New Zealand Journal of Health and Safety Practice
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A person with narrow vision has a restricted horizon; a person with wide vision has plentiful opportunities

Dermal and Inhalation Exposure to Solvents in the Petroleum Laboratory: A Study of Exposure Pathway Correlation

Vol 3; edition 2; July 2026

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DOI: https://doi.org/10.26686/nzjhsp.v3i2.10512

ABSTRACT

Laboratory workers are at risk of exposure to volatile organic compounds (VOCs) through inhalation and dermal contact, which can lead to adverse health effects. Despite the importance of dermal exposure, it is often overlooked in occupational risk assessments.

This study investigated dermal exposure to five VOCs (benzene, ethylbenzene, toluene, total hydrocarbon, and xylene) among laboratory technicians. Paired air and skin exposure measurements were collected using standard sampling methods. Statistical analysis was performed using the Wilcoxon Signed-Rank Test and Spearman's rank correlation to evaluate the relationship between air and skin exposure levels.

The results showed that dermal exposure levels were significantly higher than air exposure levels for all compounds, with mean dermal exposure concentrations ranging from 0.10 µg (ethylbenzene) to 19,086.07 µg (THC) and mean air exposure concentrations ranging from 0.0502 µg (benzene) to 13.47 µg (THC). The Wilcoxon Signed-Rank Test revealed significant differences between air and skin exposure levels for all compounds ($p < 0.05$), with V statistic values ranging from 78 (benzene) to 105 (toluene, THC, and xylene). Spearman's rank correlation analysis showed a strong positive correlation between air and skin exposure for xylene ($\rho = 0.667$, $p = 0.0092$), but no significant correlation for benzene ($\rho = 0.000$, $p = 1.000$), ethylbenzene (ρ = NA, p = NA), toluene ($\rho = -0.080$, $p = 0.786$), and THC ($\rho = 0.258$, $p = 0.373$).

This study highlights the importance of considering dermal exposure in occupational risk assessments for laboratory workers. The results emphasize the need for route-specific monitoring practices and control measures to mitigate dermal exposure risks. These findings have significant implications for occupational health and safety, and can inform the development of more effective exposure control strategies.

Key words: Dermal exposure; inhalation exposure; laboratory workers, permeation pads, risk assessment

INTRODUCTION

Volatile organic compounds (VOCs) are prevalent in a wide range of occupational environments, including chemical laboratories, healthcare facilities, and industrial operations, where they are commonly used in processes involving solvents, fuels, and cleaning agents (Bello et al., 2009). These compounds are well-documented for their potential adverse health effects, ranging from acute irritation to chronic conditions such as respiratory disorders, neurotoxicity, and cancer (Duca et al., 2019). Consequently, accurate exposure assessment is essential for effective risk management and occupational health protection.

Historically, exposure assessments have primarily focused on inhalation as the dominant route of exposure. However, increasing evidence from occupational hygiene research indicates that this singular focus may underestimate total exposure, particularly in tasks where dermal contact plays a significant role (Creta et al., 2017). Dermal exposure can occur through multiple mechanisms, including direct skin contact with liquids, transfer from contaminated surfaces, or deposition of vapors on the skin or clothing. In many occupational contexts, such as chemical laboratories, dermal

exposure may be frequent and prolonged, even when airborne concentrations remain low (Vermeulen et al., 2006).

This is especially pertinent in environments where solvent handling occurs intermittently—such as during decanting, wiping, or instrument cleaning—where short-term exposure peaks may not be adequately captured by full-shift time-weighted averages (TWAs). Studies employing time-resolved inhalation approaches have highlighted the importance of task-specific exposure peaks in solvent exposure scenarios (Preller et al., 2004). Similarly, real-time VOC exposure time series have demonstrated that task determinants significantly influence overall exposure patterns (Virji et al., 2019; Houseman & Virji, 2017). These findings raise critical questions about the alignment between airborne metrics and dermal contamination, particularly in dynamic work settings.

Laboratory technicians, who routinely handle a wide array of solvents and reagents, are particularly at risk for both inhalation and dermal exposure. While the quantities of chemicals used are often small, the frequency and nature of tasks—such as pipetting, mixing, and cleaning create ample opportunities for skin contact, especially during glove donning and doffing procedures (Jolanki, 2012). Many of the substances handled are classified as irritants, sensitizers, or carcinogens, further emphasizing the need for comprehensive exposure assessment (Rustemeyer et al., 2012).

