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Risk Quotient Analysis of Ozone Pollutants on the Occupational Health of Scavengers at Sarimukti Landfill, West Bandung Regency, Indonesia

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Abstract: Limited studies have assessed the specific health risks associated with ozone exposure among informal waste workers in landfill environments, particularly in developing countries. This study addresses this gap by evaluating the Risk Quotient (RQ) of ozone pollutants among scavengers at the Sarimukti Landfill, West Bandung Regency, Indonesia. Applying the Environmental Health Risk Assessment (EHRA) approach, ozone concentrations were measured over three periods across two sampling points. Data were collected from 101 scavengers, including variables such as exposure time, frequency, body weight, and inhalation rate. Intake values, RQ, safe concentration thresholds (Cnk), safe exposure duration ($t_{Enk(safe)}$), and safe exposure frequency ($f_{Enk(safe)}$) were calculated under both real-time and 30-year projection scenarios. The results showed that real-time RQ values substantially exceeded the safe threshold (mean RQ = 27.183), indicating substantial short-term health risks. Although the projected 30-year values were lower (mean RQ = 7.630), they remained above the acceptablelimit (RQ $>$ 1), reflecting potential chronic health risks. The average safe exposure time at maximum concentration was only 0.147 hours/day, while the safe frequency was limited to 5 days/year. These findings highlight the urgent need for integrating occupational health protections, air quality monitoring, and regulatory enforcement into landfill waste management systems.

Keywords: Air pollution; Environmental Health Risk Assessment; Ozone; Risk Quotient; Sarimukti Landfill

1 Introduction

The Ministry of Environment and Forestry reported that in 2021, the volume of waste generated in Indonesia reached 18.2 million tons per day [1]. This figure increased to 19.57 million tons per day in 2022 according to the National Waste Management Information System (SIPSN) [2]. Despite this significant volume, approximately 23.05% of the waste remained unmanaged [3], with food, plastics, and organic materials constituting the primary components [4]. Waste management practices in Indonesia still rely predominantly on landfilling, with 33 out of 46 major cities using landfills as the main disposal method, including West Bandung Regency [5].

One of the largest landfill sites in this region is the Sarimukti Landfill. Initially intended to serve 15 sub-districts, it is now jointly used by Bandung City, West Bandung Regency, and Cimahi City. In 2022, the waste volume received at the Sarimukti Landfill reached 146,676.44 tons/year, representing an increase of 33.94% compared to 2021 [4]. This landfill operates under an open dumping system, which has been associated with recurring fire incidents, including a major fire starting on August 19, 2023 [6]. The open dumping system contributes significantly to uncontrolled emissions of gases such as methane and volatile organic compounds [7, 8], which are precursors to ground-level ozone formation.

In landfill environments, ozone is generated through photochemical reactions involving methane and nitrogen oxides in the presence of sunlight. Methane, the third-largest anthropogenic greenhouse gas in the United States, alters radical chemistry in the troposphere and acts as a global precursor to ozone formation [8, 9]. Open dumping accelerates these emissions due to uncontained waste decomposition, leachate evaporation, and spontaneous combustion. Consequently, landfill workers, particularly informal scavengers, are exposed to elevated ozone levels without proper protection or regulatory oversight.

Ozone is a potent oxidizing agent that can cause a range of adverse health effects through inhalation, including respiratory inflammation, decreased lung function, cardiovascular stress, and increased risk of premature death [10, 11]. Studies have confirmed that prolonged or high-level exposure to ozone is associated with both acute and chronic health risks. While several studies have applied the Environmental Health Risk Assessment (EHRA) approach to evaluate urban air pollution risks [12–15], very few have focused specifically on informal landfill workers such as scavengers, who experience disproportionate exposure levels and vulnerabilities.

This study addresses this research gap by assessing the Risk Quotient (RQ) of ozone exposure among scavengers at the Sarimukti Landfill. It further evaluates safe exposure thresholds, including concentration, duration, and frequency, under both real-time and 30-year projected exposure scenarios. The findings are expected to provide evidence-based input for the development of targeted interventions for improving occupational health in landfill settings.

2 Methods

2.1 Study Design

This study employed a quantitative method to calculate the RQ value of ozone pollutants and to determine the limits of safe concentration, exposure duration, and exposure frequency among scavengers at the Sarimukti Landfill, West Bandung Regency. A longitudinal study design was applied, in which ozone concentration measurements were conducted for three months at two points in the landfill area. The measurements were performed by the Bandung Occupational Safety and Health Center, PT Ubar Jalindo Chemical and Environmental Laboratory, and Binalab Environmental Quality Testing Laboratory.

