The University of Tehran Press

Pollution

Print ISSN: 2383-451X
Online ISSN: 2383-4501

https://jpoll.ut.ac.ir/

Prediction of Air Pollution by Chlorinated Volatile Organic Compounds (CVOs) Using the LandGEM model and Hazard Coefficients at the West Bandung Regency landfill

Darwel[1]✉, Aidil Fitrah[2], Andi Ferina Herbourine Bonita[3], Dana Prayoga Irawan[4], Anshah Silmi Afifah[5], Mufti Rosyid Very Murtadho[6], Joshua Vidal[7], Yura Witsqa Firmansyah[8]

[1]Department of Environmental Health, Politeknik Kesehatan Kementerian Kesehatan Padang, Padang 25146, Indonesia
[2]Department of Environmental Health, Faculty of Public Health, Universitas Mulawarman, 75242, Samarinda, Indonesia
[3]Department of Occupational Health and Safety, Faculty of Public Health, Universitas Tadulako, 94148, Palu, Indonesia
[4]Department of Nursing, Politeknik Karya Husada, 16424, Jakarta, Indonesia
[5]Department of Furniture Production Engineering, Politeknik Industri Furnitur dan Pengolahan Kayu, 51371, Kendal Regency, Indonesia
[6]Doctoral Program in Management, Universitas Muhammadiyah Malang, Malang 65144, Indonesia
[7]Research Associate, Coastal Cities At Risk in the Philippines, Ateneo De Manila University, 1108, Quezon City, Philippines
[8]Department of Hospital Administration, STIKES Adi Husada, 60141, Surabaya, Indonesia

Article Info

Article type:
Research Article

Article history:
Received: 19 February 2026
Revised: 14 June 2026
Accepted: 12 September 2026

Keywords:
Chlorinated Volatile Compounds; Environmental Health Risk Assessment; Inhalation Exposure; Landfill Gas Emissions; Waste Pickers

ABSTRACT

Urban waste management through landfills remains an environmental and public health challenge in developing countries, as the biological degradation and physicochemical reactions within them produce complex gas emissions, including potentially hazardous non-methane organic compounds. Chlorinated volatile organic compounds such as 1,1,1-trichloroethane, 1,1,2,2-tetrachloroethane, and ethylidene dichloride have high persistence and significant toxicological profiles, posing a risk to vulnerable populations such as waste takers who are exposed to landfill gases during long working hours. This study used a quantitative cross-sectional design based on Environmental Health Risk Assessment to assess inhalation exposure in 101 waste takers at the Sarimukti landfill in West Java. Pollutant concentrations were estimated using the Landfill Gas Emissions Model based on waste generation data from 2006 to 2021, then converted to mg/m^3 and used to calculate inhalation intake and hazard coefficients. The results showed that 1,1-dichloroethane had the highest concentration (9.72 mg/m^3) and the largest intake (1,090 mg/kg/day), followed by 1,1,2,2-tetrachloroethane and 1,1,1-trichloroethane. All hazard coefficients values were below 1.0, indicating that the individual non-carcinogenic risk was still within safe limits. However, chronic exposure, long working hours, and exposure to a mixture of landfill gas pollutants still have the potential to increase cumulative health risks. These findings confirm that an intake-based approach is more representative in assessing occupational risks and support the need for continuous monitoring and integrated risk management strategies to protect the health of waste takers in landfill environments.

Cite this article: Darwel, Fitrah, A., Bonita, A. F. H., Irawan, D. P., Afifah, A. S., Murtadho, M. R. V., Vidal, J., & Firmansyah, Y. W. (2026). Prediction of Air Pollution by Chlorinated Volatile Organic Compounds (CVOs) Using the LandGEM model and Hazard Coefficients at the West Bandung Regency landfill. *Pollution*, 12(3), 898-910. https://doi.org/10.22059/poll.2026.411546.3299