Despite the recognized importance of dermal exposure in laboratory settings, there is a notable lack of published data specifically characterizing dermal contact among laboratory workers. Some studies have reported dermal exposure levels below the limit of detection, which may reflect limitations in sampling methods rather than the true absence of exposure (Christopher et al., 2007). Recent work by Galea et al. (submitted) has begun to address this gap, reporting dermal exposure values between 1.67 and 34.8 μg/cm² using wipe sampling methods, highlighting the variability and detectability of dermal exposure in this population.

The measurement of dermal VOC exposure has long been methodologically challenging due to the volatility and rapid absorption of many of these compounds. However, recent advances have introduced more reliable and sensitive sampling techniques, such as Activated Charcoal Cloth (ACC) pads. These pads, typically placed on high-contact areas such as the hands, offer a scientifically validated method for capturing both direct contact and vapor-phase deposition of VOCs on the skin (Creta et al., 2017). ACC pads have been successfully applied in various occupational settings, including aircraft maintenance and shoe manufacturing, where dermal exposure to benzene and toluene was found to be a significant contributor to overall exposure (Smith et al., 2010; Vermeulen et al., 2006). The pads are generally small (around 3.5 cm²), making them minimally intrusive while still providing a representative sample of localized exposure.

Building on these methodological advancements, the present study evaluates paired airborne and dermal exposure measurements for five VOCs: benzene, ethylbenzene, toluene, xylene, and total hydrocarbons (THC) as hexane among laboratory technicians in a petroleum company. The primary objectives of this study are to characterize the distribution of 8-hour time-weighted average (TWA) airborne concentrations and dermal contamination on the hands, assess the monotonic relationship between these two exposure routes using Spearman's rank correlation (ρ), and evaluate the concordance between left- and right-hand measurements to assess within-task exposure consistency. A key focus of the research is to determine whether there is a statistically significant monotonic correlation between the levels of specific volatile organic compounds (VOCs) in the air and their corresponding concentrations measured on the skin. This approach allows for a more comprehensive understanding of multi-pathway exposure dynamics in occupational settings, particularly where both inhalation and dermal routes may contribute to overall risk.

Given the small sample size, presence of outliers, and non-normal data distribution, non-parametric statistical methods were employed to ensure methodological rigor and validity. By integrating both inhalation and dermal exposure pathways and utilizing validated sampling techniques, this research contributes to the growing body of literature on multi-pathway exposure assessment. It provides critical insights for occupational hygiene, exposure modeling, and the development of more comprehensive risk management strategies that reflect the true nature of chemical exposure in laboratory environments.

The aim of this study is to quantify the inhalation and dermal exposure of laboratory technicians working in a petroleum company to common solvents (BTEX and THC) using standard air sampling techniques and commercially available adsorptive pads. In addition, the study aims to establish if there is a relationship between dermal and inhalation exposure to hydrocarbons. The core objective of this analysis is to assess whether exposure to airborne chemicals is associated with dermal

absorption or deposition of the same substances. Specifically, we are investigating five chemical compounds: Benzene, Ethyl Benzene, Toluene, Total Hydrocarbons (as Hexane), and Xylene.

For each of these compounds, paired measurements were collected from 15 matched samples, where both air and skin levels were measured simultaneously (or under the same conditions), across 15 units (workers, locations, or events). The results of this study will provide valuable insights into the exposure patterns of laboratory technicians and will inform the development of effective risk management strategies to minimize exposure to VOCs in laboratory settings

METHODOLOGY

The study focused on laboratory technicians working in chemical labs that support crude oil analysis and related testing across the company. These technicians typically work in 8-hour shifts and perform routine chemical and physical analyses of crude oil and its byproducts, following standardized procedures from the American Petroleum Institute (API) and the American Society for Testing and Materials (ASTM).

Participants were selected based on their regular involvement in handling crude oil or its derivatives, as these tasks are associated with potential exposure to volatile organic compounds (VOCs). The selection was made in consultation with laboratory supervisors to ensure involvement from workers with varying levels of exposure. All technicians followed standard safety protocols, including the use of disposable nitrile gloves, safety glasses, flame-resistant clothing, and protective footwear. Gloves were changed whenever they became contaminated or after completing a task involving chemicals.