2.2 Study Period and Population

This study was conducted across three sampling periods, with the first sampling carried out on November 12, 2024, the second on January 24, 2025, and the third on February 2, 2025. All measurements were obtained from two points in the Sarimukti landfill. Additionally, air sampling was conducted during the rainy season.

2.3 Data Collection and Procedures

Two types of research subjects were included. The first subject was ambient air, for which ozone concentration (C) in air was measured. The second subject consisted of 101 scavengers, from whom data were collected on daily exposure duration (tE), annual exposure frequency (fE), total exposure duration in years (Dt), body weight (Wb), and the average time period for non-carcinogen effects. Additional parameters included the inhalation rate (R), defined as the volume of air inhaled per hour, and the reference concentration (RfC) for ozone as an inhalation risk agent.

2.4 Environmental Health Risk Assessment

EHRA was conducted in several stages. First, the intake value (I) was calculated using the mathematical equation presented in Eq. (1). Subsequently, the RQ value was calculated by dividing the intake value by the reference concentration, as shown in Eq. (2). Safe concentrations were determined using the equations presented in Eqs. (3)–(5), which describe the calculation of non-carcinogenic safe exposure concentration, safe exposure duration (inhalation) and safe exposure frequency (inhalation).

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

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

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

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

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

2.5 Data Analysis

Data were analyzed descriptively to determine the mean, minimum, and maximum values of pollutant concentration, RQ, exposure duration and frequency, as well as safe exposure concentration.

3 Results and Discussion

3.1 Intake Value

Under real-time conditions, the minimum intake values in Table 1 showed a mean of 0.886 μg/m^3/day with a standard deviation of 0.253. The values ranged from a minimum of 0.259 μg/m^3/day to a maximum of 1.509 μg/m^3/day. These results indicate that under current conditions, the lowest levels of ozone exposure exhibit notable inter-individual variability. The real-time maximum intake values were substantially higher, with a mean of 12.523 μg/m^3/day and a standard deviation of 3.576. The minimum recorded value was 3.654 μg/m^3/day, while the maximum reached 21.313 μg/m^3/day. This range suggests that some scavengers experience considerably elevated ozone exposure. Meanwhile, the real-time average intake values yielded a mean of 5.562 μg/m^3/day, with a standard deviation of 1.588. The values ranged from 1.623 μg/m^3/day, to 9.467 μg/m^3/day, indicating that the average exposure remains quite significant among most respondents.

Table 1. Results of ozone pollutant intake values for scavengers at Sarimukti Landfill, West Bandung Regency 2024 (n = 101)

		Minimum Intake Concentration (Real-Time)	Maximum Intake Concentration (Real-Time)	Average Intake Concentration (Real-Time)	Minimum Intake Concentration (30 Years)	Maximum Intake Concentration (30 Years)	Average Intake Concentration (30 Years)
N	Valid	101	101	101	101	101	101
	Missing	0	0	0	0	0	0
Mean		0.88671	12.523	5.562	0.243	3.297	1.526
Std. Deviation		0.252	3.576	1.588	0.188	0.941	1.182
Minimum		0.259	3.654	1.509	0.000	0.962	0.003
Maximum		1.509	21.313	9.467	0.823	5.613	5.164

Under the 30-year projected scenario, the minimum intake values were lower than those under real-time conditions. The mean minimum intake was 0.243 μg/m^3/day with a standard deviation of 0.188, indicating a narrower distribution. Intake values ranged from 0.000 μg/m^3/day to 0.823 μg/m^3/day, suggesting that some scavengers may experience negligible exposure in the long term. The projected maximum intake over the 30-year period showed a mean of 3.297 μg/m^3/day and a standard deviation of 0.941, with values ranging from 0.962 μg/m^3/day to 5.613 μg/m^3/day. Although these values are lower than the real-time maximum intake values, they indicate that some scavengers may still accumulate relatively high ozone exposure. Finally, the projected average intake values over 30 years exhibited a mean of 1.526 μg/m^3/day with a standard deviation of 1.182. The minimum and maximum values were 0.003 μg/m^3/day and 5.164 μg/m^3/day, respectively. These findings demonstrate that considerable ozone exposure persists for some individuals.

