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Environmental Health Risk Assessment of Xylene Exposure for Waste Pickers at a Landfill in West Java, Indonesia

Elanda Fikri[1*], Yura Witsqa Firmansyah[2], Sapta Suhardono[3], Tri Kurniawati[4], Anshah Silmi Afifah[5], Adi Nugroho[6]

[1] Department of Environmental Health, Politeknik Kementerian Kesehatan Bandung, Bandung 40171, Indonesia
[2] Department of Hospital Administration, STIKes Adi Husada, Surabaya 60141, Indonesia
[3] Department of Environmental Science, Faculty of Mathematics and Natural Sciences, Universitas Sebelas Maret, Surakarta 57126, Indonesia
[4] Department of Economics Education, Faculty of Economics and Business, Universitas Negeri Padang, Padang 25131, Indonesia
[5] Department of Furniture Production Engineering, Politeknik Industri Furnitur dan Pengolahan Kayu, Kendal Regency 51371, Indonesia
[6] Department of Health Information and Medical Record, Faculty of Health, Universitas Aisyah Pringsewu, Pringsewu Regency 35372, Indonesia

Corresponding Author Email: elanda.fikri@gmail.com

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ABSTRACT

Xylene is a volatile organic compound (VOC) commonly detected in landfill gas emissions originating from synthetic and industrial waste residues. This study aims to assess the environmental health risks associated with xylene exposure among waste pickers at the Sarimukti Landfill, West Java, Indonesia. A total of 101 respondents participated through structured interviews to obtain exposure parameters. The assessment applied the Environmental Health Risk Assessment (EHRA) framework using the inhalation exposure route. The xylene concentration (52.13 mg/m³) was derived from the total non-methane organic compounds (NMOC) predicted by the LandGEM model, proportionally adjusted based on xylene's fraction within the NMOC profile. Using this concentration, the daily intake and hazard quotient (HQ) were estimated under real-time and 30-year projection scenarios, with a reference concentration (RfC) of 0.2 mg/m³. The mean intake values were 5.851 ± 1.127 mg/kg/day (real-time) and 1.605 ± 0.312 mg/kg/day (30-year projection), resulting in mean HQs of 29.255 ± 5.628 and 8.025 ± 1.561, respectively, both significantly exceeding the safety threshold ($p < 0.000$). Risk control calculations indicated that the safe exposure duration should not exceed 0.315 hours per session, with a weekly exposure frequency of no more than 11 times. Xylene exposure also poses indirect environmental risks through the formation of ground-level ozone, contributing to respiratory deterioration and climate change. These findings emphasize the urgent need for regulatory protection, exposure time management, and improved landfill gas monitoring systems to safeguard vulnerable populations.

1. INTRODUCTION

The management of municipal solid waste (MSW) continues to present major environmental and public health challenges worldwide. Landfilling remains the most widely practiced method of waste disposal, particularly in developing countries, due to its relative simplicity, low cost, and capacity to accommodate large volumes of waste. However, landfills are not merely passive repositories of waste materials; they are complex biogeochemical reactors that generate a variety of pollutants as a result of microbial decomposition, chemical reactions, and physical processes [1, 2]. Among the various pollutants released from landfill environments, volatile organic compounds (VOCs) represent a class of chemicals that are increasingly gaining attention due to their toxicity, volatility, and potential for long-range atmospheric transport [3, 4]. One of the most concerning VOCs commonly detected in landfill emissions is xylene, a compound often overlooked in landfill-related risk assessments.

Xylene is a colorless, flammable hydrocarbon with a sweet odor, commonly found in three isomeric forms: ortho-xylene, meta-xylene, and para-xylene [5, 6]. It is widely used in industrial processes, including the manufacture of paints, adhesives, solvents, and synthetic fibers. In the context of landfills, xylene can be released into the environment through the volatilization of waste materials containing solvents, petroleum products, plastics, or other synthetic chemicals [7, 8]. Unlike greenhouse gases such as methane, which are produced as a result of anaerobic microbial decomposition of organic waste, xylene primarily originates from anthropogenic chemical residues disposed of in landfills, making it an indicator of industrial or urbanized waste input [9].

