

Occupational Safety and Health Risk Assessment Using the Five-Step HIRADC Approach in Landfill Waste Management Operations

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Abstract: Landfill operations involve interconnected physical, chemical, biological, ergonomic, and mechanical hazards associated with waste transportation, unloading, heavy-equipment operation, waste spreading and compaction, leachate treatment, landfill-gas management, and vector and odor control. This study aimed to identify occupational hazards, assess their risk levels, and develop an integrated control and monitoring framework for operational activities at Wonokerto Landfill, Pasuruan Regency, Indonesia. A descriptive observational design was applied using an extended Five-Step Hazard Identification, Risk Assessment, and Determining Control (HIRADC) framework covering hazard and exposed-person identification, risk assessment based on probability and severity, control selection according to the hierarchy of controls, assignment of responsibilities, and performance monitoring. A total of 143 hazards were identified across ten operational stages, comprising 4 (2.8%) low-risk, 43 (30.1%) moderate-risk, 81 (56.6%) high-risk, and 15 (10.5%) very-high-risk hazards. The most prevalent mechanisms were transportation and vehicle accidents (26.6%), heavy-equipment interactions (17.5%), chemical and gas exposure (14.0%), and slips, trips, and falls (12.6%). Very-high-risk hazards were concentrated in waste unloading and transportation, waste spreading and compaction, landfill-gas management, and travel to waste-collection locations. The findings indicate that safety management should prioritize engineering and physical-separation controls, supported by administrative measures, emergency preparedness, competent supervision, and appropriate personal protective equipment. Integrating risk prioritization, Bow-Tie Analysis, responsibility assignment, and performance indicators can strengthen control implementation, verification, and continual improvement.

Article history:

Received: 17 July 2026

Revised: 29 September 2026

Accepted: 01 October 2026

Published: 06 October 2026

Keyword:

HIRADC, landfill operations, occupational safety and health, risk assessment, hierarchy of controls

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How to cite: Rahmaniah, S., Komara, I., Ni'am, A. C., & Asmara, Y. P. (2026). Occupational Safety and Health Risk Assessment Using the Five-Step HIRADC Approach in Landfill Waste Management Operations. *RESWARA: Jurnal Riset Ilmu Teknik*, 4(4), 1462-1477. <https://doi.org/10.70716/reswara.v4i4.759>

INTRODUCTION

Population growth, urbanization, and expanding economic activity have increased the volume of municipal solid waste that must be managed safely and sustainably (Bayazit et al., 2021; Mei et al., 2018). Landfills remain an essential component of municipal solid waste management systems because they function as facilities for receiving, processing, and finally disposing of waste (Chokhandre et al., 2017; Sridhar, 2022). However, landfill operations also represent complex and high-risk work environments because they involve simultaneous interactions among workers, waste collection vehicles, heavy equipment, unstable waste piles, leachate, landfill gas, and continuously changing site conditions (Reyes et al., 2026; Vaverková et al., 2026).

Workers involved in landfill operations may be exposed to various physical, chemical, biological, mechanical, and ergonomic hazards (Reddy et al., 2026; Shi et al., 2023). These hazards include traffic accidents, being struck by or caught in heavy equipment, slips, trips, and falls, exposure to hazardous

gases, direct contact with leachate and biological agents, fires and explosions, and musculoskeletal disorders caused by manual handling. If these hazards are not effectively controlled, they may result in minor or severe injuries, occupational diseases, operational disruptions, damage to equipment and infrastructure, and fatalities.

Previous studies have demonstrated that workers in the waste-management sector experience substantial occupational risks. Yafetto reported that 59.4% of municipal solid waste collectors had experienced occupational injuries during the preceding year, with puncture wounds and cuts identified as the most common injuries (Yafetto, 2022). Another research similarly found that waste-management workers were exposed to physical, chemical, and biological hazards, including sharp objects, hazardous substances, and infectious agents (Hoang & Fogarassy, 2020). These findings indicate that waste handling is associated not only with immediate accident risks but also with long-term health effects arising from repeated exposure to harmful materials and unsafe working conditions. Occupational risks become increasingly complex during landfill operations. Waste collection vehicles operate alongside bulldozers, excavators, compactors, and other heavy equipment on uneven, slippery, and muddy surfaces, frequently under conditions of limited visibility (Battini et al., 2018). Workers may also be exposed to methane and hydrogen sulphide generated by waste decomposition. Methane accumulation may increase the risk of fire and explosion, whereas hydrogen sulphide exposure may cause eye and respiratory irritation, loss of consciousness, or death at high concentrations (Reyes et al., 2026). Additional risks arise from unstable waste slopes, leachate exposure, vector- and Odor-control activities, manual handling, and vehicle movement within active landfill areas (Zhao et al., 2023).