DOI: https://doi.org/10.22059/poll.2026.411546.3299

*Corresponding Author Email: welpiero1@gmail.com

INTRODUCTION

The management of municipal solid waste remains a critical environmental and public health challenge worldwide, particularly in rapidly urbanizing regions of developing countries. Landfilling continues to be the dominant waste disposal method due to its economic feasibility and operational simplicity (Escamilla-García, 2024; Nanda & Berruti, 2021). However, landfills are not passive waste repositories, they function as complex biogeochemical systems that generate a wide range of gaseous pollutants through physical volatilization, chemical reactions, and biological degradation processes (Raimi et al., 2021; Singh, 2024; Y. Wang et al., 2025). Landfill gas emissions are commonly associated with methane and carbon dioxide, yet increasing evidence indicates that non-methane organic compounds (NMOCs), particularly hazardous air pollutants (HAPs), represent a substantial but under-recognized threat to human health (De Guzman & Schiller, 2025; El-Emam, 2025; Fikri et al., 2025; Firmansyah et al., 2025; Kiehbadroudinezhad et al., 2024).

Among NMOCs, chlorinated volatile organic compounds (VOCs) are of particular concern due to their chemical stability, persistence in the atmosphere, and elevated toxicological profiles (Plantz et al., 2025; Tsai, 2023; Yan et al., 2025). Compounds such as 1,1,1-trichloroethane (methyl chloroform), 1,1,2,2-tetrachloroethane, and ethylidene dichloride (1,1-dichloroethane) are widely used in industrial solvents, degreasing agents, adhesives, and chemical manufacturing processes. When products containing these substances are discarded into municipal waste streams, they may volatilize during landfill operations and contribute to ambient air contamination. Unlike simpler hydrocarbons, chlorinated VOCs exhibit higher lipophilicity and resistance to degradation, increasing their potential for prolonged environmental presence and human exposure.

From a toxicological perspective, chlorinated VOCs are associated with a range of adverse health effects, including neurotoxicity, hepatotoxicity, nephrotoxicity, and hematological disorders (Ahmed et al., 2021; Ogbodo et al., 2022; Zeliger, 2022). Several compounds within this group have been classified as possible or suspected human carcinogens, with long-term inhalation exposure linked to elevated risks of liver and central nervous system damage (Agboola et al., 2024; Dehghani et al., 2022; Khan et al., 2021). In addition to direct toxicity, chlorinated VOCs participate in atmospheric photochemical reactions, contributing to the formation of secondary pollutants such as ground-level ozone, which further exacerbate respiratory morbidity and environmental degradation.

Waste pickers operating in landfill environments represent a highly vulnerable population to these exposures. Informal waste workers typically operate without adequate personal protective equipment, occupational health surveillance, or regulatory oversight (Parulian et al., 2025). Their daily activities involve prolonged periods of proximity to waste piles and active emission zones, increasing inhalation exposure to landfill gases. Despite this vulnerability, most environmental health studies in landfill settings have prioritized greenhouse gases, particulate matter, or sulfur-based pollutants, while hazardous chlorinated VOCs remain overlooked, particularly in low- and middle-income countries.

In Indonesia, rapid urban growth and increasing waste generation have intensified pressure on existing landfill infrastructure. The Sarimukti landfill in West Java serves as a major disposal site for multiple urban areas and has been operating under conditions of overcapacity, frequent landfill fires, and limited gas management systems. Previous environmental health studies conducted at this site have demonstrated significant non-carcinogenic risks associated with sulfur dioxide and other gaseous pollutants, even when measured concentrations were below national ambient air quality standards (Fikri et al., 2025; Firmansyah et al., 2025; Parulian et al., 2025; Darwel et al., 2026). These findings underscore the limitations of concentration-based regulatory thresholds and highlight the importance of risk-based approaches such as Environmental Health Risk Assessment (EHRA) for evaluating real-world exposure scenarios.

However, to date, no comprehensive risk assessment has focused on hazardous chlorinated air pollutants derived from landfill gas emissions at Sarimukti or similar landfill settings in Indonesia. Moreover, direct field measurements of chlorinated VOCs are often constrained by technical, financial, and logistical limitations. In this context, the Landfill Gas Emissions Model (LandGEM), developed by the United States Environmental Protection Agency, offers a robust and widely accepted approach for estimating NMOC emissions based on waste input data and first-order decay kinetics (Firmansyah et al., 2025). When integrated with EHRA frameworks, LandGEM enables the projection of pollutant concentrations and the quantification of health risks among exposed populations.