Xylene's volatility and lipophilic properties enable it to readily vaporize and diffuse into ambient air, particularly under conditions of high temperature and low humidity [10]. Once inhaled, xylene is absorbed rapidly through the lungs into the bloodstream, distributed throughout the body, and preferentially stored in fatty tissues. Acute exposure to xylene can result in irritation of the eyes, nose, and throat, headache, dizziness, and confusion [11]. Chronic exposure, especially in occupational settings such as landfill sites or informal waste management areas, has been linked to more severe neurological effects, including memory loss, tremors, and even hearing impairment [12, 13]. Furthermore, prolonged inhalation of xylene vapors may lead to hepatic and renal damage due to the accumulation of its metabolites, primarily methyl hippuric acid, in the body [14].

From a public health perspective, waste pickers operating in landfills represent a particularly vulnerable population. Often working without adequate protective equipment, these individuals are frequently exposed to multiple environmental hazards, including dust, bioaerosols, heavy metals, and VOCs. In countries with limited regulatory oversight, landfill environments may lack gas venting systems, leachate containment measures, or ambient air quality monitoring, thereby increasing the likelihood of uncontrolled exposure. The presence of xylene in such settings further elevates health risks due to its neurotoxicity and potential to act as a respiratory irritant, particularly when exposure occurs over extended periods of time.

Additionally, xylene emissions contribute to broader environmental problems. In the atmosphere, xylene reacts with nitrogen oxides (NOx) and sunlight in photochemical reactions that lead to the formation of ground-level ozone (O_3), a major component of smog [15, 16]. Ground-level ozone is well-documented to exacerbate respiratory diseases such as asthma, bronchitis, and chronic obstructive pulmonary disease (COPD). Thus, xylene plays a dual role as both a direct health hazard through inhalation and as a precursor to secondary air pollutants with far-reaching health impacts [17, 18].

Previous environmental health studies at the Sarimukti Landfill have identified sulfur dioxide (SO_2) as a major air pollutant contributing to respiratory symptoms among waste pickers. The study by Parulian et al. [19] demonstrated that even when SO_2 concentrations were below the national air quality standard (7.38 $\mu g/m^3$ vs 150 $\mu g/m^3$), the calculated hazard quotient (HQ = 31.85) still exceeded the safety threshold (HQ $\geq$ 1), indicating a significant health risk [19]. This finding underscores that pollutant concentrations deemed "safe" by regulatory standards may still pose non-carcinogenic health risks when evaluated through risk-based approaches such as the Environmental Health Risk Assessment (EHRA). However, while SO_2 and particulate matter have been quantitatively linked to respiratory outcomes, VOCs, particularly xylene, remain insufficiently studied despite their higher volatility, persistence, and neurotoxic potential.

This gap in knowledge justifies the need to extend EHRA-based risk assessment frameworks to xylene exposure in landfill environments. By analyzing xylene emission, intake, and hazard quotient values among waste pickers, this research expands upon the methodological foundation established in prior SO_2-focused studies, while addressing the lack of empirical data on VOC-related health risks in Indonesian landfills.

Sarimukti Landfill was selected as the study site due to its strategic role in receiving waste from Bandung City, West Bandung Regency, and Cimahi City. Operational since 2006, the site now faces issues of overcapacity, frequent landfill fires, and structural damage, all of which enhance VOC volatilization. The landfill also hosts an informal community of approximately 300 waste pickers, many of whom lack access to adequate personal protective equipment or occupational health monitoring. These conditions make Sarimukti a representative yet critical site for assessing the health risks associated with chronic xylene exposure.

Accordingly, this study aims to: (1) project xylene concentrations using the LandGEM model, (2) estimate intake and hazard quotient (HQ) values for waste pickers through inhalation exposure, (3) calculate safe exposure limits based on risk control analysis, and (4) discuss implications for environmental health risk management in landfill settings.

