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Emission Characterization and Health Risk Assessment of Volatile Organic Compounds from Automotive Painting in Thailand

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Abstract

The automotive industry is a significant source of volatile organic compound (VOC) emissions, particularly from solvent-based painting processes. This study evaluated VOC characteristics and distribution to assess associated health risks for workers and communities at varying distances from automotive painting facilities in Thailand, focusing on stacks and wastewater treatment plants that handle solvent-containing wastewater. The findings revealed aromatic compounds were predominant (66% of the total emissions), followed by oxygenated VOCs (26%). The stacks mainly emitted aromatics such as toluene and ethylbenzene, whereas the wastewater released oxygenated VOCs, particularly methyl isobutyl ketone and methyl ethyl ketone. The exposure concentrations in each area were primarily influenced by wind direction, with higher levels observed by downwind. The hazard index for areas was less than 1, indicating safe noncarcinogenic risk levels. The lifetime cancer risk showed that ethylbenzene posed a probable risk in all areas (maximum 8.15×10^{-6} µg/m³), whereas 1,2-dichloroethane exhibited a probable risk within 200 meters of the facility (maximum 4.13×10^{-5} µg/m³). This study supports the development of comprehensive emission standards covering health-related compounds and guides residential planning to avoid potential health impacts.

Keywords: air pollution, automotive painting, inhalation exposure, risk assessment, volatile organic compounds

Introduction

Volatile organic compounds (VOCs) have become a growing concern in environments due to their significant roles in pollution and health effects.[1] The automotive industry is one of the major contributors to VOC emissions, primarily because of the use of solvents in painting processes.[2,3] A study in China identified 117 VOCs in automotive workshops, with concentrations ranging from 70 to 19,854 µg/m³, mostly released from the painting process.[4] Airborne VOCs from solvents such as acetone, benzene, toluene, ethylbenzene, and xylene are widely acknowledged as toxic substances by international health agencies.[5] Populations residing near emission sources are more likely to experience health effects, with studies indicating up to 2–3 times higher risks than those in distant areas,[6,7] depending on the type, dose, exposure route, and individual factors. Health effects include both carcinogenic (e.g., leukemia and lung cancer) and noncarcinogenic risks, such as respiratory irritation, asthma, and chronic bronchitis.[6,7] Therefore, identifying the types and concentrations of VOCs in relation to the distance from emission sources is crucial for evaluating exposure patterns and developing health-risk management strategies.[8]

In Thailand, ambient air quality standards for VOCs are regulated based on the annual average concentration, issued under the Pollution Control Department (PCD) notification on Industrial Emission Standards, which specifically regulate a limited group of highly hazardous VOCs such as benzene (≤1.7 µg/m³), 1,2-dichloroethane (≤0.4 µg/m³), vinyl chloride (≤10 µg/m³), trichloroethylene (≤23 µg/m³), chloroform (≤0.43 µg/m³), and 1,3-butadiene (≤0.33 µg/m³). Although most factories operate within the permissible limits set by the PCD, several VOCs with potential health effects, particularly oxygenated and chlorinated compounds, are not covered under the current standards. This regulatory gap has persisted

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for over a decade since the latest standard update in 2014, leaving many health-relevant VOCs inadequately regulated.[9,10] Most existing studies on VOC emissions have focused on the characteristics of the chemical substances used in painting processes.

However, they did not account for downstream dispersion of process emissions, which can be influenced by environmental factors that affect concentrations received by surrounding populations.[11,12] Most available research has focused on measuring total VOC concentrations or common compounds, such as benzene, toluene, ethylbenzene, and xylene (BTEX), mainly from stack emissions.[13,14] However, few investigations have characterized the specific VOC species released from both stack and wastewater treatment systems within the painting line. Furthermore, some unregulated VOCs that may pose health risks have received limited attention in previous Thai and international studies.[10,15]

Based on the gaps, this study was conducted to identify compound-specific VOCs in painting processes in Thailand's automotive manufacturing industry. This study aimed to identify key emission sources, evaluate exposure patterns, and determine compounds of potential health concern for workers and the surrounding areas. These findings were expected to support the development of emission standards that cover a wide range of air pollutants and provide guidance on appropriate distances between industrial facilities and nearby communities to help prevent potential health impacts in future site planning.