Therefore, this study aims to assess exposure levels and associated health risks of hazardous chlorinated air pollutants specifically 1,1,1-trichloroethane, 1,1,2,2-tetrachloroethane, and ethylidene dichloride among waste pickers at the Sarimukti landfill in Indonesia. By combining LandGEM modeling with Environmental Health Risk Assessment, this research seeks to estimate pollutant intake, characterize non-carcinogenic health risks, and determine safe exposure limits for vulnerable populations. The findings are expected to contribute to evidence-based risk management strategies, strengthen landfill air quality monitoring frameworks, and support the development of early warning systems for hazardous air pollutants in landfill environments.

MATERIALS AND METHODS

Study design and research approach

This study employed a quantitative, cross-sectional design using the EHRA framework to evaluate inhalation exposure to hazardous chlorinated air pollutants among waste pickers at the Sarimukti landfill, West Java, Indonesia. The EHRA approach was selected to quantify non-carcinogenic health risks based on real-world exposure scenarios, integrating modeled pollutant concentrations with individual exposure characteristics. The assessment focused on inhalation as the primary exposure pathway, considering the volatile nature of chlorinated organic compounds and the occupational activities of waste pickers in landfill environments.

Study area

The study was conducted at the Sarimukti landfill, a major municipal solid waste disposal site serving Bandung City, Cimahi City, and West Bandung Regency. Operating since 2006, the landfill has experienced chronic overcapacity, frequent landfill fires, and limited gas control infrastructure, conditions that facilitate the volatilization and dispersion of landfill gas pollutants. The site hosts a large informal workforce of waste pickers who work daily near active waste cells, making it a representative location for assessing occupational exposure to landfill gas emissions in developing country settings.

Target population and sampling

The study population consisted of waste pickers actively working at the Sarimukti landfill. Respondents were selected using accidental sampling based on accessibility and willingness to participate. Inclusion criteria included individuals aged 17 years or older, actively working at the landfill for at least six months, and providing informed consent. A total of 101 respondents were recruited. This total is based on a sample size calculation using the G*Power software, with a 5% significance level, a 95% confidence interval, and an effect size of 0.5. Primary exposure-related data were collected through structured interviews, including body weight, daily exposure duration, exposure frequency, and length of employment at the landfill.

Pollutant selection and characterization

This study focused on three hazardous chlorinated volatile organic compounds commonly associated with industrial solvents and classified as hazardous air pollutants 1,1,1-trichloroethane (methyl chloroform), 1,1,2,2-tetrachloroethane, and ethylidene dichloride (1,1-dichloroethane). These compounds were selected based on their toxicity profiles, persistence, potential presence within landfill NMOCs, and relevance to occupational inhalation exposure.

Estimation of pollutant concentrations using LandGEM

Ambient air concentrations of the selected chlorinated pollutants were estimated using the Landfill Gas Emissions Model (LandGEM) version 3.02, developed by the United States Environmental Protection Agency (USEPA). LandGEM estimates annual landfill gas emissions based on a first-order decay equation using historical waste input data, methane generation potential, and decay rate constants.

Annual waste generation data from 2006 to 2021 were obtained from the West Java Provincial Environmental Agency and used as input parameters in the model. LandGEM produces total NMOC concentrations; therefore, individual chlorinated compound concentrations were derived by applying compound-specific volume fractions based on published landfill gas composition profiles and USEPA AP-42 references.

The modeled concentrations were expressed in parts per million by volume (ppmv) and converted to mass concentrations (mg/m³) using the following equation:

$$C = \frac{\text{ppmv x MW}}{24.45} \quad (1)$$

Where MW represents the molecular weight of each compound, and 24.45 is the molar volume of an ideal gas at standard conditions (25°C, 1 atm).