3.2 Risk Quotient (RQ) Value

Under real-time conditions, the minimum RQ values presented in Table 2 showed a mean of 4.433 with a standard deviation of 1.265. The values ranged from a minimum of 1.293 to a maximum of 7.545. These results indicate that even at the lowest exposure levels, the majority of respondents exceeded the acceptablerisk threshold (RQ > 1), indicating potential health problems. The real-time maximum RQ values were markedly elevated, with a mean of 62.619 and a standard deviation of 17.881. The minimum and maximum values were 18.269 and 106.567, respectively. This range demonstrates that some scavengers are exposed to exceptionally high ozone concentrations that pose health risks in the short term. Meanwhile, the real-time average RQ values yielded a mean 27.183 with a standard deviation of 7.941, ranging from 8.114 to 47.333. These findings indicate that most respondents are consistently exposed to ozone concentrations far exceeding safe limits in the short term.

Under the 30-year projected scenario, the minimum RQ values exhibited a mean of 1.216 with a standard deviation of 0.942. The values ranged from a minimum 0.002 to a maximum of 4.115. These indicate that despite the potential for risk reduction in the long term, some scavengers continue to experience exposure exceeding the threshold. The projected maximum RQ values over the 30-year period showed a mean of 16.489 and a standard deviation of 4.708. The minimum and maximum values were 4.811 and 28.063, respectively. Although these values are lower than the real-time RQ values, they still reflect a high risk for some individuals. Finally, the projected average RQ values over 30 years exhibited a mean of 7.630 and a standard deviation of 5.914, with minimum and maximum values of 0.014 and 25.818, respectively. These results suggest that ozone-related health risks persist among scavengers although long-term risk levels are generally lower and more variable than current conditions.

Table 2. Results of ozone pollutant Risk Quotient (RQ) values for scavengers at Sarimukti Landfill, West Bandung Regency 2024 (n = 101)

		Minimum RQ Concentration (Real-Time)	Maximum RQ Concentration (Real-Time)	Average RQ Concentration (Real-Time)	Minimum RQ Concentration (30 Years)	Maximum RQ Concentration (30 Years)	Average RQ Concentration (30 Years)
N	Valid	101	101	101	101	101	101
	Missing	0	0	0	0	0	0
Mean		4.433	62.619	27.183	1.216	16.489	7.630
Std. Deviation		1.265	17.880	7.941	0.942	4.708	5.914
Minimum		1.293	18.269	8.114	0.002	4.811	0.014
Maximum		7.545	106.567	47.333	4.115	28.063	25.818

3.3 Safe Concentration of Non-Carcinogenic Ozone Pollutant ($Cnk_{(safe)}$)

Under real-time conditions, the average $Cnk_{(safe)}$ value as presented in Table 3 was 1.970, with a standard deviation of 0.745. The values ranged from a minimum of 1.047 to a maximum of 6.108. Under the 30-year projected scenario, the average $Cnk_{(safe)}$ value increased dramatically to 109.085, with a standard deviation of 490.137, indicating considerable inter-individual variability. The minimum $Cnk_{(safe)}$ value over the 30-year period was 1.920, while the maximum reached 3444.228. This wide range suggests that long-term cumulative ozone exposure may be substantial for some scavengers, especially those residing in areas with high ozone concentrations or engaging in activities that increase the risk of exposure.

Table 3. Results of ozone pollutant safe concentration values for scavengers at Sarimukti Landfill, West Bandung Regency 2024 (n = 101)

		$Cnk_{(safe)}$ (Real-Time)	$Cnk_{(safe)}$ (30 Years)
N	Valid	101	101
	Missing	0	0
Mean		1.969	109.084
Std. Deviation		0.745	490.137
Minimum		1.047	1.920
Maximum		6.108	3444.228

3.4 Safe Exposure Duration ($t_{Enk(safe)}$)

For the minimum $t_{Enk(safe)}$ value, Table 4 shows an average of 2.077 with a standard deviation of 0.419. The minimum and maximal values were 1.314 and 3.653, respectively. These findings indicate that under the lowest conditions, most scavengers can tolerate ozone exposure for only approximately two hours before exceeding the safe threshold. This relatively low duration suggests that ozone exposure tends to quickly pose potential health risks for individuals with direct and continuous exposure.

Table 4. Results of ozone pollutant safe exposure time values for scavengers at Sarimukti Landfill, West Bandung Regency 2024 (n = 101)

		Minimum $t_{Enk(safe)}$ Concentration	Maximum $t_{Enk(safe)}$ Concentration	Average $t_{Enk(safe)}$ Concentration
N	Valid	101	101	101
	Missing	0	0	0
Mean		2.077	0.147	0.331
Std. Deviation		0.419	0.029	0.066
Minimum		1.314	0.093	0.210
Maximum		3.653	0.259	0.582

In contrast, the maximum $t_{Enk(safe)}$ value represents the longest allowable exposure duration under elevated ozone concentrations. The maximum $t_{Enk(safe)}$ value showed an average of only 0.147, with a standard deviation of 0.030. The values ranged from 0.093 to 0.259. These results demonstrate that under elevated ozone concentrations, the duration of safe exposure becomes extremely limited. This indicates that high-level exposure rapidly exceeds the tolerance capacity of the human body.

