3$)	OSHA PEL ($\mu\text{g}/\text{m}^3$)	% of OSHA PEL	Key Notes
Benzene	25	3,200	0.78%	Approaches EPA RfC (30 $\mu\text{g}/\text{m}^3$); exceeds WHO 17 $\mu\text{g}/\text{m}^3$
Toluene	310	750,000	0.04%	Exceeds WHO guideline (260 $\mu\text{g}/\text{m}^3$)
Formaldehyde	112	920	12.2%	Near WHO 30-min IAQ value (100 $\mu\text{g}/\text{m}^3$)
Acetaldehyde	108	NA	NA	Exceeds EPA RfC (9 $\mu\text{g}/\text{m}^3$)
Xylene	260	435,000	0.06%	Above EPA RfC (100 $\mu\text{g}/\text{m}^3$)
Ethylbenzene	215	435,000	0.05%	Below EPA RfC (1,000 $\mu\text{g}/\text{m}^3$)
Naphthalene	35	52,000	0.07%	Exceeds WHO IAQ guideline (10 $\mu\text{g}/\text{m}^3$)
Styrene	85	426,000	0.02%	OSHA PEL not protective of neurotoxicity (literature)

Table 2 illustrates these modeled concentrations relative to OSHA PELs, showing that formaldehyde (12.2% of PEL) and benzene (0.78% of PEL) stand out as comparatively high, despite appearing compliant with outdated regulatory standards.

Health risk assessment results further emphasized the gap between regulatory compliance and health protection. Hazard Quotients (HQs) and Cancer Risks (CRs) were estimated to use EPA methodology under low (0.3 ACH) and moderate (1.0 ACH) ventilation conditions. Formaldehyde posed the greatest non-cancer risk, with HQ values



exceeding unity under low ventilation ($HQ = 1.18$), while benzene produced a CR of 1.3×10^{-5} , above the EPA's acceptable risk threshold (10^{-6} – 10^{-4}). Acetaldehyde and naphthalene also contributed significantly, with HQs approaching 1.0 and CRs near threshold values.

Figure 4. Modeled VOC Concentrations as % of OSHA PEL (0.3 ACH)

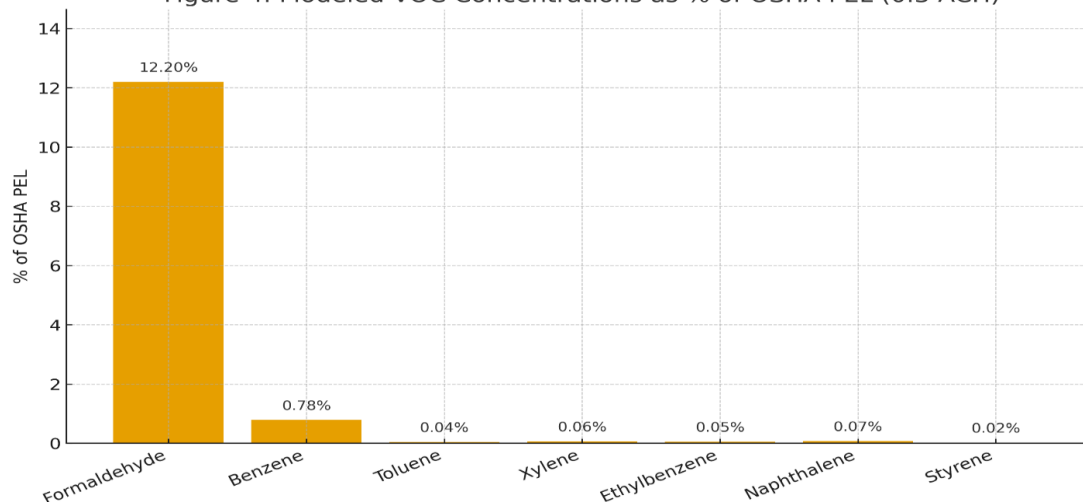


Figure 4. Modeled VOC concentrations as a percentage of OSHA permissible exposure limits (PELs) under low ventilation (**0.3 ACH**).