Effective occupational safety and health management at landfills therefore requires a systematic approach that extends beyond the provision of personal protective equipment (Jayakrishnan et al., 2013; Khrais et al., 2024). Risk management should incorporate hazard elimination where feasible, engineering controls, separation of pedestrian and heavy-equipment work zones, internal traffic management, safe operating procedures, worker training, emergency preparedness, periodic inspection, and monitoring of control effectiveness (Lombardi, Mauro, Fagnoli, et al., 2023; Saxena et al., 2025). One method commonly applied to support this process is Hazard Identification, Risk Assessment, and Determining Control (HIRADC), which provides a structured framework for identifying hazards, assessing risk levels, and selecting controls based on the hierarchy of controls (Kumalasari & Imaduddin, 2025). Although previous studies have examined occupational hazards affecting waste collection and transportation workers, many have focused only on specific activities, such as collection, transportation, or unloading. Some applied a hazard identification and risk assessment approach to waste transportation workers at the Sumompo Landfill (Ubrusun A et al., 2024). However, such studies do not fully represent the entire sequence of landfill operations, including equipment and personal protective equipment preparation, travel to waste collection locations, waste collection, transportation, weighing, unloading, waste spreading and compaction, leachate management, landfill gas management, and vector and odor control (Materazzi et al., 2015). Another limitation of previous research is that risk assessment often ends with hazard identification, calculation of risk levels, and formulation of general control recommendations. Limited attention is given to the identification of exposed parties, assignment of control responsibilities, assessment of residual risks, and establishment of monitoring and review mechanisms. As a result, recommended

controls may not be clearly linked to responsible personnel or systematically evaluated for their continuing effectiveness (Hollá et al., 2024; Sadewa & Hafid Syaifullah, 2025).

This study addresses these limitations by applying a five-step HIRADC-based framework to ten stages of landfill operations at the Wonokerto Landfill, Pasuruan Regency, Indonesia. The framework integrates hazard identification, identification of exposed parties, risk assessment, determination of control measures, assignment of responsibilities, residual risk evaluation, and monitoring and review mechanisms. The analysis is further supported by Bow-Tie Analysis for a critical heavy-equipment interaction risk, a Responsible, Accountable, Consulted, and Informed (RACI) Matrix for assigning control responsibilities, and the development of an occupational safety and health monitoring dashboard containing leading and lagging indicators. This integration is intended to strengthen the practical implementation, monitoring, and continuous improvement of occupational safety and health controls. Accordingly, this study aims to identify the dominant hazards associated with landfill operations, classify occupational risks based on likelihood and severity, analyze risk characteristics according to operational stage and hazard mechanism, determine appropriate risk-control measures, assign control responsibilities, and develop monitoring mechanisms to support continuous improvement in occupational safety and health performance at the Wonokerto Landfill.

RESEARCH METHOD

Research Design Framework

This study assessed occupational health and safety risks in waste-management operations at the Wonokerto Landfill, Pasuruan Regency, East Java, Indonesia. The assessment covered the operational sequence shown in Figure 1, from equipment and personal protective equipment (PPE) preparation to waste collection, transportation, weighing, unloading, spreading and compaction, leachate and landfill-gas management, and vector and odor control. A descriptive-analytical design was applied using five risk-assessment steps: identifying hazards; identifying who could be harmed and how; evaluating risks and selecting controls; recording findings, responsibilities, and implementation time frames; and reviewing the assessment. This sequence follows the workplace risk-assessment guidance of the International Labour Organization (ILO, 2013). The unit of assessment was a hazard scenario within a defined work stage, rather than a work stage as a whole. For each scenario, the assessment recorded the activity, hazard, exposed persons, credible consequence, available evidence, existing controls, initial risk rating, proposed additional controls, and residual risk rating. The document review covered records dated June – August 2026. These dates distinguish the period represented by the operational and incident records from the date on which the records were assessed.