Finally, the average $t_{Enk(safe)}$ value reflects the general safe exposure duration for ozone inhalation. The mean value was 0.331, with a standard deviation of 0.066, and ranged from 0.210 and 0.582.

3.5 Safe Exposure Frequency ($f_{Enk(safe)}$)

Under conditions of minimum ozone concentration (Table 5), the mean value of safe exposure frequency was 73.972 days/year, with a standard deviation of 27.848. The values ranged from a minimum of 41.749 days/year to a maximum of 259.773 days/year. These findings indicate that under the lowest ozone pollution conditions, scavengers can be exposed relatively frequently without exceeding the risk threshold, although considerable inter-individual variability remains evident. In contrast, under conditions of maximum ozone concentration, the safe exposure frequency decreased dramatically. The mean value was only 5.237 days/year, with a standard deviation of 1.972. The minimum and maximum values were 2.956 and 18.392 days/year. These results demonstrate that during periods of poor air quality, only limited exposure can be tolerated before health risks arise, and the tolerance between individuals becomes considerably narrower. At the average ozone concentration, the mean $f_{Enk(safe)}$ value was 11.791 days/year, with a standard deviation of 4.439 and values ranging from 6.655 to 41.409 days/year. This suggests that under typical ozone exposure conditions, scavengers have a moderate but limited tolerance for exposure, with most individuals able to be safely exposed for approximately 12 days/year.

Table 5. Results of ozone pollutant safe exposure frequency values for scavengers at Sarimukti Landfill, West Bandung Regency 2024 (n = 101)

		Minimum $f_{Enk(safe)}$ Concentration	Maximum $f_{Enk(safe)}$ Concentration	Average $f_{Enk(safe)}$ Concentration
N	Valid	101	101	101
	Missing	0	0	0
Mean		73.972	5.237	11.791
Std. Deviation		27.848	1.971	4.439
Minimum		41.749	2.956	6.655
Maximum		259.773	18.392	41.409

Based on the EHRA analysis of ozone exposure among 101 scavengers at the Sarimukti Landfill in West Bandung Regency in 2024, several parameters were measured to characterize ozone-related health risks. These parameters included intake value, RQ, Cnk, $t_{Enk(safe)}$, and $f_{Enk(safe)}$. Each parameter was assessed under two scenarios: real-time conditions representing current exposure and a 30-year projection.

For the intake parameter, the results showed that the highest average real-time ozone intake occurred under maximum exposure conditions, with a value of 12.523 μg/kg/day. The average intake was 5.562 μg/kg/day, while the minimum intake was 0.886 μg/kg/day. Under the 30-year projected exposure scenario, the highest intake value was 3.297 μg/kg/day, with an average intake of 1.526 μg/kg/day and a minimum intake of 0.243 μg/kg/day. In general, the intake values decreased with longer exposure duration, reflecting a more evenly distributed accumulation process over the long term. However, the maximum intake values under both scenarios indicate a substantial potential health risk under extreme conditions or environments with persistently elevated ozone concentrations [16, 17].

RQ calculations, which serves as a parameter to assess the magnitude of potential health risks, revealed concerning results under real-time conditions. The maximum real-time RQ reached 62.619, while the average and minimum RQ values were 27.183 and 4.433, respectively. These findings suggest that most individuals were exposed to ozone concentrations exceeding the acceptablerisk threshold, as RQ values greater than 1 signify potential adverse health effects. Under the 30-year projected exposure scenario, RQ values decreased significantly, with a maximum of 16.489, an average of 7.630, and a minimum of 1.216. Nevertheless, the average RQ remaining above 1 indicates that long-term chronic health risks may still occur for some individuals [18–20].

These findings must be contextualized within Indonesia's environmental policies. According to the Decree of the Minister of Environment and Forestry No. 10 of 2021, ambient ozone concentration limits are set at 235 $\mu g/m^3$ for a one-hour average and 157 $\mu g/m^3$ for an eight-hour average. However, the present study demonstrates that real-time exposures among scavengers poses health risks even when concentrations remain below these regulatory thresholds. This discrepancy is likely attributable to the vulnerability of the scavenger population and their prolonged exposure patterns. Furthermore, the absence of specific occupational exposure limits for ozone under Indonesia's labor regulations complicates the assessment of workplace safety for informal workers such as scavengers. When compared with the American Conference of Governmental Industrial Hygienists threshold limit value for ozone of 0.1 ppm or approximately 196 μg/m^3 for heavy work, the average concentrations observed in this study indicate that the landfill is considered to be an unsafe environment.