Method

The automotive painting facility investigated in this study is located in an urban area in Thailand and is surrounded by nearby communities. This facility has an annual production capacity of more than 200,000 vehicles and is one of the largest automotive manufacturing operations in the country. The system operates as a closed process, in which VOCs are primarily emitted through exhaust stacks, whereas high-concentration wastewater is discharged into an open wastewater treatment plant (WWTP). Therefore, this study focused on the VOC emissions from stacks and the WWTP during normal operation under full production capacity from March to April 2019.

Sampling was performed during both normal operations and at full production capacity, in accordance with U.S. Environmental Protection Agency (EPA) guidelines.[16] These internationally recognized standards were adopted to ensure consistency, accuracy, and comparability of VOC data, which are essential for reliable health-risk assessment and are widely accepted in air pollution studies.[17,18] Air samples were collected from seven stacks at a constant flow rate using Tedlar® bags, with five samples per stack. Sampling point selection, velocity, and moisture content measurements followed EPA Methods: 1 (Sample and Velocity Traverses, 2016), 2 (Stack Gas Velocity and Flow Rate, 2017), and 4 (Moisture Content in Stack Gases, 2020).[16] Wastewater samples were taken in 1-liter glass bottles, preserved with hydrochloric acid (1:20 mL), and stored at 2–4 °C.

Analysis was conducted using Purge and Trap Gas Chromatography–Mass Spectrometry, following the WATER9 emission model guidelines.[19] The gas chromatography column was programmed from –50 °C (held for 5 min) to 200 °C at 8 °C/min, with helium (99.9%) as the carrier gas at 1.5 mL/min. The ion source, quadrupole, and interface temperatures were set at 230 °C, 150 °C, and 250 °C, respectively. VOCs were identified and quantified based on their boiling points using a capillary column and Mass Spectrometry detection.[20] VOC emissions from the stacks were quantified directly. In contrast, emissions from the WWTP were estimated using the WATER9 model, which was developed to estimate VOC emissions from wastewater systems based on mass-balance equations and chemical properties.[19] Source locations are presented in Figure 1.

Air samples from the stack were collected in 1-liter Tedlar® bags with shut-off valves, using nitrogen gas for blanks, dilution, and purging. The transport and analysis were performed within 12 hours to minimize errors. Method variation was controlled with a relative standard deviation below 30% and a correlation coefficient above 0.95. Detection limits ranged from 0.03 to 0.25 μg/m^3. Duplicate and blank analyses were performed on WWTP samples. Gas chromatography–mass spectrometry (GC–MS) showed repeatability with an accuracy within 10% and recoveries between 85% and 115%. The limit of detection (LOD) ranged from 0.000012 to 0.6 μg/m^3, and the limit of quantitation (LOQ) ranged from 0.00004 to 2.0 μg/m^3.

The emissions obtained from field sampling and laboratory analyses were compiled into an emission inventory and categorized into aromatic compounds, alkanes, alkenes, oxygenated VOCs, halocarbons, aldehydes, and others based on molecular structure to characterize them. The emission factors were subsequently calculated using Equation 1. The emission rate was derived from stack measurements and the WATER9 model for the WWTP, and total emissions were estimated based on a plant operating hours of 7,200 per year.

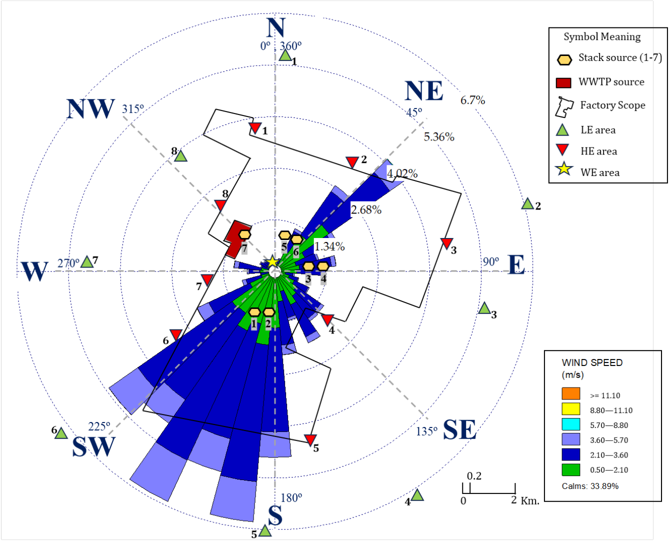
$$EF = \frac{\sum ER_i \; x \; Working\ period}{N}$$

Equation 1. Emission Factor Calculation

Notes: EF = VOCs emission factor (kg/vehicle); ER = emission rate (g/s); N = annual capacity (vehicles/year).