Exposure assessment

Individual inhalation exposure was estimated to be using EHRA principles by integrating pollutant concentrations with respondent-specific exposure parameters. The intake of each pollutant was calculated using the following equation:

$$\text{Ink} = \left(\frac{C \times R \times tE \times fE \times Dt}{Wb \times tavg} \right) \quad (2)$$

Correlation analyses using Pearson's and Spearman's tests were conducted to assess the strength and direction of associations between DDE exposure and health outcomes. Risk estimates were calculated using odds ratios (OR) and relative risks (RR) with 95% confidence intervals (CI). Statistical significance was determined at a p-value of < 0.05.

Risk characterization

Non-carcinogenic health risks were characterized by calculating the hazard coefficients (HQ) for each pollutant using the following equation:

$$\text{RQ} = \left(\frac{\text{Ink}}{RfC} \right) \quad (3)$$

Where RfC represents the inhalation reference concentration for each compound, obtained from the USEPA Integrated Risk Information System (IRIS). An HQ value greater than 1 indicates the potential for adverse non-carcinogenic health effects.

The reference concentration value for 1,1,1-Trichloroethane is 555 mg/m3 based on the European Commission Directive 2000/39/EC establishing a first list of indicative occupational exposure limit values. Mild respiratory effects in humans have been reported following exposure to 1,1,2,2-tetrachloroethane. Mucosal irritation was observed at a concentration of 13 ppm (89.2 mg/m^3) in two individuals exposed for 10 to 30 minutes, whereas no such effects were reported at a lower concentration of 2.9 ppm (Agency for Toxic Substances and Disease Registry, 2008). Reference concentration of 1,1-Dichloroethane at 100 ppm (400 mg/m^3) (Agency for Toxic Substances and Disease Registry, n.d.).

RESULTS AND DISCUSSION

Pollutant concentration and intake values

The concentrations of hazardous chlorinated air pollutants used in this study were derived from LandGEM modeling outputs, which estimate landfill gas composition in volumetric units (ppmv) as part of total non-methane organic compounds. To enable quantitative exposure and health risk assessment using the EHRA framework, these modeled concentrations were converted into mass-based units (mg/m^3). This conversion is essential for estimating inhalation intake and calculating hazard coefficientss, as EHRA equations require pollutant concentrations expressed in mass per unit volume of air. The conversion was performed using molecular weight–based calculations under standard atmospheric conditions.

The modeled concentrations of hazardous chlorinated volatile organic compounds derived from LandGEM are presented in Table 1. After conversion from ppmv to mg/m^3, 1,1-dichloroethane showed the highest estimated concentration (9.72 mg/m^3), followed by 1,1,2,2-tetrachloroethane (7.55 mg/m^3) and 1,1,1-trichloroethane (2.62 mg/m^3). These findings indicate that chlorinated VOCs constitute a measurable fraction of the NMOC emissions at the Sarimukti landfill.

In addition to concentration estimates, LandGEM modeling generated long-term emission projections across the landfill lifecycle, as illustrated in Figure 1. The emission curves exhibit a characteristic first-order decay pattern, with a pronounced peak during the early operational phase followed by a gradual exponential decline. This behavior reflects the kinetic assumptions of the LandGEM model, in which gas generation is driven by the degradation rate constant (k) and the degradable organic carbon fraction within deposited waste. Similar temporal dynamics of VOC emissions have been consistently reported in recent landfill modeling and field-based monitoring studies, confirming that emission intensity typically reaches its maximum shortly after waste placement due to accelerated anaerobic biodegradation and enhanced volatilization processes (Nurjaya et al., 2025; Ramprasad et al., 2022).

The elevated early-stage emissions are particularly significant in tropical landfill settings such as Sarimukti, where higher ambient temperatures and moisture availability can accelerate

Table 1. Conversion of Pollutant Concentration Based on the LandGEM Model

Pollutant	Concentration (ppmv)	Molecule Weight	Concentration Conversion (mg/m^3)
1,1,1-Trichloroethane	0.48	133.41	2.62
1,1,2,2-Tetrachloroethane	1.10	167.85	7.55
1,1-Dichloroethane	2.4	98.97	9.72