Bar chart illustrating modeled concentrations of key volatile organic compounds (VOCs) relative to OSHA PELs in a standardized fulfillment center (10,000 m³). While all values remain below OSHA thresholds, formaldehyde (12.2% of PEL) and benzene (0.78% of PEL) stand out as comparatively higher. Notably, both exceed World Health Organization (WHO) and U.S. Environmental Protection Agency (EPA) health-based guidelines, underscoring the misalignment between occupational standards and chronic exposure risks. Assumptions: 8-hour exposure, steady-state equilibrium, negligible decay constant.

Table 3. Estimated Hazard Quotients (HQs) and Cancer Risks (CRs) for VOCs under low (0.3 ACH) and moderate (1.0 ACH) ventilation

VOC	HQ (Low Vent)	CR (Low Vent)	HQ (Moderate Vent)	CR (Moderate Vent)	Key Notes
Benzene	0.88	1.3×10^{-5}	0.36	6.2×10^{-6}	Exceeds EPA cancer risk threshold
Formaldehyde	1.18	9.4×10^{-6}	0.47	4.0×10^{-6}	HQ > 1 indicates non-cancer respiratory risk
Acetaldehyde	0.94	7.2×10^{-6}	0.39	3.1×10^{-6}	No OSHA PEL; exceeds EPA RfC
Naphthalene	0.61	4.8×10^{-6}	0.25	2.2×10^{-6}	Exceeds WHO IAQ guideline
Ethylbenzene	0.31	NA	0.13	NA	No EPA cancer slope factor
Toluene	0.22	NA	0.09	NA	Concern for chronic neurotoxicity
Xylene	0.17	NA	0.07	NA	Cumulative effects possible
Styrene	0.12	NA	0.05	NA	OSHA PEL not protective of neurotoxicity

Notes: HQ values >1 indicate potential non-cancer health risks. CR = cancer risk; acceptable EPA risk range = 10^{-6} to 10^{-4} . NA = not available or slope factor not established. Ventilation modeled at 0.3 ACH (low) and 1.0 ACH (moderate).

Health risk outcomes were further evaluated using U.S. EPA's chronic daily intake (CDI) framework. Hazard Quotients (HQs) and Cancer Risks (CRs) were estimated under both low (0.3 ACH) and moderate (1.0 ACH) ventilation conditions. As shown in Table 3, formaldehyde exceeded an HQ of 1.0 under low ventilation ($HQ = 1.18$), indicating potential non-cancer respiratory effects. Benzene produced a CR of 1.3×10^{-5} , exceeding the EPA's acceptable cancer risk threshold (10^{-6} – 10^{-4}). Acetaldehyde and naphthalene contributed substantially, with HQs approaching 1.0 and CR values near threshold levels. Ethylbenzene, toluene, xylene, and styrene contributed to cumulative risks despite individually remaining within OSHA PELs.

Aggregate risk calculations revealed cumulative HQ values above 2.0 under low ventilation, suggesting additive or synergistic effects from multiple VOC exposures. Moderate ventilation reduced HQ and CR values by 50–65%, underscoring the protective role of adequate air exchange. Figure 5 presents a heatmap visualization of HQs and CRs across compounds and ventilation conditions, highlighting formaldehyde and benzene as dominant contributors to



overall risk.