The emission rates of VOCs from the stacks and the WWTP were obtained through sampling and using the WATER9 model, as described above. These data were used in the AERMOD dispersion model (version 9.9.0), developed by the U.S. EPA and the American Meteorological Society (AMS), to estimate ground-level concentrations in each area. The required data, including source emissions, meteorological data, and terrain data, were evaluated in the AERMOD module to generate a pollution map showing VOC concentrations and their dispersion at the receptor locations.[21] Meteorological data (2016–2020) from the Thailand Meteorological Department were analyzed using the Wind Rose Plot (WRPLOT) software to generate the wind pattern. The results show predominantly southwesterly winds, 33.9% calm conditions, and an average wind speed of 1.48 m/s, as presented in Figure 1.

This study classified exposure areas in all wind directions around the factory to evaluate ground-level concentrations as a function of distance and wind patterns. The exposed areas were classified into three categories based on their distance from the factory boundaries. Low-exposure area (LE) was defined as the area where sensitive receptors were located more than 200 m from the factory boundary. High-exposure area (HE) was near the communities, within 0–200 m of the factory boundary. The worker exposure area (WE) was a representative point at the center of the facility to reflect worker exposure. Figure 1 integrates the wind rose with the locations of the receptors and emission sources. The stack sources and the WWTP were positioned near the facility center, whereas the LE, HE, and WE receptors were distributed across all wind directions. This visualization supports the assessment of ground-level concentrations at each receptor by illustrating the relationships among wind direction, wind speed frequency (%), and distance from the emission sources, as indicated by the legend. The directional angles and precise coordinates of each receptor can also be cross-referenced using the coordinate table presented on the right side of Figure 1.



Receptor types	Receptor	Direction from Sources (°)	Distance from Boundary (km)
Low exposure area (LE)	LE-1	2.0 (N)	3.88
	LE-2	70.0 (NE)	4.27
	LE-3	100.1 (E)	2.77
	LE-4	143.5 (SE)	5.03
	LE-5	185.9 (S)	4.49
	LE-6	228.2 (SW)	6.05
	LE-7	275.0 (W)	4.02
	LE-8	317.2 (NW)	1.89
High exposure area (HE)	HE-1	349.4 (N)	0–0.20
	HE-2	43.3 (NE)	
	HE-3	87.1 (E)	
	HE-4	136.3 (SE)	
	HE-5	163.7 (S)	
	HE-6	241.6 (SW)	
	HE-7	253.1 (W)	
	HE-8	316.8 (NW)	
Working exposure area (WE)	WE	-	-

Figure 1. Prevailing Wind Characteristics of the Area as Generated by the Wind Rose Plot Model and Receptor Locations

Notes: N = North; NE = Northeast; E = East; SE = Southeast; S = South; SW = Southwest; W = West; NW = Northwest.

This study analyzed the health effects of inhalation exposure to VOCs, the primary exposure pathway in industrial areas,[22] across three receptor categories. The hazard index (HI) and lifetime cancer risk (LCR) were calculated using equations introduced by the U.S. EPA to assess noncarcinogenic and carcinogenic risks, respectively.[23] This approach focused on the inhalation exposure concentration (EC), as shown in Equation 2.

$$EC_i = \frac{C_i \times ET \times EF \times ED}{AT}$$

Equation 2. Inhalation Exposure Concentration (EC) Calculation
Notes: EC = inhalation exposure concentration of VOCs (µg/m^3); C = ground-level concentration at each receptor (µg/m^3); ET = exposure time (hours/day); EF = exposure frequency (days/year); ED = exposure duration (years) ; AT = averaging time (hours)

The exposure concentration was defined based on the exposure duration and location. The HE and LE areas represented outdoor exposure, whereas the WE area reflected indoor occupational exposure. For outdoor scenarios (HE and LE areas), the exposure parameters were ET = 24 hours/day, EF = 365 days/year, and ED = 70 years. A lifetime exposure duration of 70 years was adopted to represent continuous residential exposure without relocation, reflecting a conservative scenario. For indoor occupational exposure (WE area), the parameters were ET = 8 hours/day, EF = 300 days/year, and ED = 30 years, corresponding to the average working period up to the retirement age.[24] The averaging time (AT) was defined as 70 years × 365 days/year × 24 hours/day for carcinogenic risk assessment, and as ED × 365 days/year × 24 hours/day for noncarcinogenic risk assessment. VOC concentrations (C_i) used in the calculations were derived from AERMOD modeling results and expressed in µg/m^3.[24]