Air and Dermal Sample Collection: Personal Air Sampling

Air samples were collected from each technician’s breathing zone while they performed their regular duties, using the active sampling method outlined in NIOSH methods 1501 and 1550. Charcoal sorbent tubes (Anasorb, SKC Inc.) were connected to calibrated personal sampling pumps (Gilian brand), which were set to a flow rate of 200 ml/min at the start of the day and rechecked at the end to ensure accuracy.

Field blank samples were collected to account for any background contamination. After sampling, the tubes were sealed and stored in resealable plastic bags to prevent any loss or contamination before laboratory analysis.

Dermal Sampling

Dermal exposure was assessed using the interception method, in which a collection pad is placed on the skin to capture contaminants that come into contact with it. This method assumes that the mass collected reflects the actual or potential dermal exposure.

Breakthrough indicator permeation pads have become commercially available and are widely used in occupational hygiene. These pads typically contain activated carbon, which adsorbs chemicals that permeate through protective gloves, allowing for subsequent quantification using gas chromatography–mass spectrometry (GC–MS) (Evanly et al., 1999).

In this study, Permea-Tec™ pads (Colorimetric Laboratories Inc.) were used. These pads are composed of cotton and carbon cloth with a central color-changing indicator strip that responds to polar solvents. Non-polar solvents, which do not activate the color indicator, were extracted and analyzed in the laboratory to ensure comprehensive exposure assessment.

Before applying the pads, technicians were instructed to wash and thoroughly dry their hands. Each hand was then wiped twice with Hypaclean Clinical Wipes (13 x 13 cm), containing 70% isopropyl alcohol, to remove any potential background contamination. New disposable nitrile gloves were donned prior to placing the pads.

Each pad was positioned on the thumb, middle finger, and palm of both hands—areas most likely to come into contact with chemicals and where abrasion may increase the risk of chemical penetration.

Throughout the task, technicians removed their gloves hourly to inspect the pads and ensure they remained securely attached. If the pads were still in place, new gloves were donned, and the task continued for another hour. This process was repeated hourly until the task was completed, which generally lasted between 1 to 4 hours.

After task completion, the pads were carefully removed and separated from their adhesive backing. Three pads from one hand were stored together in a single airtight glass bottle and labeled with a unique identification number for traceability.

To account for any environmental contamination, field blank samples were collected alongside the exposure samples. All samples were refrigerated during the sampling period and later shipped to an AIHA-accredited laboratory for analysis.

The interception method is based on the principle that a collection substrate, when attached to the skin or clothing, intercepts and retains contaminants transported toward the skin surface. The mass collected from the substrate serves as a surrogate for dermal exposure. In this study, Permea-Tec™ pads were used to monitor exposure to solvents. Manufactured by Colorimetric Laboratories Inc. (Des Plaines, IL), these pads consist of a cotton-carbon cloth square with a reactive indicator strip that changes color upon contact with polar solvents. Since non-polar solvents do not activate the indicator, they were extracted and analyzed quantitatively in the laboratory to ensure a complete assessment of exposure.

Laboratory Analysis

Both air and dermal samples were analyzed for BTEX compounds (benzene, toluene, ethylbenzene, xylene) and total hydrocarbons (THC), represented as hexane. The analyses were performed using gas chromatography–mass spectrometry (GC/MS) and gas chromatography with flame ionization detection (GC/FID).

For air samples, NIOSH methods 1501 and 1550 were followed. The detection limits were 2 µg for benzene and 5 µg for ethylbenzene, toluene, and xylene. For THC, the detection limit was 20 µg.

For dermal samples, the detection limits were higher due to the nature of the collection method: 6 µg for benzene, 15 µg for ethylbenzene, toluene, and xylene, and 60 µg for THC.

Data Analysis: Statistical Methods

A total of 15 matched air and skin exposure samples were collected, with each sample representing exposure levels for five VOCs: benzene, ethylbenzene, toluene, xylene, and total hydrocarbons (as hexane). To explore the relationship between airborne and skin exposure levels, Spearman's rank correlation (ρ) was used. This non-parametric method was chosen because:

- The relationship between exposure routes may not be linear,
- The data may not follow a normal distribution,
- The sample size is small (n=15),
- There may be outliers.

Spearman's correlation evaluates the strength and direction of a monotonic (consistently increasing or decreasing) relationship by comparing the ranks of the data points.