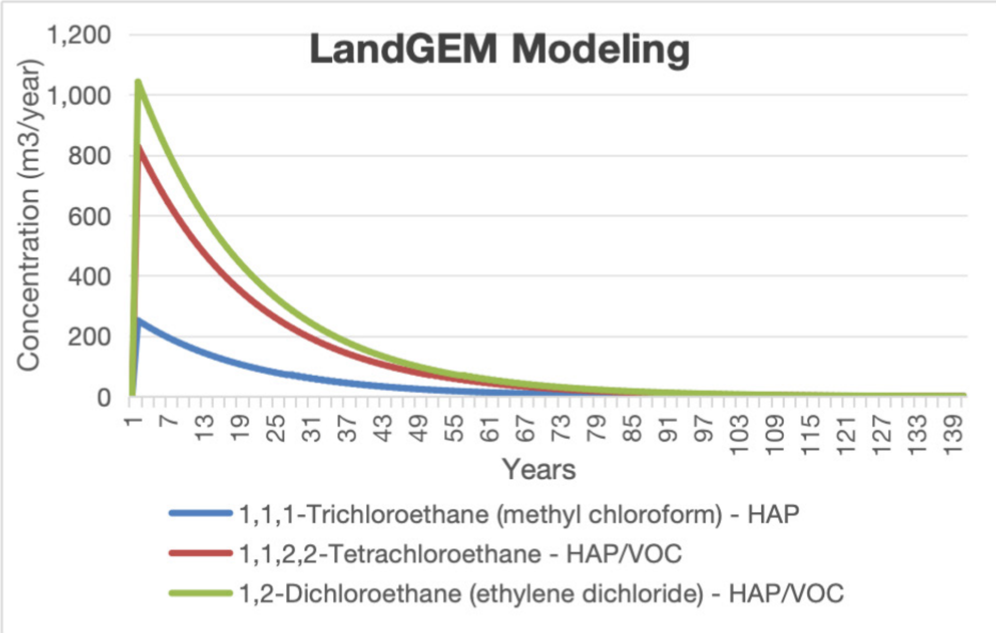

Fig. 1. ***

microbial activity and organic matter decomposition. Enhanced biodegradation rates may consequently increase the mobilization of halogenated compounds entrained within mixed municipal waste streams. Such environmental conditions potentially amplify short- to medium-term exposure intensity, especially in unmanaged or semi-controlled landfill systems where gas capture infrastructure is limited (Rasapoor et al., 2021).

Among the evaluated compounds, 1,1-dichloroethane consistently demonstrated the highest emission magnitude. This dominance suggests substantial solvent-related waste inputs and limited upstream segregation of hazardous household and small-scale industrial waste. Recent investigations have shown that halogenated VOCs remain persistent constituents of landfill gas, particularly in sites where municipal and industrial wastes are co-disposed or where historical waste management practices lacked source separation protocols (Agency for Toxic Substances and Disease Registry, 2015; Gao et al., 2025; X.-G. Wang et al., 2025). Although chlorinated VOCs typically constitute only a minor fraction of total landfill gas compared to methane and carbon dioxide, their toxicological relevance is disproportionately high due to greater systemic toxicity, lipophilicity, and potential for bioaccumulation (X.-G. Wang et al., 2025).

The long emission tail observed in Figure 1 further indicates that chlorinated VOC release may persist for several decades, even after peak decomposition phases have subsided. This prolonged emission period has important implications for both environmental quality and occupational exposure. Persistent low-level emissions can sustain chronic inhalation exposure among informal workers who remain active at landfill sites over extended timeframes. Moreover, the absence of engineered gas collection systems may result in diffuse emissions from active working faces, temporary waste piles, and uncovered cells, thereby increasing spatial variability in exposure intensity.

From an occupational health perspective, the temporal emission pattern is particularly critical. Waste pickers operating during peak emission years or in freshly deposited waste zones are likely to experience higher short-term exposure concentrations. Empirical evidence from working-face monitoring studies indicates that VOC concentrations can fluctuate due to operational activities such as waste unloading, compaction, and disturbance of previously buried layers, which can temporarily elevate airborne contaminant levels (Liu et al., 2023). These microenvironmental fluctuations are often not captured by regulatory ambient monitoring but may significantly influence personal exposure.