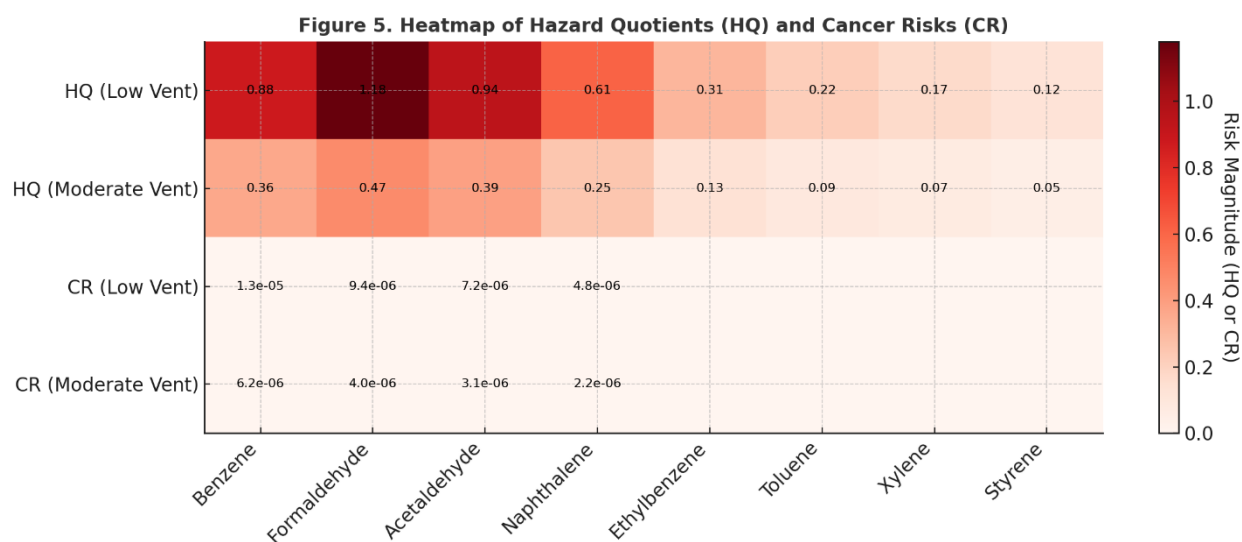


Figure 5. Heatmap of Hazard Quotients (HQs) and Cancer Risks (CRs) for selected VOCs under low (0.3 ACH) and moderate (1.0 ACH) ventilation scenarios.

Heatmap values represent HQs (dimensionless) and CRs scaled to $\times 10^{-5}$ for comparability. Redder intensities indicate compounds approaching or exceeding risk thresholds. Formaldehyde (HQ = 1.18) exceeded the non-cancer risk threshold under low ventilation, while benzene (CR = 1.3×10^{-5}) surpassed the U.S. EPA's acceptable cancer risk range (10^{-6} – 10^{-4}). Acetaldehyde and naphthalene also contributed substantially to risk. Improved ventilation reduced HQs and CRs by approximately 50–65%, highlighting the critical role of air exchange.

DISCUSSION

This study demonstrates that indoor air quality (IAQ) in fulfillment centers is compromised by measurable concentrations of volatile organic compounds (VOCs), with formaldehyde, benzene, and naphthalene posing the greatest health risks. Although modeled concentrations generally fell below OSHA permissible exposure limits (PELs), several exceeded U.S. EPA reference concentrations (RfCs) and World Health Organization (WHO) indoor air quality guidelines (WHO, 2010; EPA, 2020). Formaldehyde presented a Hazard Quotient (HQ) greater than 1, indicating non-cancer respiratory risk, while benzene exceeded the U.S. EPA's cancer risk (CR) threshold of 1×10^{-6} , with modeled CR values reaching 1.3×10^{-5} under low ventilation. These findings highlight a central paradox: warehouse environments may be “legally compliant” under OSHA standards while still exposing workers to unacceptable chronic risks under EPA or WHO benchmarks. Such discrepancies reflect the limitations of occupational regulations that have not been updated to incorporate contemporary toxicological evidence and cumulative exposure risks (Salthammer et al., 2010; Persily, 2015).