For noncarcinogenic risk assessment, the hazard quotient (HQ) and HI were calculated based on the VOC exposure concentration. The HQ was calculated as the ratio of the exposure concentration (EC_i, µg/m^3) to the EPA reference concentration (RfC_i, µg/m^3), as shown in equation 3. If HQ <1, the exposure to that substance is considered safe, whereas if HQ ≥1, the exposure may pose potential health effects.[5]

$$\mathrm{HQ} = \frac{EC_i}{RfC_i}$$

Equation 3. Hazard Quotient (HQ) Calculation
Notes: HQ = hazard quotient; EC_i = inhalation exposure concentration of of chemical i (µg/m^3); RfC_i = EPA reference concentration of chemical i (µg/m^3)

Based on the VOC species identified in this study, several compounds were associated with adverse effects in multiple organ systems, including the respiratory, circulatory, nervous, cardiovascular, reproductive, developmental, digestive, renal, urinary, and ocular systems. To evaluate the combined noncarcinogenic risk, the HI was calculated by summing the HQ of all VOCs affecting the same target organ at each receptor, following the Integrated Risk Information System (IRIS) guideline.[5] An HI ≤1 indicates a negligible health risk, whereas an HI >1 suggests a potential for significant adverse health effects.[25]

$$\mathrm{HI} = \Sigma \mathrm{HQ}_{\text{same target organ}}$$

Equation 4. Hazard Index (HI) Calculation
Notes: HI = hazard index; ΣHQ = summation of hazard quotient at the same target organ

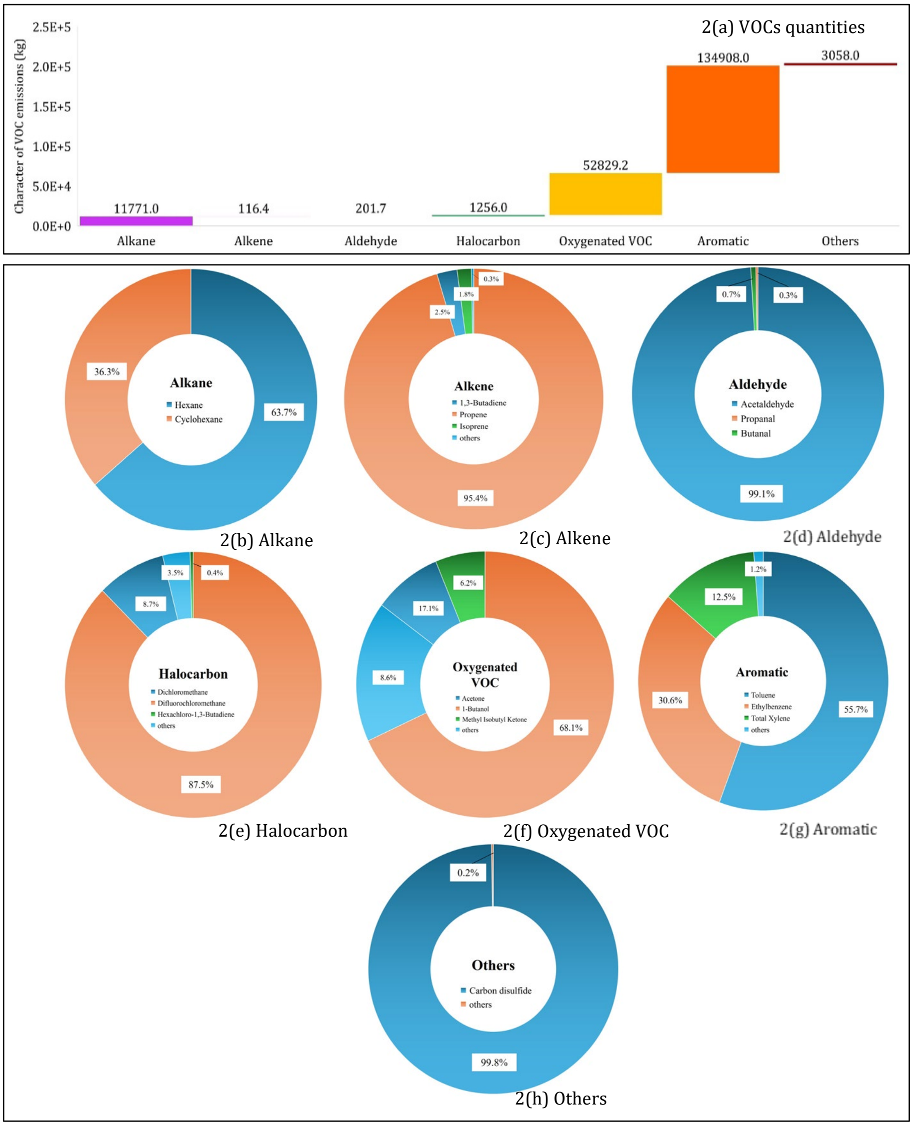
Carcinogenic risk was evaluated using the LCR equation by comparing the inhalation exposure concentration with the inhalation unit risk (IUR), as shown in Equation 5. Compounds with an LCR $>1.0 \times 10^{-4}$ are classified as high risk, an LCR between 1.0×10^{-5} and 1.0×10^{-4} as moderate risk, an LCR between 1.0×10^{-6} and 1.0×10^{-5} as probable risk, and an LCR $<1.0 \times 10^{-6}$ as negligible risk.[26] The specific RfC and IUR values for each substance were sourced from the U.S. EPA Guidelines for Carcinogen Risk Assessment and the IRIS. Additional sources include the Agency for Toxic Substances and Disease Registry (ATSDR), the California Environmental Protection Agency (CALEPA), the Provisional Peer-Reviewed Toxicity Values (PPRTV), and the Health Effects Assessment Summary Tables (HEAST).[5]