Although the modeled concentrations reported in Table 1 remain below many short-term occupational exposure limits, reliance solely on concentration thresholds may underestimate long-term health implications. Chronic inhalation exposure to chlorinated VOCs has been associated with neurological impairment, hepatotoxicity, and renal dysfunction, particularly under sustained low-dose scenarios (Nie et al., 2018). Risk-based assessment frameworks, such as EHRA, emphasize cumulative exposure metrics rather than instantaneous concentration exceedances. Indeed, studies conducted in Indonesian landfill contexts have demonstrated that even when ambient concentrations comply with national regulatory standards, intake-based calculations frequently identify non-carcinogenic risks among informal waste workers due to extended exposure duration and lack of protective equipment (Qolifah et al., 2024).

The integration of concentration magnitude (Table 1) with lifecycle emission dynamics (Figure 1) therefore provides a more comprehensive exposure characterization framework. Concentration values represent the environmental burden at a given time point, whereas emission projections contextualize the temporal persistence and potential variability of that burden. Together, these findings underscore the importance of transitioning from concentration-based compliance assessment toward risk-based evaluation approaches that account for occupational vulnerability, exposure duration, and cumulative pollutant interactions.

Collectively, the modeled emission trends and concentration estimates establish a robust quantitative foundation for subsequent inhalation intake estimation and non-carcinogenic risk characterization among waste pickers at the Sarimukti landfill.

Inhalation Intake Levels among Waste Pickers

The estimated inhalation intake levels of chlorinated pollutants among waste pickers at the Sarimukti landfill are presented in Table 2. Intake values were calculated under two exposure scenarios: real time exposure conditions based on current occupational characteristics and a projected 30-year exposure duration to reflect chronic risk assessment assumptions.

The inhalation intake estimates presented in Table 2 provide critical insight into the biologically relevant exposure burden experienced by waste pickers operating in the Sarimukti landfill environment. Under real time exposure conditions, 1,1-dichloroethane exhibited the highest average intake (1.090 mg/kg/day), followed by 1,1,2,2-tetrachloroethane (0.847 mg/kg/day) and 1,1,1-trichloroethane (0.294 mg/kg/day). This intake hierarchy closely mirrors the modeled ambient concentration patterns (Table 1 and Figure 1), reinforcing the fundamental exposure science principle that inhalation intake is directly proportional to contaminant concentration, inhalation rate, and exposure duration (Pan et al., 2023; Zhao et al., 2023). In occupational

Table 2. Pollutant Intake Levels among Waste Takers at Sarimukti Landfill (n=101)

Variable	Average (mg/kg/day)
Intake of 1,1,1-Trichloroethane real time	0.294
Intake of 1,1,1-Trichloroethane 30 years	0.080
Intake of 1,1,2,2-Tetrachloroethane real time	0.847
Intake of 1,1,2,2-Tetrachloroethane 30 years	0.232
Intake of 1,1-Dichloroethane real time	1.090
Intake of 1,1-Dichloroethane real time	0.299

microenvironments such as landfill working faces, where waste disturbance, compaction, and gas release occur continuously, airborne chlorinated VOC concentrations can increase, resulting in elevated internal dose among workers (Kiviranta et al., 1999; Liu et al., 2023).

When intake was projected over a 30-year exposure duration, the estimated values decreased to 0.299 mg/kg/day for 1,1-dichloroethane, 0.232 mg/kg/day for 1,1,2,2-tetrachloroethane, and 0.080 mg/kg/day for 1,1,1-trichloroethane. This reduction reflects the time-averaging component incorporated within EHRA, where intake is normalized over a longer averaging time period to represent chronic exposure scenarios (United States Environmental Protection Agency, 2025). Although lower than real time values, these chronic intake estimates remain toxicologically significant because long-term health effects are primarily determined by cumulative dose rather than short-term peak exposure concentrations. Chronic inhalation exposure to chlorinated aliphatic hydrocarbons has been shown to result in bioaccumulation and repeated systemic distribution, particularly affecting lipid-rich tissues such as the central nervous system, liver, and kidneys (Qolifah et al., 2024; United States Department of Health and Human Services, 2015, 2024).