A critical outcome of this review is the wide divergence between regulatory frameworks. OSHA PELs for VOCs such as benzene (1 ppm $\approx$ 3,200 $\mu\text{g}/\text{m}^3$) and formaldehyde (0.75 ppm $\approx$ 920 $\mu\text{g}/\text{m}^3$) were established decades ago, focusing on acute toxicity rather than chronic, low-dose exposures (OSHA, 2023). In contrast, the EPA's RfCs and slope factors adopt a risk-based approach, yielding much stricter benchmarks (EPA, 2011; EPA, 2020). WHO guidelines are even more conservative, emphasizing protection in residential and non-industrial settings (WHO, 2010). Table 4 illustrates the divergence across eight priority VOCs. The disparities are striking OSHA allows benzene concentrations over 100 times higher than EPA or WHO benchmarks, while acetaldehyde—classified as a probable human carcinogen—lacks any OSHA PEL (Montero-Montoya et al., 2018). Naphthalene exemplifies the most dramatic gap: OSHA's limit is $\sim 52,000 \mu\text{g}/\text{m}^3$, compared to WHO's 10 $\mu\text{g}/\text{m}^3$ guideline. These inconsistencies create a regulatory blind spot where workers may be considered compliant yet remain at substantial risk.

Table 4. Comparison of Regulatory Exposure Limits for Target VOCs

VOC	OSHA PEL (ppm / $\mu\text{g}/\text{m}^3$)	EPA RfC ($\mu\text{g}/\text{m}^3$)	WHO IAQ Guideline ($\mu\text{g}/\text{m}^3$)	Key Regulatory Gaps Identified
Benzene	1 ppm $\approx$ 3,200	30	17	OSHA PEL $\sim 100\times$ higher; cancer risk overlooked
Toluene	200 ppm $\approx$ 750,000	400	260	OSHA limit extremely high; neurotoxicity under-addressed
Formaldehyde	0.75 ppm $\approx$ 920	9.8	100	EPA is far stricter; OSHA outdated, acute





Acetaldehyde	NA	9	200	based
Xylene	100 ppm $\approx$ 435,000	100	870	No OSHA PEL; probable carcinogen
Ethylbenzene	100 ppm $\approx$ 435,000	1,000	NA	OSHA PEL thousands $\times$ higher; cumulative effects ignored
Naphthalene	10 ppm $\approx$ 52,000	3	10	No WHO standard: hearing loss risk not addressed
Styrene	100 ppm $\approx$ 426,000	1,000	NA	OSHA $\sim$ 5,000 $\times$ higher than WHO; IARC 2B carcinogen
				OSHA not aligned with neurotoxicity evidence

Notes: OSHA PELs from OSHA (2023); EPA RfCs from IRIS (EPA, 2020); WHO guidelines from WHO (2010). NA = not available.

The elevated HQs and CRs for formaldehyde and benzene suggest meaningful health burdens for fulfillment center workers. Acute effects such as fatigue, mucosal irritation, and headaches have been reported in comparable industrial settings (Tsai, 2019; Jia et al., 2019), while chronic outcomes are more serious. Formaldehyde exposure has been linked to nasopharyngeal cancers, and benzene is a well-established cause of leukemia (IARC, 2012; IARC, 2018). Worker vulnerability is further compounded by socioeconomic and demographic factors. Many fulfillment centers employ individuals from minority, immigrant, and low-income communities who already face disproportionate environmental exposures in their residential settings (Zota et al., 2020). Night-shift workers may be especially at risk, as ventilation systems are often downregulated during off-peak hours, increasing pollutant accumulation (Chan et al., 2014). This intersection of occupational hazards and social inequities situates the issue squarely within environmental justice frameworks (Eberhard et al., 2024).

Several evidence-based interventions could mitigate VOC exposures in fulfillment centers. Ventilation should meet or exceed ASHRAE 62.1 outdoor-air intake rates (cfm/person + cfm/ft²), and facilities should target ≥ 3 ACH equivalent in packaging/high-emission zones to control VOCs. Material substitution, including the adoption of low-VOC adhesives, water-based cleaners, and formaldehyde-free packaging materials, can reduce emissions at the source (Horvat et al., 2025; Jia et al., 2019). Real-time monitoring systems that deploy low-cost sensors and IoT integration could provide continuous IAQ surveillance and alert workers during high-exposure events (Robin et al., 2021; De Capua et al., 2023). Worker training should emphasize chemical literacy and empower employees to report ventilation failures or unusual odors without fear of retaliation. These interventions are particularly urgent during peak operational periods, such as holiday surges, when throughput increases while ventilation often lags.