2. METHOD

2.1 Research type and design

This study is a quantitative study that aims to evaluate the environmental health risks of exposure to xylene gas at the Sarimukti Landfill in West Bandung Regency. The research design used is cross-sectional, in which all data is collected at a specific time and analyzed to calculate exposure and non-carcinogenic risks based on the Environmental Health Risk Assessment (EHRA) approach. This study does not use direct measurements in the field but instead utilizes gas concentration projections from the LandGEM (Landfill Gas Emissions Model). The specific version used in this study is LandGEM version 3.02, developed by the United States Environmental Protection Agency (USEPA, 2005), which estimates annual landfill gas emissions based on the first-order decay equation for waste decomposition. The study has obtained ethical clearance from the Ethics Committee of Krister Maranatha University under approval number 049/KEP/IV/2025.

2.2 Location and data sources

The study was conducted at the Sarimukti Landfill, which has been operating since 2006 and receives waste from the cities of Bandung and Cimahi, as well as the regency of West Bandung. The main data used in this study were annual waste generation data from 2006 to 2021, obtained from the West Java Provincial Environment Agency. This data was used as the main input in the LandGEM simulation to project landfill gas emissions, including xylene content as part of non-methane organic compounds (NMOC).

Because LandGEM produces a total NMOC concentration, the xylene concentration was estimated using a fixed mass fraction assumption. Based on the USEPA AP-42 database and prior studies on landfill gas composition, xylene represents approximately 0.081% of total NMOC emissions. This proportion was used to isolate xylene concentrations from the total NMOC output generated by LandGEM.

2.3 Population and sampling technique

The population in this study was scavengers who actively worked at the Sarimukti Landfill. Sampling was conducted using accidental sampling of 101 respondents who met the inclusion criteria, namely being at least 17 years old, actively working at the site for at least the last 6 months, willing to be a respondent, and not having a severe disability. Primary data collection was conducted through direct interviews using a structured questionnaire to obtain information on the duration and frequency of exposure, as well as individual characteristics such as body weight.

2.4 Environmental Health Risk Assessment (EHRA)

To obtain intake values, respondents were interviewed to obtain individual intake data, including daily exposure time (in hours), exposure frequency per year (days), length of time working at the landfill (years), body weight (kg), and demographic characteristics. The hazard quotient was obtained by dividing the intake value by the reference concentration (RfC) of 0.2 mg/m^3 [20].

Mathematical formula for calculating intake value:

$$\mathrm{Ink} = \left(\frac{\mathrm{C} \times \mathrm{R} \times \mathrm{tE} \times \mathrm{fE} \times \mathrm{Dt}}{\mathrm{Wb} \times \mathrm{tavg}} \right) \quad (1)$$

Mathematical formula for calculating risk quotient:

$$\mathrm{RQ} = \left(\frac{\mathrm{Ink}}{RfC} \right) \quad (2)$$

Mathematical formula for calculating safe concentration (inhalation and non-carcinogenic):

$$\mathrm{Cnk} = \left(\frac{\mathrm{RfC} \times \mathrm{Wb} \times \mathrm{tavg}}{\mathrm{R} \times \mathrm{tE} \times \mathrm{fE} \times \mathrm{Dt}} \right) \quad (3)$$

Mathematical formula for calculating safe time (inhalation and non-carcinogenic):

$$\mathrm{tEnk} = \left(\frac{\mathrm{RfC} \times \mathrm{Wb} \times \mathrm{tavg}}{\mathrm{R} \times \mathrm{C} \times \mathrm{fE} \times \mathrm{Dt}} \right) \quad (4)$$

Mathematical formula for calculating safe frequency (inhalation and non-carcinogenic):

$$\mathrm{fEnk} = \left(\frac{\mathrm{RfC} \times \mathrm{Wb} \times \mathrm{tavg}}{\mathrm{R} \times \mathrm{C} \times \mathrm{tE} \times \mathrm{Dt}} \right) \quad (5)$$

where,

Ink: The amount of a risk agent (mg) that enters the human body per unit of body weight (kg) per day, through inhalation exposure (mg/kg/day);

C: Risk agent concentration in the air (ambient air) (mg/m^3);

R: Inhalation rate or the volume of air entering every hour per person (m^3/hour);

tE: Duration or number of hours of exposure per day (hours/day);

fE: Duration or number of days of exposure per year (days/year);

Dt: Duration or number of years of exposure (years);

Wb: Body weight of humans/population/population group (kg);

tavg: Average time period for non-carcinogenic effects (days);

RfC: Reference value for risk agents in inhalation exposure;

Cnk: Safe concentration of risk agents in ambient air.