$$\mathrm{LCR} = EC_i \times IUR_i$$

Equation 5. Lifetime Cancer Risk (LCR) Calculation
Notes: LCR = Lifetime cancer risk (Continuous lifetime exposure during adulthood); EC_i = inhalation exposure concentration of of chemical i (µg/m^3); IUR_i = inhalation unit risk of chemical i (µg/m^3)$^{-1}$

Results

From the emission analysis of painting activities, a total of 82 VOCs were detected, with concentrations ranging from 2.19 to 9,325.29 µg/m^3. The VOC emissions were classified into seven groups: aromatics (66%) were the dominant category, followed by oxygenated VOCs (26%), alkanes (6%), halocarbons (1%), alkenes (0.1%), aldehydes (0.1%), and others (1%). The quantities of VOC emissions are shown in Figure 2(a), followed by Figure 2(b–h), which represent the percentage contribution of the seven categories of VOCs released from the process.



2(b) Alkane

2(c) Alkene

2(d) Aldehyde

2(e) Halocarbon

2(f) Oxygenated VOC

2(g) Aromatic

2(h) Others

Figure 2. (a) Quantities of Volatile Organic Compounds Emissions; (b–h) Percentage contribution of seven categories of Volatice Organic Compounds

Field measurements of stacks and the WWTP from the painting process revealed annual VOC emissions of 204 tons. The top ten VOCs accounted for 95.5% of the total emissions. Stack emissions were the dominant source, accounting for over 99% of emissions for most compounds (Table 1). The emission factor analysis revealed that toluene, ethylbenzene, and 1-butanol were the major VOC contributors, followed by total xylene (m-, p-, and o-xylene). Methyl isobutyl ketone and methyl ethyl ketone were primarily emitted from the WWTP.

The distribution of EC revealed notable differences across the receptor zones, as presented in Figure 3. The HE area, located within 200 m of the source, exhibited the highest EC levels, followed by the WE area. Elevated EC values were observed in wind directions between 0° and 45° (north–northeast) and 315°–360° (north–northwest), corresponding to the prevailing wind patterns in the area, as shown in Figure 1.

In the LE area, farther from the source, EC values ranged from 0.15 to 3.17 μg/m^3. The highest concentrations were found at LE-1 (3.17 μg/m^3) and LE-2 (2.46 μg/m^3), located 3.88 km north and 4.27 km northeast of the source, respectively. Despite being closer to the emission source, LE-8 (1.98 km) exhibited a slightly lower EC of 1.91 μg/m^3. The lowest EC values were observed at LE-4 (0.18 μg/m^3) and LE-5 (0.15 μg/m^3) toward the southwest–south direction.