To compare overall exposure levels between air and skin, the Wilcoxon signed-rank test was applied. This test is ideal for small sample sizes and non-normal distributions, helping determine whether there was a consistent difference in exposure levels between the two routes.

One outlier was observed in the benzene skin data (22.1 ng/cm²). To understand how it affected the results, analyses were run both with and without the outlier. For ethylbenzene, all skin measurements were identical (0.1 ng/cm²), which meant a correlation could not be calculated for that compound. All statistical analyses were conducted using R software.

For each air sample, an 8-hour time-weighted average (TWA) was calculated to reflect the average airborne concentration over a full work shift. This metric is commonly used in occupational health to assess exposure over time.

Descriptive and Inferential Statistics

Air data were analyzed in Microsoft Excel using descriptive statistics, correlation analysis, and ANOVA to summarize and explore patterns in the data.

Handling of Values Below the Detection Limit

When exposure levels were below the limit of detection (LOD), a method based on beta substitution (Ganser & Hewett, 2010) was used to estimate values. This approach uses the distribution of

detected values to impute reasonable estimates for undetected ones, depending on whether the arithmetic or geometric mean is being calculated.

Advanced Statistical Analysis in Stata

Data were later imported into Stata for more advanced statistical modeling. The Mann–Whitney U test was used to compare inhalation exposure with dermal exposure on both the left and right hands. The Wilcoxon matched-pairs signed-ranks test was used to compare exposure levels between the two hands. A p-value less than 0.05 was considered statistically significant for all analyses

RESULTS

Table 1, below summarizes the central tendency and dispersion of five volatile organic compounds (VOCs) across two exposure routes: dermal (skin) and inhalation (air). The data highlight notable differences between air and skin exposure levels, suggesting distinct exposure dynamics and potential implications for occupational health risk assessment.

Table1: Summary Statistics of VOC Concentrations by Exposure Route

Compound	Source	Mean	Median	SD	Min	Max
Benzene	Skin	1.6293	0.0550	5.8919	0.050	22.1
	Air	0.0502	0.0520	0.0236	0.005	0.111
Ethyl Benzene	Skin	0.10	0.10	0.0000	0.100	0.100
	Air	0.0831	0.0960	0.0337	0.003	0.101
Toluene	Skin	383.3748	78.9	806.5169	17.447	2695
	Air	0.1576	0.1110	0.1252	0.083	0.578
THC (Hexane)	Skin	19086.07	19905	5357.506	7065	28800
	Air	13.4741	2.0105	41.6433	0.473	157.948
Xylene	Skin	278.0174	41.35	578.2154	0.100	1635.5
	Air	0.1709	0.0960	0.2391	0.031	0.991

Table 2, showed that result of Wilcoxon Signed-Rank Test results to compare the skin and air concentrations of five volatile organic compounds (VOCs), including benzene, ethylbenzene, toluene, THC (hexane), and xylene, in order to determine if there were any statistically significant differences between the two exposure routes.

Table 2: Wilcoxon Signed-Rank Test Results

Compound	V Statistic	p-value	Significance (α = 0.05)	Interpretation
Benzene	78	0.0202	Significant	Skin > Air
Ethylbenzene	104	0.00070	Highly significant	Skin > Air
Toluene	105	0.00109	Highly significant	Skin > Air
THC (Hexane)	105	0.00012	Highly significant	Skin > Air
Xylene	105	0.00012	Highly significant	Skin > Air

The statistical analysis of the table reveals that the Wilcoxon Signed-Rank Test results show significant differences between skin and air concentrations for all compounds. The V statistic values are 78 for benzene ($p = 0.0202$), 104 for ethylbenzene ($p = 0.00070$), 105 for toluene ($p = 0.00109$), 105 for THC (hexane) ($p = 0.00012$), and 105 for xylene ($p = 0.00012$), indicating a significant difference between skin and air concentrations. The p-values for all compounds are less than 0.05, with benzene having a p-value of 0.0202 (significant), ethylbenzene having a p-value of 0.00070 (highly significant), toluene having a p-value of 0.00109 (highly significant), and THC (hexane) and xylene having p-values of 0.00012 (highly significant). The results also show that skin concentrations are significantly higher than air concentrations for all compounds, with a significance level of $\alpha = 0.05$. Overall, the statistical analysis suggests that dermal exposure is a significant route of exposure for all compounds, with highly significant differences between skin and air concentrations.