Respondents were interviewed to obtain individual data for ET, EF, ED, and BW. The hazard quotient (HQ) was then calculated by dividing the intake value by the reference concentration (RfC) for xylene, which is 0.2 mg/m^3 as determined by USEPA (IRIS, 2003). An HQ greater than 1 indicates a potential health risk due to xylene exposure.

3. RESULT AND DISCUSSION

3.1 Intake value

The concentration of xylene used in predicting intake values was obtained from LandGEM modeling projections, taking into account waste entering the Sarimukti Landfill from 2006 to 2021. A xylene concentration of 12 ppm with a molecular weight of 106.16 was obtained, which was then converted to 52.13 mg/m^3 and used as the concentration value in the intake calculations for 101 waste pickers. The complete results are presented in Table 1 below.

Table 1. Xylene pollutant intake levels at Sarimukti Landfill in 2025 (n = 101)

		Statistics	
		Intake Real-time	**Intake Projection 30 Years**
N	Valid	101	101
	Missing	0	0
Mean		5.851	1.605
Std. Deviation		1.670	1.244
Minimum		1.71	0.01
Maximum		9.96	5.43

The mean real-time xylene intake was 5.851 mg/kg/day, while the 30-year projected value decreased to 1.605 mg/kg/day. The relatively wide range of values reflects individual variability in daily exposure time, frequency, and body weight among the respondents. The reduction in intake over time is attributed to the assumption of declining ambient concentrations and adjustments for cumulative exposure duration.

3.2 Hazard quotient

The hazard quotient (HQ) was calculated by dividing the intake values by the reference concentration (RfC) of xylene, which is 0.2 mg/m^3. The HQ values reflect the level of health risk, with HQ > 1 indicating potential for adverse non-carcinogenic effects. The complete results are shown in Table 2.

The mean real-time HQ value was 29.255 (95% CI: 26.606 - 29.904), significantly exceeding the threshold of 1 ($p < 0.000$), indicating a high level of non-carcinogenic health risk under current conditions. Similarly, the 30-year projected HQ had a mean value of 8.025 (95% CI: 5.797 – 8.253), which also remained significantly above the acceptable risk level ($p < 0.000$).

Table 2. Xylene pollutant hazard quotient values at Sarimukti Landfill in 2025 (n = 101)

One-Sample Statistics					
	N	Mean	Std. Deviation	Std. Error Mean	p-Value (CI)
Hazard Quotient Real-time	101	29.255	8.353	831	0.000 (26.606 - 29.904)
Hazard Quotient Projection 30 Years	101	8.025	6.220	618	0.000 (5.797 - 8.253)

The results of this study demonstrate that xylene exposure levels among waste pickers at the Sarimukti Landfill exceed acceptable thresholds for non-carcinogenic risk. The real-time hazard quotient (HQ) averaged 29.255, while the 30-year projection remained high at 8.025, both far above the reference value of 1. These findings suggest that the population is chronically exposed to concentrations of xylene, which can have a significant impact on human health. Even under projected future scenarios, where waste decomposition and gas release tend to decline, xylene remains a persistent hazard.

3.3 Pollutant management based on concentration, time, and frequency of safe exposure

To reduce the health risks posed by xylene exposure, a risk management analysis was conducted to estimate the maximum safe limits for concentration (Cnk), time of exposure (tEnk), and frequency of exposure (fEnk) for waste pickers. These values were calculated using the Environmental Health Risk Assessment (EHRA) approach and are presented in Table 3 below.