In addition, the wide variation in safe Cnk observed in Table 3, especially under the 30-year projected exposure scenario, may be attributed to individual differences in exposure parameters such as inhalation rate, body weight, and exposure duration. The mathematical model used to calculate Cnk is highly sensitive to these variables, resulting in the broad range of outcomes. This heterogeneity reflects the diverse working conditions experienced by scavengers. Some individuals are exposed for longer durations or in areas with higher ozone concentrations, thereby influencing the risk profiles. These findings underscore the urgent need for the development of localized occupational standards and the implementation of targeted protective measures.

The health risks identified in this study, as reflected by elevated RQ values under both real-time and 30-year projection scenarios, are consistent with established biological mechanisms of ozone toxicity. Ozone is a strong oxidizing agent that reacts rapidly upon contact with the epithelial lining of the respiratory tract. According to Xue et al. [20], inhaled ozone disrupts epithelial cell integrity, leading to oxidative stress, lipid peroxidation, and activation of inflammatory signaling pathways such as nuclear factor kappa B (NF-κB) and mitogen-activated protein kinase (MAPK). This process triggers the release of cytokines (e.g., IL-6, IL-8), promotes immune cell infiltration, and sustains chronic inflammation, ultimately resulting in structural and functional impairments of the lungs [20].

Repeated or chronic exposure to zone even at relatively low concentrations can lead to persistent respiratory inflammation, decreased lung capacity, airway remodeling, and heightened susceptibility to allergens or pathogens. These mechanisms underpin the elevated RQ values observed in the 30-year projection scenario despite lower intake values. Although intake appears numerically lower due to time-averaged accumulation, the RQ remains high because chronic exposure amplifies biological vulnerability. In addition, the RfC applied in the calculations reflects long-term health sensitivity rather than immediate toxicological response.

Moreover, individual vulnerability factors such as pre-existing health conditions, inadequate nutrition, and the lack of protective equipment likely exacerbate the physiological response to ozone exposure, especially among informal workers such as scavengers. Therefore, even modest long-term exposure may translate into substantial cumulative health risks, thereby justifying the persistently elevated RQ values across projected exposure scenarios.

Furthermore, the safe Cnk value showed a marked contrast between real-time and long-term conditions. The average real-time Cnk was 1.969 μg/m^3 with a standard deviation of 0.745 and a maximum value of 6.108 μg/m^3. In comparison, the 30-year projected Cnk increased dramatically, with an average of 109.084 μg/m^3 and a maximum value reaching 3444.228 μg/m^3. This pattern suggests that longer exposure durations correspond to higher concentration thresholds considered acceptablewithin the risk assessment framework, based on the assumption that risk is distributed over an extended time period [21–23].

The $t_{Enk(safe)}$ parameter, or safe exposure duration, describes the maximum time an individual can be exposed to ozone without incurring health risks and is calculated under various concentration scenarios. At minimum concentrations, the average safe exposure duration was 2 hours/day, with a maximum of 3.6 hours/day. In contrast, at maximum concentrations, the average safe exposure duration dropped drastically to 0.14 hours/day, with a maximum of only 0.25 hours/day. At average concentrations, the safe exposure duration was 0.33 hours/day. These values indicate that the higher ozone concentrations substantially reduce the duration during which exposure can be considered safe [24–26].

Finally, the $f_{Enk(safe)}$ parameter, or safe exposure frequency, further supports the findings. At minimum ozone concentrations, the average safe exposure frequency was 73.972 days/year, indicating that in low-ozone environments, individuals may be exposed quite frequently without jeopardizing their health. Conversely, at maximum concentrations, the average safe exposure frequency was only 5.237 days/year, with a minimum of 2.956 days/year. At average ozone concentrations, the safe exposure frequency was 11.791 days/year. This pattern aligns with earlier findings that elevated ozone concentrations limit both the duration and frequency of exposure considered safe for human health [27].

Ozone exposure in humans, especially at high concentrations or over prolonged periods, can lead to a range of adverse health effects, particularly involving the respiratory system [28]. Ozone is a strong oxidizing gas that, when inhaled, can irritate the respiratory tract, induce lung inflammation, decrease lung function, and exacerbate chronic conditions such as asthma and bronchitis [29]. At higher levels of exposure, ozone may also trigger oxidative stress in body tissues, leading to systemic effects, especially among vulnerable groups such as children, the elderly, and individuals with pre-existing respiratory conditions [30]. The primary mechanism underlying these effects involves oxidative reactions that damage the epithelial lining of the respiratory tract, increase cell membrane permeability, and activate inflammatory immune responses.