Table 1. Top Ten Emission Factors

Ranking	VOCs species	Emission factor (kg/Vehicle)	% Contribution from process	% Weight from sources	
				Stacks	WWTP
1	Toluene	0.494	36.8	99.99	0.01
2	Ethylbenzene	0.271	20.2	99.99	0.01
3	1-Butanol	0.237	17.7	100	ND
4	Total Xylene	0.111	8.3	99.99	0.01
5	Hexane	0.038	3.7	100	ND
6	Acetone	0.049	2.2	100	ND
7	Cyclohexane	0.028	2.1	100	ND
8	Methanol	0.021	1.6	100	ND
9	Methyl Isobutyl Ketone	0.021	1.5	75.89	24.11
10	Methyl Ethyl Ketone	0.018	1.4	99.75	0.25
Top 10 summary		**1.288**	**95.5**		

Note: ND = Not detected

The high-exposure (HE) area, located closer to the source, exhibited substantially higher EC values. HE-2 (16.36 μg/m^3) and HE-1 (12.43 μg/m^3), both located within 200 m to the north and northeast, showed the highest concentrations. Other receptors within the HE area, including HE-3, HE-4, and HE-5, had lower concentrations ranging from 2.24 to 3.82 μg/m^3. HE-6 and HE-7, although located outside the main wind direction, showed higher EC levels due to the influence of the WWTP, which continuously emitted VOCs as a fugitive source. In contrast, EC levels in the WE area were similar to those in the LE area.

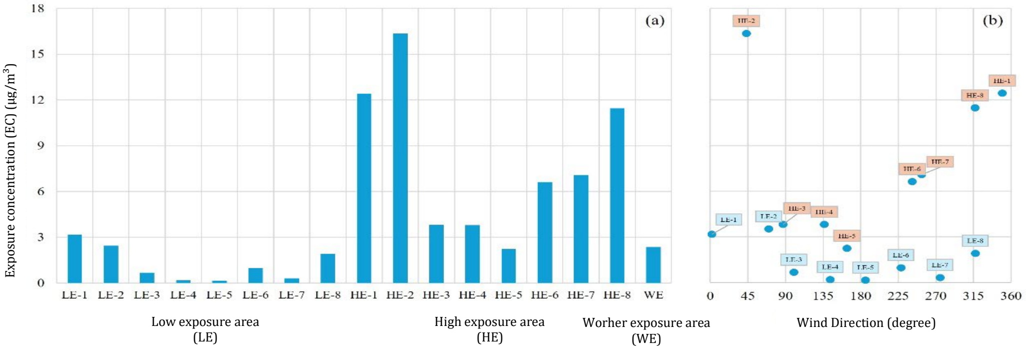


Figure 3. Exposure Concentration (EC) at the Receptor Sites; (b) Relationship Between EC and Wind Direction

The distribution of VOC exposure concentrations across the receptor sites was modeled using AERMOD, and the source contributions are illustrated in Figure 4. The results indicated that stacks were the predominant emission sources across all areas, particularly stack 5. In the LE area, stack 5 accounted for over 52% of the total exposure, whereas in the HE area, it accounted for more than 40%. This dominance corresponds to its larger stack diameter (3.00 × 6.10 m), which was approximately three times that of stacks 1–4 and four times that of stacks 6–7. In contrast, the HE area was additionally affected by the continuous VOC emissions from the WWTP. Directional analysis further indicated that the stacks predominantly affected receptors in the north-to-southeast quadrants, whereas the WWTP contributed more noticeably to the northwest and WE areas.

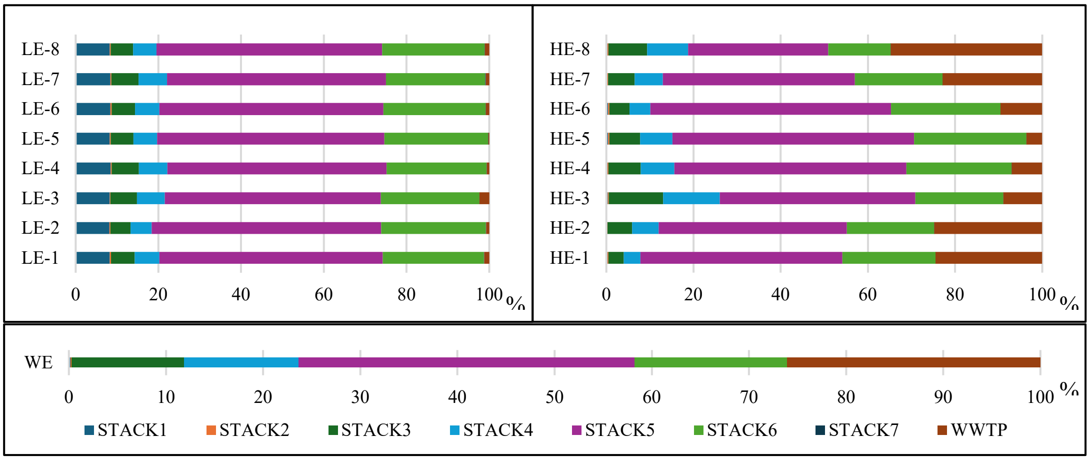


Figure 4. Percent Contribution of Volatile Organic Compounds Exposure Concentration at Receptor Locations