Table 3 presents Spearman's rank correlation coefficients (ρ) and corresponding p-values to evaluate the monotonic relationship between air and skin exposure levels for a range of compounds, including benzene, ethyl benzene, toluene, THC (as hexane), and xylene**.**

Table 3: Spearman Rank Correlation Between Air and Skin Exposure

Compound	Spearman's ρ	p-value	Interpretation
Benzene	0.000	1.000	No correlation
Ethyl Benzene	NA	NA	No variance
Toluene	–0.080	0.786	No correlation
THC (as Hexane)	0.258	0.373	Weak, not significant
Xylene	0.667	0.0092	Strong positive correlation

The results of the analysis showed that benzene had a Spearman's ρ of 0.000 and a p-value of 1.000, indicating no correlation between air and skin exposure. Ethyl benzene had no variance, with NA values for both Spearman's ρ and p-value. Toluene exhibited a weak negative correlation with a Spearman's ρ of -0.080 and a p-value of 0.786, indicating no correlation. THC (as hexane) had a Spearman's ρ of 0.258 and a p-value of 0.373, indicating a weak but not significant correlation. In contrast, xylene showed a strong positive correlation with a Spearman's ρ of 0.667 and a p-value of 0.0092, indicating a significant association between air and skin exposure.

DISCUSSION

As shown in Table 1, the study's results reveal that dermal exposure to volatile organic compounds (VOCs) is a significant concern in laboratory settings, with levels often exceeding airborne concentrations. For instance, benzene dermal exposure is highly variable, with a mean of 1.23 µg and a standard deviation (SD) of 5.89, indicating extreme right-skewness and potential outliers (Kromhout et al., 2000). The maximum value of 22.1 µg was significantly higher than the median of 0.055 µg, suggesting sporadic high exposure events. This is consistent with previous studies that have shown that dermal exposure to benzene can be a significant contributor to total body burden, especially in occupational settings (Garrod and Rajan, 2003; Hodgson and Levin, 2003; Julien et al., 2001).

Similarly, toluene dermal exposure was highly variable, with a mean of 383.37 µg and a SD of 806.52, indicating strong evidence of right skewness and outliers. The maximum value of 2695.6 µg was significantly higher than the median of 78.90 µg, suggesting non-airborne exposure routes, such as direct contact with solvents (Rajan, 2008; Tan et al., 1999). This is consistent with previous studies that have shown that toluene dermal exposure can be a significant contributor to total body burden, especially in occupational settings (Julien et al., 2001; Kromhout et al., 2000).

Xylene dermal exposure showed a statistically significant correlation with air levels, with a Spearman's rank correlation coefficient (ρ) of 0.667 ($p = 0.0092$), indicating that airborne exposure contributes to skin contamination, possibly through deposition or vapor absorption (Garrod and Rajan, 2003; Hodgson and Levin, 2003). The mean xylene dermal exposure was 278.02 µg, with a SD of 578.22, and a maximum value of 1635.5 µg. This is consistent with previous studies that have shown that xylene dermal exposure can be a significant contributor to total body burden, especially in occupational settings (Julien et al., 2001).

The findings also highlight the importance of considering dermal exposure in occupational risk assessment, as it can exceed inhalation exposure, especially in laboratory and industrial settings (Kromhout et al., 2004). The use of personal protective equipment (PPE), hygiene practices, and environmental controls is essential for reducing exposure to VOCs (Julien et al., 2001; Tan et al., 1999). The monitoring data revealed that the 8-hour time-weighted average (TWA) exposures were below the occupational exposure limits (OELs) for each of the assessed solvents, with the highest 8-hr TWA reported as 0.48 ppm for THC (hexane) (ACGIH, 2022). The mean mass of dermal exposure of THC (hexane) was 9877 µg and 9222 µg on the left and right hand, respectively.

The results of this study have significant implications for occupational health and safety. The high variability in dermal exposure to VOCs highlights the need for more effective control measures, such as improved ventilation, use of PPE, and regular cleaning and decontamination of surfaces (Hodgson & Levin, 2003; Julien et al., 2001). Additionally, the significant correlation between air and skin exposure for xylene suggests that airborne exposure may be a significant contributor to skin contamination, and therefore, control measures should be implemented to reduce airborne exposure (Garrod and Rajan, 2003; Kromhout et al., 2000).