Based on the aforementioned EHRA results, it was found that most ozone intake values exceeded the safe thresholds, particularly under real-time conditions. Although a decrease was observed under the 30-year duration scenario, the average RQ values remained above one. This indicates that both short-term and long-term health risks remain significant. The high Cnk values in the long-term projection also suggests that the safe threshold standards for ozone exposure should be considered more adaptively in the context of chronic exposure scenarios. Additionally, the safe exposure duration and frequency are increasingly limited as ozone concentrations rise, underscoring the urgency of implementing public health interventions. It is also necessary to control ozone emissions and their precursors such as nitrogen oxides and volatile organic compounds around the landfill area, including from open waste burning, vehicles, or nearby industries [31]. Furthermore, it is important to use appropriate personal protective equipment, such as high-filtration masks, to reduce direct exposure among scavengers [32].

4 Conclusions

This study demonstrates that ozone exposure among scavengers at the Sarimukti Landfill in West Bandung Regency poses a significant health risk. The EHRA approach revealed that the RQ values under both real-time and 30-year projected scenarios exceeded the safe threshold (RQ $>$ 1), indicating both acute and chronic exposure risks. The average real-time RQ value reached 27.183, while the projected 30-year average remained at 7.630. Additionally, the safe exposure duration and frequency were found to be extremely limited, especially under maximum concentration scenarios, where individuals could only be safely exposed for an average of 0.147 hours/day and 5 days/year. These findings highlight the urgent need for comprehensive ozone exposure control measures, particularly for informal workers in landfill settings. Effective interventions, including emission reductions, protective equipment provision, regulated working hours, and health monitoring, are essential to mitigate long-term health risks and improve occupational safety for vulnerable populations.

Author Contributions

Conceptualization, D.D. and Y.W.F.; methodology, Y.W.F.; software, S.S.; validation, A.F., Y.W.F., and D.D.; formal analysis, S.S.; investigation, Y.W.F.; resources, D.D.; data curation, S.S.; writing—original draft preparation, D.D.; writing—review and editing, Y.W.F.; visualization, A.F.; supervision, A.F.; project administration, Y.W.F. All authors have read and agreed to the published version of the manuscript.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

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Conflicts of Interest

The authors declare that they have no conflicts of interest.

References

[1] Kementerian Lingkungan Hidup dan Kehutanan, "Memperkuat sumbangan tapak untuk pemulihan ekonomi nasional dan reformasi struktural," 2022. https://www.kehutanan.go.id/s/uploads/LKJ_KLHK_2022_1_Mar_kecill_compressed_1_823be11b23_930223f6c5.pdf

[2] National Waste Management Information System (SIPSN), "Waste management performance achievements," 2024. https://sipsn.menlhk.go.id/sipsn/

[3] Kementerian PPN/ Bappenas, "Policy brief: Enabling condition to waste energy: Untuk pengelolaan sampah di Indonesia," 2020. https://lcdi-indonesia.id/wp-content/uploads/2020/06/Policy-Brief-Waste-to-Energy-REV-1.pdf

[4] National Waste Management Information System (SIPSN), "Waste generation data," 2024. https://sipsn.menlhk.go.id/sipsn/public/data/timbulan

[5] P. Nyiramigisha, Komariah, and Sajidan, "The concentration of heavy metals zinc and lead in the soil around the Putri Cempo landfill, Indonesia," *IOP Conf. Ser. Earth Environ. Sci.*, vol. 824, no. 1, p. 012050, 2021. https://doi.org/10.1088/1755-1315/824/1/012050

[6] Public Relations of Bandung City, "Bandung city disaster management agency deploys fleet to help extinguish fire at Sarimukti landfill," 2023. https://www.bandung.go.id/news/read/8328/diskar-pb-kota-bandung-kerahkan-armada-bantu-padamkan-kebakaran-tpa-sa

[7] Y. W. Firmansyah, A. Probandari, B. Murti, and P. Setyono, "Environmental health risk analysis of methane gas pollutants in a landfill of West Bandung, Indonesia: Risk quotient study and LandGEM model," *BIO Web Conf.*, vol. 190, p. 01001, 2025. https://doi.org/10.1051/bioconf/202519001001