Table 3. Xylene pollutant management at Sarimukti Landfill in 2025 (n = 101)

		Statistics			
		Safe Limit Concentration - Real-time	Safe Limit Concentration - Projection-time	Safe Limit Time-Real-time	Safe Limit Frequency - Real-time
N	Valid	101	101	101	101
	Missing	0	0	0	0
Mean		1.969	109.084	0.314	11.2101
Std. Deviation		0.745	490.137	0.063	4.22031
Minimum		1.05	1.92	0.20	6.33
Maximum		6.11	3444.23	0.55	39.37

The results show that the real-time safe concentration (Cnk) of xylene in ambient air was 1.969 mg/m³, far below the modeled exposure concentration of 52.13 mg/m³. This discrepancy highlights the urgency of exposure reduction efforts in the field. Meanwhile, the average Cnk in the 30-year projection was significantly higher due to reduced intake but exhibited wide variation, as shown by the large standard deviation.

The average safe duration of exposure (tEnk) per session was estimated at 0.314 hours, equivalent to approximately 19 minutes. This duration indicates that to stay below the threshold of non-carcinogenic risk, waste pickers should limit their daily exposure sessions to less than 20 minutes. Additionally, the average safe frequency of exposure (fEnk) was calculated to be 11.21 times per week. However, some individuals exceeded 30 exposures per week, indicating that a portion of the population may already be at elevated risk without control measures.

Previous research on environmental health at the Sarimukti Landfill has primarily focused on sulfur dioxide (SO_2) exposure. Parulian et al. [19] reported that even though the measured SO_2 concentration (7.38 µg/m³) was far below the national ambient air quality standard (150 µg/m³), the calculated hazard quotient (HQ = 31.85) exceeded the acceptable safety limit (HQ ≥ 1), indicating a potential non-carcinogenic health risk to scavengers [19]. This study highlights that pollutants considered "safe" under regulatory standards may still pose health threats when evaluated through risk-based frameworks such as the Environmental Health Risk Assessment (EHRA).

In contrast, the present study extends this line of inquiry by examining xylene, a volatile organic compound (VOC) with higher volatility and neurotoxic potential compared to SO_2. Despite its persistence in landfill gas emissions, xylene-related health risks remain understudied, particularly among waste pickers in developing countries. By applying similar EHRA principles, this study aims to fill the knowledge gap by quantifying xylene exposure risk and identifying safe exposure limits within the same landfill setting.

Xylene is a volatile organic compound (VOC) that originates primarily from anthropogenic sources. Unlike methane, which is generated via anaerobic microbial degradation of organic waste, xylene is released into the landfill environment through the volatilization of synthetic and chemical waste products [20, 21]. Common sources include discarded paints, solvents, adhesives, plastics, and industrial residues that contain petroleum-derived compounds [22]. In landfills, the combination of high temperatures, low humidity, poor ventilation, and extensive plastic-based waste accelerates the volatilization of xylene and its migration into the surrounding atmosphere.

From a health perspective, xylene is a neurotoxic compound with both acute and chronic health effects. Short-term exposure can cause mucosal irritation, headache, dizziness, nausea, and impaired coordination [23, 24]. Long-term exposure, particularly through inhalation in occupational environments like landfills, has been associated with cognitive impairment, memory loss, tremors, liver and kidney dysfunction, and damage to auditory function [25]. These health effects are mediated by xylene's lipophilic nature, which enables it to accumulate in fat-rich tissues, including the central nervous system and vital organs [26]. Once inhaled, xylene is absorbed rapidly through the lungs and metabolized in the liver into methyl hippuric acid, which exerts systemic toxicity when accumulated [27, 28].

In the context of landfill environments, such as Sarimukti, where personal protective equipment is rarely used, and workers may be exposed for several hours daily, the risk becomes magnified. This is particularly troubling considering that the safe exposure time calculated in this study was limited to just 19 minutes per session, with a weekly exposure frequency of no more than 11 times. Yet, waste pickers often work beyond these thresholds, placing them at significant and sustained risk.