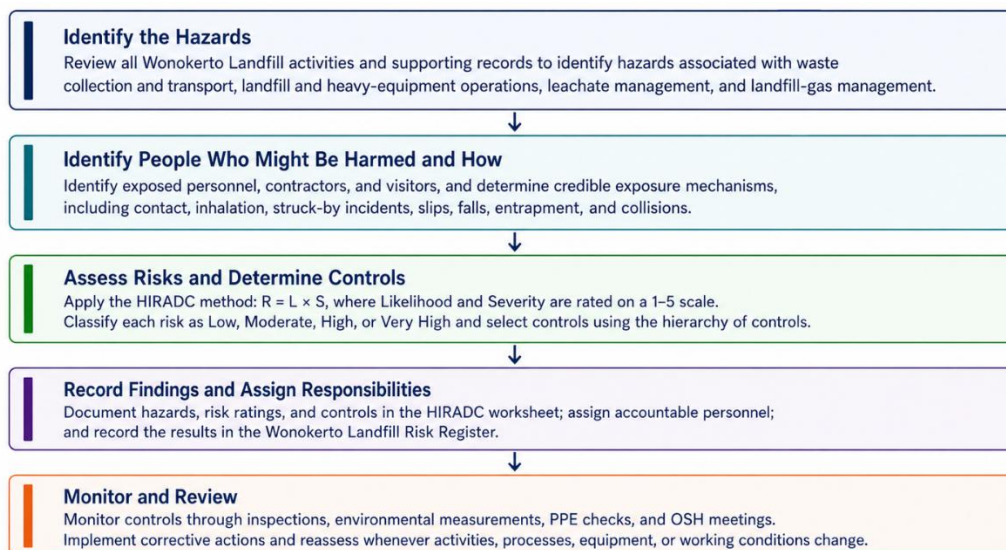


Figure 1. HIRADC risk assessment workflow

Decomposition Strategies

Secondary data were obtained from custodian records of Wonokerto Landfill. The operational sequence was divided into ten stages: (1) equipment and PPE preparation; (2) travel to waste-collection locations; (3) waste collection; (4) transportation to the landfill; (5) vehicle weighing; (6) unloading in the active landfill area; (7) waste spreading and compaction; (8) leachate management; (9) landfill-gas management; and (10) vector and odor control (Figure 2). This division allowed hazards associated with different tasks, locations, and exposed worker groups to be assessed separately. Hazards were identified with input from safety officer. Probability and severity ratings were assigned by supervisor and reviewed by identifier. The completed worksheet retained the evidence and reasoning supporting each rating so that another assessor could review the decision. The decomposition of landfill waste-management operations into ten work stages is presented in Figure 2.

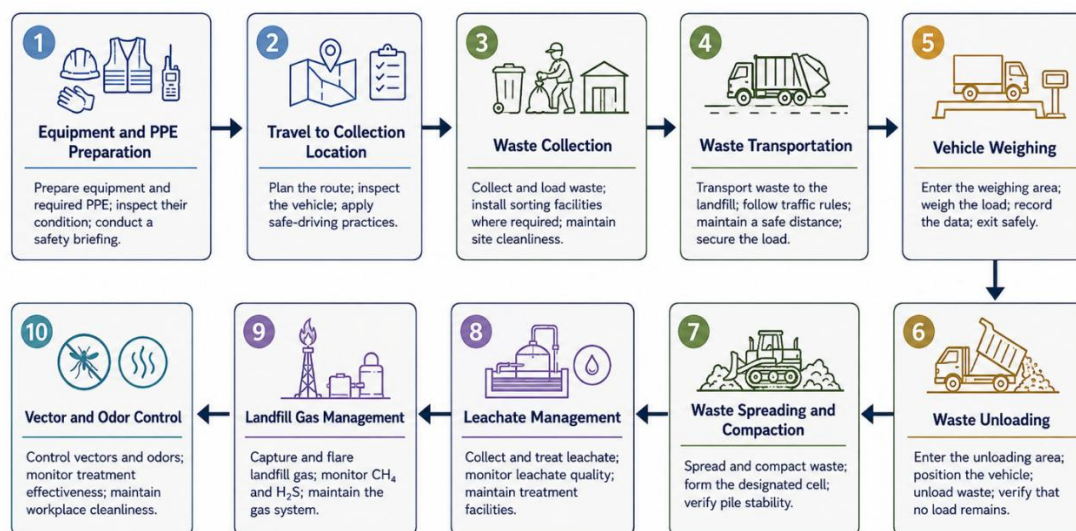


Figure 2. Decomposition of Work Stages in Landfill Waste-Management Operations in Wonokerto