The noncarcinogenic risk was assessed using the HQ method based on inhalation exposure. All HQ values were below 1, indicating that the exposure levels were within the safe range. The highest HQ was observed at LE-1 (8.55×10^{-3}) in the northern direction, mainly attributed to acrolein exposure. In contrast, LE-4 and LE-5 exhibited the lowest HQ values at 2.82×10^{-4} and 2.31×10^{-4}, respectively, where total xylene contributed to more than 50% of the risk. In the HE area, HE-1 and HE-8 showed elevated HQ values of 7.73×10^{-2} and 7.05×10^{-2}, respectively, due to their proximity to the emission source and their location along the prevailing wind direction, as shown in Figure 1. The WE area exhibited an HQ value of 2.44×10^{-2}. However, when considering the proportional contribution of each compound to HQ, acrolein, xylene, ethylbenzene, benzene, and 1,2,4-trimethylbenzene were identified as the top five contributors across all locations. Because all HQ values were substantially below 1, the corresponding HI values for all receptors were also well below 1, indicating negligible noncarcinogenic health risks across the study area. The overall HQ values aggregated across all VOC species in the LE, HE, and WE areas are shown in Figure 5(a).

The LCR of individual compounds was aggregated for each area, revealing differences in pollutant concentrations and the relative contributions of specific compounds, as shown in Figures 5(b), 5(c), and 5(f). In the LE area, LE-1 and LE-2, which are located along the prevailing wind direction, showed the highest LCR values (1.6×10^{-6} µg/m^3 and 1.8×10^{-6} µg/m^3), primarily attributed to ethylbenzene and 1,2-dichloroethane, indicating probable risk levels. In the HE area, the highest LCR was observed at HE-8 (4.65×10^{-5} µg/m^3), located along the prevailing wind path and influenced by emissions transported from the stacks, indicating a moderate risk. Notably, at HE-8, which was situated near the WWTP, the contribution of ethylbenzene was relatively low (10.38%), whereas 1,2-dichloroethane was the dominant compound, accounting for 88.86% of the total LCR. Other compounds, such as 1,2-dibromoethane, benzene, and acetaldehyde, were present in very low proportions, ranging from 0.21% to 1.92% across all sites. The proportions of key compounds contributing to LCR are shown in Figures 5(d), 5(e), and 5(g). Overall, ethylbenzene posed a probable risk in the LE and WE areas, with an LCR between 1.0 × 10-6 and 1.0 × 10-5, while both ethylbenzene and 1,2-dichloroethane were identified as probable risks in the HE areas.

Discussion

This study demonstrated that the automotive manufacturing facility predominantly emitted aromatic VOCs from painting activities, particularly compounds such as toluene and ethylbenzene, which are characteristic of traditional solvent-based coating systems. The persistent dominance of aromatic species in automotive painting processes is consistent with other coating-related industries without air pollution control systems that prioritize surface durability and aesthetics,[27] such as wood furniture, metal surface, and shipbuilding industries, where aromatics commonly account for more than 60% of total VOC emissions.[12] Conversely, automotive painting in China exhibited more diverse VOC characteristics, especially at facilities using water-based paint systems and advanced emission controls such as regenerative thermal oxidizers (RTOs),[28] which demonstrated a significant increase in oxygenated VOCs, reaching up to 51.6%, with a corresponding decrease in aromatics. This shift reflects a technological transition toward lower-toxicity formulations aligned with environmental and health goals. Sectors adopting pure low-VOC or water-based formulations show a clear shift toward oxygenated VOCs, which are generally considered less hazardous and more environmentally friendly, particularly in terms of health risks and ozone formation.[29,30] The use of combined treatment technologies, particularly the installation of RTOs in high-emission stacks, can effectively reduce aromatic VOCs.[29]

From the distribution of exposure concentrations, the influence of meteorological factors, such as wind direction and topography, was clearly evident. Lower concentrations in the LE area confirmed the effectiveness of natural dispersion, as pollutants released from elevated sources, such as stacks, are diluted in the ambient before reaching ground level, supported by the prevailing south–southeast wind patterns.[31] This demonstrates how site planning and environmental conditions can naturally enhance pollutant dispersion. Therefore, industrial facilities should be located at least 200 m away from residential areas to minimize potential exposure risks.[24,32]