This review has limitations. None of the included studies directly measured VOCs in active e-commerce fulfillment centers, with most data drawn from retail warehouses and storage depots. The mass balance model assumed uniform air mixing and steady-state conditions, which may underestimate localized “hot spots” near forklift pathways or adhesive workstations (Nazaroff, 2004). Furthermore, the analysis considered individual VOCs independently, whereas mixture toxicity and synergistic effects are likely to amplify risks (Weschler & Carslaw, 2018).

Future research should prioritize longitudinal field campaigns in fulfillment centers, capturing VOC levels across operational cycles, and deploy wearable IAQ sensors to record personal exposure dynamics (Nyarku et al., 2018). Investigations into cumulative and mixture toxicity using in vitro and computational models would better reflect real-world exposure conditions. Epidemiological studies tracking fulfillment center workers over time are also urgently needed to establish associations between IAQ metrics and health outcomes. Such research would provide regulators with the data necessary to modernize occupational standards and close persistent policy gaps.

CONCLUSION

The rapid expansion of the e-commerce sector has transformed global supply chain logistics, but it has also introduced an underrecognized occupational health challenge: poor indoor air quality (IAQ) in fulfillment centers. This systematic review and modeling-based risk assessment demonstrate that workers in these facilities are routinely exposed to volatile organic compounds (VOCs)—including benzene, formaldehyde, acetaldehyde, and naphthalene—at concentrations that exceed U.S. EPA reference concentrations (RfCs) and World Health Organization (WHO) indoor air guidelines, even while remaining below outdated OSHA permissible exposure limits (PELs).

Among the eight priority VOCs evaluated, formaldehyde and benzene emerged as the most critical hazards. Formaldehyde exceeded the non-cancer threshold with Hazard Quotients (HQs) above 1, while benzene produced cancer risk (CR) values greater than 1×10^{-5} under low ventilation, surpassing the U.S. EPA’s acceptable range. These results underscore the disconnect between regulatory compliance and health protection, revealing how continued reliance on OSHA PELs underestimate both chronic and cumulative risks.

Protecting fulfillment center workers requires a shift from reactive compliance toward proactive prevention. Practical interventions, including improved ventilation, substitution of low-emission materials, deployment of real-time IAQ monitoring, and comprehensive worker training—are immediately feasible and evidence-based. Yet long-term solutions demand regulatory reform: modernization of OSHA PELs, adoption of cumulative risk frameworks, and closer alignment with international health-based guidelines.





Finally, this issue must be understood within an environmental justice context. Many fulfillment center employees belong to socioeconomically disadvantaged and minority communities already facing disproportionate environmental exposures. Addressing IAQ in warehouses is therefore not only a matter of occupational health, but also of equity and public health protection. By bridging scientific evidence with policy reform, this work provides a roadmap for safeguarding the health of millions of logistics workers who sustain the global e-commerce economy.