Risk Assessment and Control Determination

Each hazard scenario was assigned a probability rating (P) and a severity rating (S) on five-point ordinal scales. The initial rating represented the risk under the operating conditions documented for the review period, including existing controls only when their presence and use could be supported by the available records. The score was calculated as expressed in Equation (1).

$$R = P \times S \quad (1)$$

where (R) is the risk score, (P) is the probability or likelihood rating, and (S) is the severity rating. Both parameters were evaluated using a five-point scale. Probability ranged from 1 (very unlikely) to 5 (very likely), whereas severity ranged from 1 (very low consequence) to 5 (very high consequence). Accordingly, the calculated risk scores ranged from 1 to 25.

Based on the risk matrix shown in Fig. 3, the risks were classified into four levels: Low ((R=1–5)), Moderate ((R=6–9)), High ((R=10–16)), and Very High ((R=20–25)). Because the risk score was obtained by multiplying two integer ratings ranging from 1 to 5, scores of 17–19 could not occur in the applied matrix. The resulting risk level was used to establish the priority and urgency of the required control measures. Low risks were managed through existing procedures and routine monitoring. Moderate risks required additional controls and periodic evaluation. High risks required prompt corrective measures and closer supervision, whereas activities classified as Very High were not permitted to continue until the risk had been reduced to an acceptable level.

Control measures were determined according to the hierarchy of controls, prioritizing elimination, substitution, engineering controls, administrative controls, and personal protective equipment, in descending order of effectiveness. Elimination or substitution was considered whenever the hazardous activity, material, or work method could be removed or replaced. Where these measures were not practicable, engineering controls were applied to isolate workers from the hazard, followed by administrative controls such as standard operating procedures, training, work permits, traffic management, inspection schedules, and safety supervision. Personal protective equipment was applied as the final protective layer rather than as the primary control measure.