[8] E. Fikri, Y. W. Firmansyah, S. Suhardono, T. Kurniawati, A. S. Afifah, and T. A. Nugroho, "Environmental health risk assessment of xylene exposure for waste pickers at a landfill in West Java, Indonesia," *Int. J. Des. Nat. Ecodyn.*, vol. 20, no. 10, pp. 2423–2429, 2025. https://doi.org/10.18280/ijdne.201019

[9] O. O. Sonibare, J. A. Adeniran, and I. S. Bello, "Landfill air and odour emissions from an integrated waste management facility," *J. Environ. Health Sci. Eng.*, vol. 17, no. 1, pp. 13–28, 2019. https://doi.org/10.1007/s40201-018-00322-1

[10] E. Fikri, Y. W. Firmansyah, A. S. Afifah, and R. K. Dewi, "A projection study of gaseous pollutants formed, potential health effects and clinical codification in Piyungan landfill," *Nat. Env. Poll. Tech.*, vol. 23, no. 1, pp. 517–523, 2024. https://doi.org/10.46488/nept.2024.v23i01.048

[11] Australian Centre for Disease Control, "enHealth Guidance: Guidelines for assessing human health risks from environmental hazards," 2022. https://www.cdc.gov.au/resources/publications/enhealth-guidance-guidelines-assessing-human-health-risks-environmental-hazards

[12] M. Fitra and Awaluddin, *Pedoman Analisis Risiko Kesehatan Lingkungan (ARKL).* Andalas University Press, 2020.

[13] M. M. Simatupang, E. Veronika, A. Irfandi, and R. Garmini, "Environmental health risk assessment of air pollutants in online motorcycle taxi drivers in the special capital region of Jakarta," *J. Kesehat. Lingkung.*, vol. 14, no. 2, pp. 114–121, 2022. https://doi.org/10.20473/jkl.v14i2.2022.114-121

[14] N. D. Aulia and B. Hartono, "Environmental environmental health risk analysis SO_2 and NO_2 in Kemiri Muka Village, Depok City, Indonesia," *Kesmas*, vol. 19, no. 5, pp. 56–60, 2024. https://doi.org/10.21109/kesmas.v19isp1.1310

[15] S. Nurhisanah and H. Hasyim, "Environmental health risk assessment of sulfur dioxide (SO_2) at workers around in combined cycle power plant (CCPP)," *Heliyon*, vol. 8, no. 5, p. e09388, 2022. https://doi.org/10.1016/j.heliyon.2022.e09388

[16] M. Erdem, S. Ucar, S. Karagöz, and T. Tay, "Removal of lead (II) ions from aqueous solutions onto activated carbon derived from waste biomass," *Sci. World J.*, vol. 1, p. 146092, 2013. https://doi.org/10.1155/2013/146092

[17] T. Y. Zhao, I. Markevych, E. Fuertes, S. Accordini, A. Boudier, L. Casas, B. Forsberg, J. G. Aymerich, M. Gnesi, and et al., "Impact of long-term exposure to ambient ozone on lung function over a course of 20 years (The ECRHS study): A prospective cohort study in adults," *Lancet Reg. Health Eur.*, vol. 34, p. 100729, 2023. https://doi.org/10.1016/j.lanepe.2023.100729

[18] J. H. Xu, Y. Shi, G. B. Chen, W. L. Tang, C. L. Wu, S. R. Liang, Z. G. Huang, G. H. He, X. M. Dong, and et al., "Joint effects of long-term exposure to ambient fine particulate matter and ozone on asthmatic symptoms: Prospective cohort study," *JMIR Public Health Surveill*, vol. 9, p. e47403, 2023. https://doi.org/10.2196/47403

[19] X. Fang, S. Huang, Y. Zhu, J. Lei, Y. Xu, Y. Niu, and R. Chen, "Short-term exposure to ozone and asthma exacerbation in adults: A longitudinal study in China," *Front. Public Health*, vol. 10, p. 1070231, 2023. https://doi.org/10.3389/fpubh.2022.1070231

[20] T. Xue, N. Kang, and T. Zhu, "Health-oriented strategy for clean air and climate actions: Differential health effects of atmospheric components," *Annu. Rev. Public Health*, vol. 46, no. 1, pp. 275–294, 2025. https://doi.org/10.1146/annurev-publhealth-071723-015722

[21] W. Wang, W. Zhang, D. Hu, L. Li, L. Cui, J. Liu, S. Liu, J. Xu, S. Wu, F. Deng, and et al., "Short-term ozone exposure and metabolic status in metabolically healthy obese and normal-weight young adults: A viewpoint of inflammatory pathways," *J. Hazard. Mater.*, vol. 424, p. 127462, 2022. https://doi.org/10.1016/j.jhazmat.2021.127462