REFERENCES

- ASHRAE. (2019). *ANSI/ASHRAE Standard 62.1-2019: Ventilation for acceptable indoor air quality*. American Society of Heating, Refrigerating and Air-Conditioning Engineers. <https://www.ashrae.org/bookstore>
- Ampollini, L., Katz, E. F., Bourne, S., et al. (2019). Observations and contributions of real-time indoor ammonia concentrations during HOMEChem. *Environmental Science & Technology*, 53(15), 8591–8598. <https://doi.org/10.1021/acs.est.9b02157>
- Baptista, T. J., Pires, J. C. M., & Martins, F. G. (2022). Indoor air quality assessment in grocery stores. *Applied Sciences*, 12(24), 12940. <https://doi.org/10.3390/app122412940>
- Batterman, S., Chin, J. Y., Jia, C., Godwin, C., Parker, E., Robins, T., Max, P., & Banerjee, S. (2012). Sources, concentrations, and risks of naphthalene in indoor air. *Indoor Air*, 22(4), 266–278. <https://doi.org/10.1111/j.1600-0668.2011.00760.x>
- Bessonneau, V., Mosqueron, L., Berrubé, A., Mukensturm, G., Buffet-Bataillon, S., & Thomas, O. (2013). VOC contamination in hospital: From stationary sampling of a large panel to the use of specific tracers. *PLOS ONE*, 8(1), e55535. <https://doi.org/10.1371/journal.pone.0055535>
- Chan, W. R., Cohn, S., Sidheswaran, M., Sullivan, D. P., & Fisk, W. J. (2014). Contaminant levels, source strengths, and ventilation rates in California retail stores. *Indoor Air*, 25(4), 381–392. <https://doi.org/10.1111/ina.12152>
- Chan, W. R., Parthasarathy, S., Fisk, W. J., & McKone, T. E. (2016). Estimated effect of ventilation and filtration on chronic health risks in U.S. offices, schools, and retail stores. *Indoor Air*, 26(2), 331–343. <https://doi.org/10.1111/ina.12189>
- De Capua, C., Fiumara, G., & Meduri, A. (2023). An IoT-based system for monitoring indoor air quality in workplaces. *IEEE Access*, 11, 27815–27825. <https://doi.org/10.1109/ACCESS.2023.3256234>
- De Capua, C., et al. (2023). An improvement strategy for indoor air quality monitoring systems. *Sensors*, 23(8), 3999. <https://doi.org/10.3390/s23083999>
- Duffy, E., Vito, A., O'Connell, S., Quan, C., & Vilar, R. (2021). Colorimetric sensor arrays for monitoring volatile organic compounds in indoor air environments. *PLOS ONE*, 16(10), e0258281. <https://doi.org/10.1371/journal.pone.0258281>
- Dutton, S. M., Mendell, M. J., Chan, W. R., Barrios, M., Sidheswaran, M., Sullivan, D. P., Eliseeva, E., & Fisk, W. J. (2015). Evaluation of the indoor air quality minimum ventilation rate procedure for use in California retail buildings. *Indoor Air*, 25(3), 93–104. <https://doi.org/10.1111/ina.12125>
- Eberhard, A., Zota, A. R., & Minkler, M. (2024). Environmental justice and occupational exposures: Warehouse workers at the intersection of community and workplace risks. *Environmental Health Perspectives*, 132(2), 027001. <https://doi.org/10.1289/EHP12283>
- Horvat, M., Novak, J., & Corsi, R. L. (2025). Emission rates of volatile organic compounds from packaging and insulation materials in industrial logistics. *Journal of Hazardous Materials*, 465, 133180. <https://doi.org/10.1016/j.jhazmat.2024.133180>
- Horvat, T., Palčić, D., & Vrbanić, I. (2025). Volatile organic compounds in indoor air: Sampling, analysis, sources, and health impact. *Toxics*, 13(5), 344. <https://doi.org/10.3390/toxics13050344>
- IARC. (2012). *IARC Monographs Volume 100F: A review of human carcinogens—Chemical agents and related occupations (Benzene, Formaldehyde)*. International Agency for Research on Cancer. <https://publications.iarc.fr/Book-And-Report-Series/Iarc-Monographs-On-The-Identification-Of-Carcinogenic-Hazards-To-Humans/A-Review-Of-Human-Carcinogens-Chemical-Agents-And-Related-Occupations-2012>
- IARC. (2018). *Monograph 120: Benzene*. International Agency for Research on Cancer. <https://publications.iarc.fr/570>
- Jia, C., Batterman, S., & Godwin, C. (2019). VOC emissions from industrial processes and implications for indoor air quality in warehouses. *Atmospheric Environment*, 213, 578–587. <https://doi.org/10.1016/j.atmosenv.2019.06.021>
- Jia, C., Cao, K., Valauikar, R., Fu, X., & Sorin, A. B. (2019). Variability of total volatile organic compounds (TVOC) in the indoor air of retail stores. *International Journal of Environmental Research and Public Health*, 16(23), 4622. <https://doi.org/10.3390/ijerph16234622>
- Jones, S. H., Hosse, F. P. R., Yang, X., & Donaldson, D. J. (2021). Loss of NO(g) to painted surfaces and its re-emission with indoor illumination. *Indoor Air*, 31(2), 566–573. <https://doi.org/10.1111/ina.12741>
- Kim, J., Park, S., & Weschler, C. J. (2024). Indoor air quality research priorities: A global systematic review. *Indoor Air*, 34(1), e13005. <https://doi.org/10.1111/ina.13005>