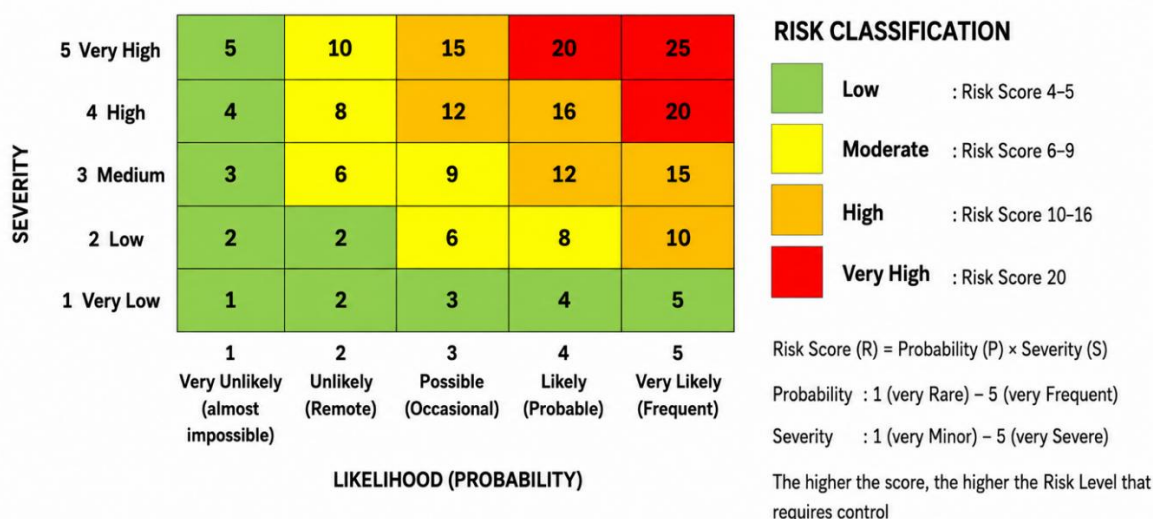


Figure 3. The 5 × 5 Risk Matrix of HIRADC Assessment

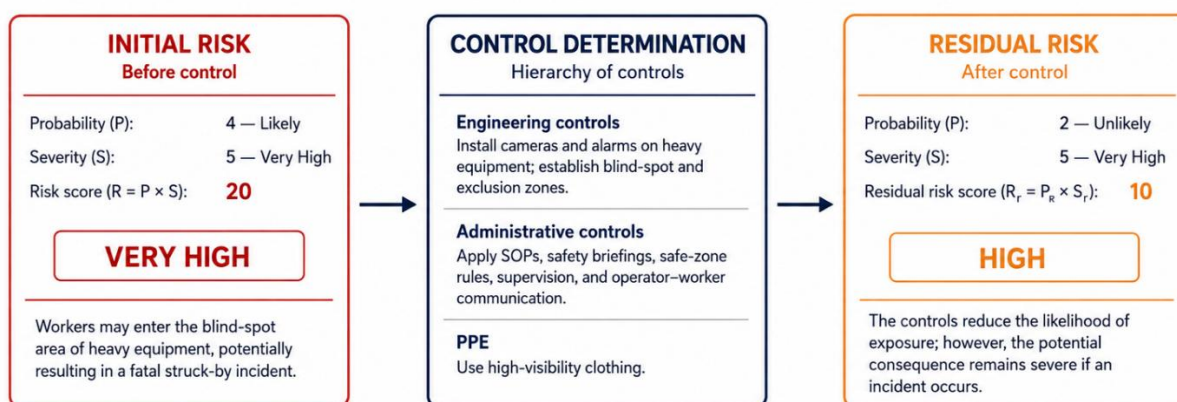


Figure 4. Concept of Initial and Residual Risk Assessment

For Wonokerto Landfill operations, the selected controls were matched to the relevant operational stage, including equipment and PPE preparation, travel to collection locations, waste collection and transportation, vehicle weighing, waste unloading, spreading and compaction, leachate management, landfill-gas management, and vector and odor control. Each control measure was assigned to responsible personnel and documented in the HIRADC worksheet and landfill risk register. Residual risk was subsequently reassessed using Eq. (1) after the proposed controls had been considered. The control was regarded as adequate when the residual risk had been reduced to an acceptable level and could be maintained through routine monitoring and periodic review.

Risk-control measures were selected in accordance with the hierarchy of controls, prioritizing elimination and substitution, followed by engineering controls, administrative controls, and personal protective equipment. The selection process considered the anticipated effectiveness of each measure, technical feasibility, site-specific operational constraints, ease of implementation, and its capacity to reduce the likelihood and/or consequences of the identified hazard. Following control determination, the residual risk associated with each hazard was reassessed using the same probability and severity scales applied in the initial assessment. The residual risk score was then compared with the corresponding initial risk score to quantify the anticipated risk reduction and identify activities requiring additional controls, continued monitoring, or periodic review. Figure 4 illustrates the relationship between the initial risk, the selected control measures, and the resulting residual risk.

RESULTS AND DISCUSSION

Hazard Mapping

The assessment identified 143 hazard scenarios across the ten work stages of landfill waste-management operations. The largest number was recorded during waste unloading in the active landfill area, with 22 hazards (15.4%). This was followed by waste transportation to the landfill, with 20 hazards (14.0%), and waste spreading and compaction, with 18 hazards (12.6%). The fewest hazards were identified during equipment and PPE preparation, with nine hazards (6.3%). The complete distribution is presented in Table 1.

The concentration of hazards during waste unloading is associated with the simultaneous presence of collection vehicles, landfill workers, heavy equipment, waste piles, and changing ground conditions within the active disposal area. Vehicle manoeuvring, reversing, and unloading frequently

occur within a restricted operational space. These conditions increase the potential for vehicle collisions, struck-by incidents, falls, direct contact with waste, and loss of stability on uneven or weakened ground.

Waste transportation and waste spreading and compaction also generated a relatively large number of hazards because they involve repeated movement of vehicles and heavy equipment, interaction with ground personnel, and exposure to changing traffic and surface conditions. In contrast, equipment and PPE preparation generally occurs before the main waste-handling activities and involves fewer simultaneous interactions among workers, vehicles, and landfill equipment.

The distribution demonstrates that hazards are unevenly distributed across the landfill operation. Work stages involving vehicle movement, unloading, mechanical handling, and interaction with waste piles produce more complex hazard scenarios than preparatory activities. This finding is consistent with Ubrusun et al. (Ubrusun A et al., 2024), who reported occupational hazards associated with waste transportation and unloading at Sumompo Landfill. The present assessment covers a broader operational sequence, extending from equipment and PPE preparation to vector and odor control, and therefore provides a more comprehensive representation of hazards across landfill activities.