The elevated intake observed for 1,1-dichloroethane can be attributed to both its higher environmental concentration and prolonged daily exposure duration reported by respondents. Intake is mathematically influenced by exposure time, frequency, and duration, meaning that informal waste pickers who spend extended hours near emission sources experience greater cumulative dose compared to the general population. Similar landfill-based studies have reported that inhalation intake among waste workers is strongly influenced by localized VOC concentrations and behavioral exposure factors, including working hours, proximity to waste deposition zones, and absence of respiratory protection (Li et al., 2023). These findings highlight the importance of considering occupational activity patterns when evaluating environmental exposure risks.

From a toxicological perspective, chlorinated VOCs such as 1,1-dichloroethane and tetrachloroethane are classified as systemic toxicants with well-documented neurotoxic, hepatotoxic, and nephrotoxic effects following chronic inhalation exposure. Experimental and epidemiological studies have demonstrated that repeated inhalation of chlorinated solvents can impair cognitive function, disrupt hepatic enzyme systems, and induce renal tubular damage, even at low exposure concentrations when sustained over long periods. These adverse outcomes occur because inhaled VOCs are rapidly absorbed through the pulmonary alveoli and distributed via systemic circulation, resulting in repeated internal organ exposure (Huang et al., 2020; Pan et al., 2023). Importantly, toxicological risk is driven more strongly by cumulative internal dose than by isolated concentration exceedances.

The findings of this study are particularly relevant in the context of informal occupational settings, where waste pickers typically operate without adequate personal protective equipment and are exposed for prolonged periods. Research conducted in Indonesian landfill environments has demonstrated that even when ambient VOC concentrations comply with national environmental standards, intake-based risk assessment frequently identifies elevated non-carcinogenic risk due to prolonged exposure duration and cumulative dose effects (Yuan & Zoungrana, 2025). This discrepancy occurs because environmental standards are generally designed to protect the general population rather than highly exposed occupational subgroups (de Titto & Savino, 2024; World Health Organization, 2010).

The intake estimates presented in this study therefore provide a more biologically meaningful measure of exposure compared to concentration data alone. While environmental concentrations represent external exposure conditions, intake calculations translate these concentrations into internal dose metrics that directly determine toxicological risk.

Hazard coefficients of pollutants

The non-carcinogenic risk characterization results are presented in Table 3, expressed as HQ values for both real time and 30-year exposure scenarios.

All calculated HQ values were below the safety threshold of 1.0, indicating that non-carcinogenic risks from individual chlorinated compounds remain within acceptable limits under current exposure assumptions. Under real time conditions, HQ values were 0.0005 for 1,1,1-trichloroethane, 0.0095 for 1,1,2,2-tetrachloroethane, and 0.0027 for 1,1-dichloroethane. When averaged over a 30-year exposure duration, HQ values decreased further to 0.0001, 0.0026, and 0.0007, respectively.

From an exposure science perspective, HQ values below unity indicate that estimated intake remains lower than the threshold considered unlikely to produce appreciable adverse health effects during a lifetime of exposure (United States Environmental Protection Agency, 2011, 2025). However, HQ values represent risk estimates for individual compounds and do not account for potential additive or synergistic interactions among multiple co-occurring pollutants. In landfill environments, workers are exposed to complex mixtures of VOCs, methane, and other gaseous contaminants generated from waste decomposition processes. Previous landfill-based risk assessments have similarly reported HQ values below 1 for individual VOCs while emphasizing that cumulative exposure and occupational activity patterns significantly influence overall health risk, particularly among informal waste workers lacking adequate respiratory protection (Danjou et al., 2019; Li et al., 2023; Ravina et al., 2020).

The consistently higher HQ observed for 1,1,2,2-tetrachloroethane reflects the combined influence of exposure magnitude and toxicological sensitivity. Chlorinated solvents are known to exert systemic toxicity through repeated inhalation exposure, primarily affecting the central nervous system, liver, and kidneys due to their lipophilic properties and efficient pulmonary absorption (Abidin et al., 2024; Ravina et al., 2020). Even when HQ values remain below 1, chronic low-dose exposure over extended occupational durations may contribute to subclinical physiological alterations, including hepatic enzyme changes, neurobehavioral effects, and renal stress. This is particularly relevant in informal landfill settings, where workers may experience prolonged daily exposure without consistent use of personal protective equipment, increasing cumulative internal dose despite relatively low environmental concentrations.