In addition to direct health hazards, xylene plays a role in broader atmospheric and environmental degradation. As a reactive VOC, xylene contributes to the formation of ground-level ozone through photochemical reactions with nitrogen oxides (NOx) in the presence of sunlight [29, 30]. Ground-level ozone is a major component of urban smog and is well-documented to exacerbate respiratory conditions such as asthma, bronchitis, and chronic obstructive pulmonary disease (COPD) [31]. Thus, xylene's contribution is twofold: it acts directly as a toxicant and indirectly by amplifying the presence of secondary pollutants.

Moreover, while xylene itself is not a greenhouse gas in the conventional sense like methane or carbon dioxide, its role in ozone formation indirectly exacerbates climate change. Ground-level ozone is a short-lived climate pollutant (SLCP) with significant warming potential [32]. Elevated ozone levels in the lower atmosphere contribute to radiative forcing, increase heatwaves, and reduce carbon sequestration by impairing plant growth. In this sense, unmanaged xylene emissions from landfills indirectly support feedback loops that intensify global warming and climate disruption [33, 34].

This study also highlights that, unlike other more regulated pollutants, xylene is often under-monitored in landfill assessments. Most environmental monitoring programs prioritize greenhouse gases, leachate, or heavy metals, overlooking VOCs despite their serious public health and climate implications. The lack of VOC monitoring infrastructure in landfills such as Sarimukti leaves critical data gaps and hampers the ability to formulate evidence-based mitigation strategies.

Therefore, building upon the current findings on xylene exposure risk at the Sarimukti Landfill, future research should focus on the development of an early-warning detection system for volatile organic compounds (VOCs), particularly xylene. This direction aligns with previous innovations in landfill gas monitoring, such as the prototype system developed by Firmansyah et al. [35] for detecting methane, sulfur dioxide, and nitrogen dioxide using integrated sensor technology and health-based alarm thresholds [35]. Adapting this concept, future studies are encouraged to design a real-time xylene detection prototype utilizing high-sensitivity VOC sensors (e.g., MQ-series or metal oxide sensors), calibrated through both laboratory testing and modeled data from LandGEM simulations.

Immediate interventions are essential to protect vulnerable populations such as waste pickers. These include the enforcement of exposure time limits, the introduction of protective equipment, restriction of landfill working hours, and the installation of active gas capture systems that target both VOCs and greenhouse gases. Environmental agencies must expand the scope of air quality assessments to include a wider range of pollutants, particularly VOCs like xylene, in their routine evaluations.

4. CONCLUSIONS

This study successfully achieved its objective of assessing the environmental health risks of xylene exposure among waste pickers at the Sarimukti Landfill using the Environmental Health Risk Assessment (EHRA) approach and LandGEM gas emission projections. Through real-time and 30-year simulation scenarios, the study quantified intake values and hazard quotients (HQ) and defined safe exposure thresholds for xylene, thereby addressing the previously underexplored issue of volatile organic compound (VOC) toxicity in landfill environments. Quantitatively, the average real-time xylene intake among waste pickers was recorded at 5.851 mg/kg/day, with a corresponding hazard quotient (HQ) of 29.255. Both values significantly exceeded the safe threshold, indicating a high level of non-carcinogenic risk ($p < 0.0001$; 95% CI: 27.615–30.895). The 30-year projected intake dropped to 1.605 mg/kg/day with an HQ of 8.025 ($p < 0.000$; 95% CI: 6.797–9.253) but remained above the acceptable safety level. These findings confirm that workers at the landfill are consistently exposed to harmful concentrations of xylene, both in current conditions and in the long-term scenario.

Risk management analysis revealed that the average safe concentration (Cnk) of xylene for real-time conditions is 1.970 mg/m³, substantially lower than the ambient concentration of 52.13 mg/m³ estimated through LandGEM modeling. Safe exposure duration (tEnk) was calculated at 0.315 hours (approximately 19 minutes per session), while the recommended safe exposure frequency (fEnk) was 11.21 times per week. These constraints highlight the urgent need for practical and regulatory interventions.

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