Further supporting these findings, AERMOD dispersion modeling showed that stacks were the main emission source for most receptors. Their large size influences airflow and exhaust patterns, leading to higher pollutant concentrations near the source, which gradually decrease with distance as pollutants are carried along the prevailing wind direction.[33] Although the WWTP contributed only a small portion overall, its localized effects highlighted the dynamic nature of fugitive emissions. VOCs emitted from wastewater diffuse passively without air pumps or active release mechanisms, resulting in smaller but strategically important contributions.[34] Continuous passive diffusion can sustain low-level chronic exposure near facility boundaries, as shown in HE-7 and HE-8 (close to the WWTP). Therefore, WWTP units should not be located close to communities, and the use of cover systems or emission controls is recommended when community receptors are present.

The noncarcinogenic risk assessment confirmed that all receptors remained within safe limits (less than 1). However, slightly higher values were noted for xylene, a main solvent component, and acrolein, which can form when aromatic VOCs are exposed to high temperatures in exhaust stacks.[35] However, the assessment identified the HE and WE areas as having the highest HQ values, highlighting the need for focused monitoring, particularly for workers and nearby residents located close to the stack emission sources.[36] The lifetime cancer risk assessment showed that VOCs from automotive painting activities were mainly influenced by ethylbenzene and 1,2-dichloroethane. Although these compounds had relatively low emission inventories, both are classified as Group 2B carcinogens by the International Agency for Research on Cancer (IARC) and have low IUR values, indicating their high toxicity and low threshold levels for human exposure.[5] Consequently, the LCR values were within the moderate and probable risk range in some LE, HE, and WE areas along the prevailing wind direction.[37] Notably, 1,2-dichloroethane was found to disperse and dilute more rapidly in ambient air before reaching ground level compared with ethylbenzene. This is likely due to the greater environmental persistence of benzene-related compounds, such as ethylbenzene, supporting a mechanistic explanation for the observed ground-level distribution patterns.[38]

Figure 5. (a) HQ for Noncarcinogenic Risk in the LE, HE, and WE areas; (b) LCR for the LE area; (c) LCR for the HE area; (d) VOCs contributing to LCR in the LE area; (e) VOCs contributing to LCR in the HE area; (f) LCR for the WE area; (g) VOCs contributing to LCR in the WE area.

This study provided compound-specific insights into VOC emissions from representative automotive painting operations in Thailand. The integration of field measurements, dispersion modeling, and health risk analysis in different areas was a key strength that supports evidence-based control planning to protect both workers and nearby communities. These limitations included the sampling conducted during normal full-capacity operations to represent a likely worst-case scenario. Nevertheless, this approach provided a conservative basis for pollution control planning. Future studies should include multi-seasonal monitoring, environmental receptor measurements, and further investigation of other environmental impacts, such as ozone formation, to support the development of more comprehensive emission standards.[11]

Conclusion

This study demonstrates the value of a compound-specific, bottom-up approach for understanding VOC emissions from automotive painting facilities. By integrating field measurements with dispersion modeling, it highlights how emission sources and local meteorology jointly shape exposure patterns for workers and surrounding communities. The health risk assessment identifies specific VOCs that warrant regulatory attention, emphasizing the need for updated emission standards. Overall, the findings support evidence-based planning and targeted emission control strategies to better protect public health in industrial areas.

Abbreviations

VOCs: volatile organic compounds; PCD: Pollution Control Department; WWTP: wastewater treatment plant; EPA: Environmental Protection Agency; LE: low exposure; HE: high exposure; WE: worker exposure; HI: hazard index; LCR: lifetime cancer risk; EC: exposure concentration; HQ: hazard quotient; IRIS: Integrated Risk Information System; IUR: inhalation unit risk.

Ethics Approval and Consent to Participate

This study was reviewed and approved in accordance with the Standard Operating Procedures of the Ethical Review Committee for Human Research, Faculty of Public Health, Mahidol University, on November 22, 2022, under the protocol titled *Integrated Management of Odor and Air Pollutant Emission Control from the Motor Vehicle Manufacturing Industry.* This protocol complies with the Research with Exemption category.

Competing Interest

The authors declare no competing financial or personal interests that may influence the performance or presentation of the work described in this manuscript.

Availability of Data and Materials

Please contact the corresponding author for any inquiries regarding the data supporting these findings. Owing to data privacy restrictions, the research team could not publicly share the data.

Authors' Contribution

VK: Conceptualization, methodology, software, validation, and writing—original draft preparation. JK, NP, and WM: writing, reviewing, and editing. ST: supervision.

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