Importantly, the reduction in HQ values observed in the 30-year exposure scenario reflects the time-averaging principle incorporated within EHRA, where intake is normalized over a lifetime exposure period. While this approach provides a standardized framework for evaluating chronic risk, it may underestimate short-term peak exposure risks occurring during active waste handling and gas release events. Landfill working-face environments are characterized by dynamic emission patterns, where localized concentrations can fluctuate due to waste disturbance, meteorological conditions, and landfill operational activities (Fikri et al., 2025; Pan et al., 2023). Consequently, real time exposure conditions remain highly relevant

Table 3. Pollutant Hazard Quotient among Waste Takers at Sarimukti Landfill (n=101)

Variable	Average
Intake of 1,1,1-Trichloroethane real time	0.0005
Intake of 1,1,1-Trichloroethane 30 years	0.0001
Intake of 1,1,2,2-Tetrachloroethane real time	0.0095
Intake of 1,1,2,2-Tetrachloroethane 30 years	0.0026
Intake of 1,1-Dichloroethane real time	0.0027
Intake of 1,1-Dichloroethane real time	0.0007

for understanding occupational risk among waste pickers. This study has limitations in that it used a predictive model for the pollutants 1,1,1-trichloroethane, 1,1,2,2-tetrachloroethane, and ethylidene dichloride without conducting field validation; furthermore, no assessment of the relationship with respiratory symptoms was performed.

Although individual HQ values indicate acceptable non-carcinogenic risk, these findings should be interpreted cautiously within the broader context of cumulative exposure and mixed-pollutant environments. Risk assessment frameworks recommend evaluating the hazard index, which represents the sum of HQ values across multiple pollutants, to provide a more comprehensive assessment of combined exposure effects. This approach is particularly important in landfill settings, where simultaneous exposure to multiple chlorinated VOCs and other gaseous contaminants may result in additive toxicological effects. Therefore, while the present findings suggest that individual compound exposures remain within acceptable limits, continued monitoring and integrated risk assessment are essential to ensure long-term occupational health protection among informal waste workers.

ACKNOWLEDGEMENT

Authors would like to express our deepest gratitude to the Dinas Lingkungan Hidup Provinsi Jawa Barat (West Java Provincial Environment Agency) for its support, data facilitation, and administrative assistance provided during the implementation of this research. The contribution in providing data on waste generation and information related to the management of the Sarimukti landfill played a very important role in the process of emission modeling and environmental health risk analysis. This support enabled this research to be carried out comprehensively to improve scientific studies related to landfill air quality and the protection of vulnerable populations, especially waste takers at the Sarimukti landfill.

GRANT SUPPORT DETAILS

The present research did not receive any financial support.

CONFLICT OF INTEREST

The authors declare that there is not any conflict of interest regarding the publication of this manuscript. In addition, ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancy have been completely observed by the authors.

CONCLUSION

This study quantified inhalation exposure and non-carcinogenic health risks associated with chlorinated VOC emissions among waste pickers at the Sarimukti landfill using LandGEM modeling and the EHRA framework. The results showed that 1,1-dichloroethane exhibited the highest concentration and intake, followed by 1,1,2,2-tetrachloroethane and 1,1,1-trichloroethane, reflecting the direct influence of ambient concentration and exposure duration on internal dose. Emission projections demonstrated a typical landfill decay pattern, indicating that exposure potential persists over extended operational periods.

Although all HQ values remain below the safety threshold of 1.0, indicating acceptable non-carcinogenic risk under current assumptions, continuous occupational exposure and cumulative intake remain relevant concerns in informal landfill environments. These findings highlight the importance of intake-based risk assessment for accurately characterizing occupational exposure. Continued monitoring and integrated risk management strategies are essential to ensure long-term health protection for waste pickers exposed to landfill gas emissions.

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