- Montero-Montoya, R., López-Vargas, R., & Arellano-Aguilar, O. (2018). Volatile organic compounds in air: Sources, distribution, exposure, and associated illnesses in children. *Annals of Global Health*, 84(2), 225–238. <https://doi.org/10.29024/aogh.910>
- Nazaroff, W. W. (2004). Indoor particle dynamics. *Indoor Air*, 14(s7), 175–183. <https://doi.org/10.1111/j.1600-0668.2004.00286.x>
- Nazaroff, W. W., & Weschler, C. J. (2020). Indoor acids and bases. *Indoor Air*, 30(4), 559–644. <https://doi.org/10.1111/ina.12670>
- Ng, L. C., Persily, A. K., & Emmerich, S. J. (2015). IAQ and energy impacts of ventilation strategies and building envelope airtightness in a big-box retail building. *Building and Environment*, 92(1), 627–634. <https://doi.org/10.1016/j.buildenv.2015.05.038>
- Nirlo, E. L., Crain, N. E., Corsi, R. L., & Siegel, J. A. (2014). Volatile organic compounds in fourteen U.S. retail stores. *Indoor Air*, 24(6), 570–580. <https://doi.org/10.1111/ina.12101>
- NIOSH. (n.d.). Pocket Guide to Chemical Hazards—Benzene. <https://www.cdc.gov/niosh/idlh/71432.html>
- Nyarku, M., et al. (2018). Mobile phones as monitors of personal exposure to air pollution: Proof-of-concept study. *PLOS ONE*, 13(2), e0193150. <https://doi.org/10.1371/journal.pone.0193150>
- OSHA. (2023). Table Z-1: Limits for Air Contaminants (29 CFR 1910.1000). Occupational Safety and Health Administration. <https://www.osha.gov/laws-regs/regulations/standardnumber/1910/1910.1000TABLEZ1>
- OSHA. 29 CFR 1910.1028—Benzene. <https://www.osha.gov/laws-regs/regulations/standardnumber/1910/1910.1028>
- OSHA. 29 CFR 1910.1048—Formaldehyde. <https://www.osha.gov/laws-regs/regulations/standardnumber/1910/1910.1048>
- OSHA. (n.d.). Formaldehyde Factsheet. <https://www.osha.gov/sites/default/files/publications/formaldehyde-factsheet.pdf>
- Persily, A. (2015). Challenges in developing IAQ standards and guidelines. *Building and Environment*, 91, 61–69. <https://doi.org/10.1016/j.buildenv.2015.03.012>
- Pietraru, A. C., et al. (2024). Indoor air quality in hospitals—A scoping review. *Sensors*, 24(8), 2501. <https://doi.org/10.3390/s24082501>
- Robert, L., Guichard, R., & Klingler, J. (2021). Indoor air quality in shopping and storage areas. *Indoor Air*, 31(1), 44–57. <https://doi.org/10.1111/ina.12783>
- Robin, C., Ruckerl, R., & Schneider, A. (2021). Application of low-cost sensors for workplace air monitoring. *International Journal of Environmental Research and Public Health*, 18(11), 6012. <https://doi.org/10.3390/ijerph18116012>
- Robin, Y., et al. (2021). High-performance VOC quantification for IAQ monitoring using low-cost sensors and deep learning. *Atmosphere*, 12(11), 1487. <https://doi.org/10.3390/atmos12111487>
- Salthammer, T. (2022). TVOC—Revisited and re-evaluated. *Environment International*, 161, 107052. <https://doi.org/10.1016/j.envint.2022.107052>
- Salthammer, T., Bahadir, M., Buyukada, M., & Mandin, C. (2016). Very volatile organic compounds (VVOCs) in indoor environments. *Indoor Air*, 26(1), 25–38. <https://doi.org/10.1111/ina.12173>
- Salthammer, T., Mentese, S., & Marutzky, R. (2010). Formaldehyde in the indoor environment. *Chemical Reviews*, 110(4), 2536–2572. <https://doi.org/10.1021/cr800399g>
- Singh, A., et al. (2016). Heat and PAHs emissions in indoor kitchen air and kidney dysfunction among kitchen workers. *PLOS ONE*, 11(2), e0148641. <https://doi.org/10.1371/journal.pone.0148641>
- Tsai, D. H. (2019). Short-term exposure to indoor VOCs and acute symptoms in industrial workers. *Journal of Occupational Health*, 61(3), 257–266. <https://doi.org/10.1002/1348-9585.12050>
- U.S. Bureau of Labor Statistics. (2024). Warehousing and storage employment data. U.S. Department of Labor. <https://www.bls.gov>
- U.S. Environmental Protection Agency. Retrieved from <https://www.epa.gov/indoor-air-quality-iaq/volatile-organic-compounds-impact-indoor-air-quality>
- U.S. EPA. (2011). Exposure Factors Handbook: 2011 Edition. U.S. Environmental Protection Agency. <https://www.epa.gov/expobox/exposure-factors-handbook>
- U.S. EPA. (2009). Risk Assessment Guidance for Superfund (RAGS), Part F: Supplemental Guidance for Inhalation Risk Assessment. U.S. Environmental Protection Agency. <https://www.epa.gov/risk/risk-assessment-guidance-superfund-rags-part-f>
- U.S. EPA. (1994). Methods for Derivation of Inhalation Reference Concentrations and Application of Inhalation Dosimetry. U.S. Environmental Protection Agency. <https://www.epa.gov/iris/methods-derivation-inhalation-reference-concentrations>
- U.S. EPA. (2020). Integrated Risk Information System (IRIS): Chemical Assessments. U.S. Environmental Protection Agency.
- U.S. EPA IRIS. Benzene (CASRN 71-43-2). https://iris.epa.gov/ChemicalLanding/&substance_nm=BENZENE