[22] C. Chen, T. Li, Q. Sun, W. Shi, M. Z. He, J. Wang, J. Liu, M. Zhang, Q. Jiang, M. Wang, and et al., "Short-term exposure to ozone and cause-specific mortality risks and thresholds in China: Evidence from nationally representative data, 2013–2018," *Environ. Int.*, vol. 171, p. 107666, 2023. https://doi.org/10.1016/j.envint.2022.107666

[23] G. Donzelli and M. M. Suarez-Varela, "Tropospheric ozone: A critical review of the literature on emissions, exposure, and health effects," *Atmosphere*, vol. 15, no. 7, p. 779, 2024. https://doi.org/10.3390/atmos15070779

[24] L. Zhu, J. Fang, Y. Yao, Z. Yang, J. Wu, Z. Ma, R. Liu, Y. Zhan, Z. Ding, and Y. Zhang, "Long-term ambient ozone exposure and incident cardiovascular diseases: National cohort evidence in China," *J. Hazard. Mater.*, vol. 471, p. 134158, 2024. https://doi.org/10.1016/j.jhazmat.2024.134158

[25] Y. Niu, T. Yang, X. Y. Gu, R. J. Chen, X. Meng, J. Y. Xu, L. Yang, J. P. Zhao, X. Y. Zhang, C. X. Bai, and et al., "Long-term ozone exposure and small airway dysfunction: The China Pulmonary Health (CPH) study," *Am. J. Respir. Crit. Care Med.*, vol. 205, no. 4, pp. 450–458, 2022. https://doi.org/10.1164/rccm.202107-1599OC

[26] Z. P. Niu, Z. Z. Duan, J. Wei, F. L. Wang, D. H. Han, K. Y. Zhang, Y. M. Jing, W. H. Wen, W. J. Qin, and X. J. Yang, "Associations of long-term exposure to ambient ozone with hypertension, blood pressure, and the mediation effects of body mass index: A national cross-sectional study of middle-aged and older adults in

China," *Ecotoxicol. Environ. Saf.*, vol. 242, p. 113901, 2022. https://doi.org/10.1016/j.ecoenv.2022.113901
[27] Q. Y. Tan, B. Wang, Z. Ye, G. Mu, W. Liu, X. Q. Nie, L. L. Yu, M. Zhou, and W. H. Chen, "Cross-sectional and longitudinal relationships between ozone exposure and glucose homeostasis: Exploring the role of systemic inflammation and oxidative stress in a general Chinese urban population," *Environ. Pollut.*, vol. 329, p. 121711, 2023. https://doi.org/10.1016/j.envpol.2023.121711
[28] A. R. Soares and C. Silva, "Review of ground-level ozone impact in respiratory health deterioration for the past two decades," *Atmosphere*, vol. 13, no. 3, p. 434, 2022. https://doi.org/10.3390/atmos13030434
[29] Z. H. Gui, Z. Y. Guo, Y. Zhou, S. Dharmage, L. Morawska, J. Heinrich, Z. K. Cheng, H. Gan, Z. W. Lin, D. Y. Zhang, and et al., "Long-term ambient ozone exposure and childhood asthma, rhinitis, eczema, and conjunctivitis: A multi-city study in China," *J. Hazard. Mater.*, vol. 478, p. 135577, 2024. https://doi.org/10.1016/j.jhazmat.2024.135577
[30] X. Zhang, F. Osei, A. Stein, C. Cheng, and K. J. Maji, "Temporal and spatial evolution of short-term exposure to ozone pollution: Its health impacts in China based on a meta-analysis," *J. Clean. Prod.*, vol. 373, p. 133938, 2022. https://doi.org/10.1016/j.jclepro.2022.133938
[31] E. Fikri, T. R. Dwidjartini, E. Puspitasari, E. Chalimah, M. Evalisa, and Y. W. Firmansyah, "Analysis of the environmental impact of radiation doses on dental and oral diseases (K03.6, K05.1, and K05.3) in workers in the Indonesian National Nuclear Energy Agency," *Int. J. Saf. Secur. Eng.*, vol. 13, no. 6, pp. 1061–1068, 2023. https://doi.org/10.18280/ijsse.130608
[32] E. Fikri, Y. W. Firmansyah, S. Arlinda, T. R. Dwidjartini, M. Y. Yunus, and E. Puspitasari, "Particulate matter (PM) levels and associated health risks at the Indonesian National Nuclear Energy Agency," *Int. J. Des. Nat. Ecodyn.*, vol. 19, no. 2, pp. 699–704, 2024. https://doi.org/10.18280/ijdne.190237