As shown in Table 2, the statistical analysis of skin and air exposure levels for selected VOCs reveals that the differences between the two exposure routes are statistically significant for all compounds ($p < 0.05$). This suggests that skin exposure plays a notable role in overall chemical uptake, often more than what would be predicted by air sampling alone. The V statistic, which reflects the magnitude of this difference, is particularly high for ethylbenzene, toluene, THC, and xylene ($V = 105$), indicating a strong and consistent divergence between skin and air concentrations. Benzene, with a lower V value of 78, still shows a significant difference, albeit to a lesser extent.

The correlation between air and skin exposure to VOCs was analyzed using Spearman's rank correlation coefficient (ρ) and p-value. The results showed that xylene had a strong positive correlation between air and skin exposure, with a Spearman's ρ of 0.667 and a p-value of 0.0092. In contrast, benzene, ethyl benzene, and toluene showed no significant correlation between air and skin exposure, with Spearman's ρ values of 0.000, NA, and -0.080, respectively, and p-values of 1.000,

NA, and 0.786, respectively. THC (as hexane) showed a weak, but not significant, positive correlation between air and skin exposure, with a Spearman's ρ of 0.258 and a p-value of 0.373.

The strong association between air and skin levels for xylene highlights the potential for dermal exposure even under controlled conditions, such as when workers are using personal protective equipment or operating in well-ventilated areas. These results underscore the need for route-specific exposure monitoring strategies in occupational health assessments. While air sampling may be sufficient for estimating xylene exposure, direct dermal measurement is necessary for compounds like benzene, toluene, and THC (as hexane) to ensure accurate and comprehensive exposure characterization. This is particularly important in industries where workers are exposed to multiple VOCs, and where dermal exposure may be a significant contributor to total exposure (Zhang et al., 2020; Liu et al., 2020; Wang et al., 2020).

The findings of this study have important implications for occupational health and safety, highlighting the need to consider dermal exposure when assessing the risks associated with VOCs in the workplace. The results are consistent with previous research on dermal exposure to VOCs, which has shown that dermal exposure can be a significant contributor to total exposure in occupational settings (Liu et al., 2020; Wang et al., 2020; Garrod et al., 2003; Hodgson et al., 2003). Overall, the study emphasizes the importance of considering dermal exposure when assessing the risks associated with VOCs in the workplace, and the need for route-specific exposure monitoring strategies to ensure accurate and comprehensive exposure characterization.

CONCLUSIONS

In conclusion, this study demonstrates that dermal exposure to volatile organic compounds (VOCs) is a critical and often overlooked component of occupational risk assessment in laboratory and industrial settings. Statistical analyses, including the Wilcoxon Signed-Rank Test and Spearman’s rank correlation, revealed significant differences between air and skin exposure levels across all tested compounds, with skin exposure frequently exceeding airborne concentrations. Notably, dermal exposure to compounds such as benzene, toluene, and THC (as hexane) occurred independently of air levels, underscoring the need for direct dermal monitoring to accurately assess worker risk.

Xylene, in contrast, exhibited a strong positive correlation between air and skin exposure, suggesting that airborne monitoring may serve as a useful proxy for dermal risk in this case. However, for other compounds, reliance on air sampling alone may lead to a significant underestimation of total exposure. These findings align with previous research highlighting the importance of dermal pathways in total body burden and support the call for more comprehensive exposure control strategies.

The results emphasize the importance of adopting route-specific monitoring practices in occupational health programs. Effective risk management must include both inhalation and dermal exposure assessments, particularly in environments where workers handle multiple VOCs. Implementing improved hygiene practices, enhanced personal protective equipment (PPE), and regular surface decontamination can further mitigate exposure risks.

Ultimately, this study reinforces the need to integrate dermal exposure into standard occupational exposure limits (OELs) and risk assessment protocols. By doing so, occupational health and safety practices can better protect workers from the potentially harmful effects of VOCs in the workplace.

Acknowledgments

We would like to thank Saudi Aramco for the full support and funding this study. The authors would like to thank the laboratory technicians for participating in this measurement campaign, also special thanks is extended to Dr. Mohammed Al-Omair and IOM, UK for their assistance with the statistical analysis of study data.

Conflicts of interest

All authors have made substantial intellectual contributions to the design and execution of the research and in the writing, and subsequent revisions, of this manuscript. Its contents, including any opinions and/or conclusions expressed, are solely those of the authors.

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