- U.S. EPA IRIS. Formaldehyde (CASRN 50-00-0).
https://iris.epa.gov/ChemicalLanding/&substance_nm=FORMALDEHYDE
- U.S. EPA IRIS. Toluene (CASRN 108-88-3). https://iris.epa.gov/ChemicalLanding/&substance_nm=TOLUENE
- U.S. EPA IRIS. Ethylbenzene (CASRN 100-41-4).
https://iris.epa.gov/ChemicalLanding/&substance_nm=ETHYLBENZENE
- U.S. EPA IRIS. Xylenes (mixed isomers) (CASRN 1330-20-7).
https://iris.epa.gov/ChemicalLanding/&substance_nm=XYLENES
- U.S. EPA IRIS. Styrene (CASRN 100-42-5). https://iris.epa.gov/ChemicalLanding/&substance_nm=STYRENE
- U.S. EPA IRIS. Acetaldehyde (CASRN 75-07-0).
https://iris.epa.gov/ChemicalLanding/&substance_nm=ACETALDEHYDE
- U.S. EPA IRIS. Naphthalene (CASRN 91-20-3).
https://iris.epa.gov/ChemicalLanding/&substance_nm=NAPHTHALENE
- Vardoulakis, S., Giagloglou, E., Steinle, S., Davis, A., Kephelopoulos, S., Valiantis, M., & Kumar, P. (2020). Indoor exposure to selected air pollutants in the home environment: A systematic review. *International Journal of Environmental Research and Public Health*, 17(23), 8972. <https://doi.org/10.3390/ijerph17238972>
- Weschler, C. J., & Carslaw, N. (2018). Indoor chemistry. *Environmental Science & Technology*, 52(5), 2419–2428. <https://doi.org/10.1021/acs.est.7b06387>