The findings are also consistent with Lombardi et al., (Lombardi, Mauro, Fargnoli, et al., 2023) who identified work equipment and environmental conditions as important contributors to occupational accidents in landfill operations and reported excavator operation as a particularly hazardous activity. These findings support the prioritization of active landfill areas where workers, vehicles, heavy equipment, waste piles, and ground conditions interact simultaneously.

Based on the hazard distribution, control efforts should initially focus on waste unloading, internal waste transportation, and spreading and compaction. Priority measures include the implementation of an internal traffic-management system, physical or operational separation of pedestrian and equipment routes, controlled access to active landfill areas, standardized communication between equipment operators and ground personnel, reversing controls, and regular inspection of ground and waste-pile stability. The relatively high number of hazards associated with leachate and landfill-gas management also indicates the need for specific controls addressing chemical, biological, atmospheric, and confined-area exposures.

Table 1. Distribution of Hazards by Work Stage

No.	Work Stage	Number of Hazards	Percentage (%)
1	Equipment and PPE Preparation	9	6.3%
2	Travel to Waste Collection Locations	12	8.4%
3	Waste Collection	10	7.0%
4	Waste Transportation to the Landfill	20	14.0%
5	Vehicle Weighing	10	7.0%
6	Waste Unloading in the Active Landfill Area	22	15.4%
7	Waste Spreading and Compaction	18	12.6%
8	Leachate Management	17	11.9%
9	Landfill Gas Management	15	10.5%
10	Vector and Odor Control	10	7.0%
TOTAL		143	100.0%

Risk Level Distribution

Figure 5 illustrates the distribution of the 143 identified hazard scenarios according to their initial risk levels. High-risk hazards represented the largest category, comprising 81 scenarios (56.6%), followed by moderate-risk hazards with 43 scenarios (30.1%). Fifteen scenarios (10.5%) were classified as very high risk, while four scenarios (2.8%) were classified as low risk. In total, high- and very-high-risk scenarios accounted for 96 hazards, or 67.1% of all identified hazards. When moderate-risk scenarios were included, 139 hazards (97.2%) required additional controls, enhanced monitoring, or corrective action.



Figure 5. Distribution of Risk Levels in Landfill Waste-Management Operations

The predominance of high- and very-high-risk scenarios indicates that the landfill operations presented substantial occupational risks under the conditions assessed before the proposed additional controls were applied. These classifications may result from a high likelihood of occurrence, severe potential consequences, or the combination of both factors. Very-high-risk activities therefore require immediate intervention and should not continue under unchanged operating conditions. High-risk activities require prompt corrective action and close supervision, whereas moderate-risk activities should be managed through planned controls and periodic review. Although low-risk scenarios accounted for only a small proportion of the total, they should remain subject to routine monitoring because changes in equipment, work practices, environmental conditions, or worker behaviour may increase their risk level.

The distribution also demonstrates that personal protective equipment (PPE) alone cannot provide adequate risk reduction for landfill operations. Control measures should follow the hierarchy of controls, beginning with elimination or substitution where practicable. Engineering controls should then be considered, including equipment guarding, warning systems, physical barriers, exclusion zones, ventilation, and containment systems. These measures should be supported by administrative controls, such as standard operating procedures, traffic-management plans, safety briefings, competency training, inspection schedules, communication protocols, and operational supervision. PPE should remain the final protective layer.

After the selected controls have been implemented, each hazard scenario should be reassessed using the same probability and severity criteria applied in the initial assessment. This reassessment is necessary because the potential consequence of many landfill hazards may remain severe even when

the likelihood of occurrence has been reduced. A control should therefore be considered effective only when its implementation is documented, responsibility is assigned, its operation is verified through inspection or monitoring, and the resulting residual risk is reduced to an acceptable level. The initial risk distribution shown in Figure 5 provides a clear basis for prioritizing corrective measures and allocating occupational safety resources to the most critical landfill activities.

Hazard Mechanism

The 143 identified hazard scenarios were grouped into eight principal hazard mechanisms. Transportation and vehicle-related accidents were the most frequently identified mechanism, accounting for 38 hazards (26.6%). This was followed by interaction with heavy equipment, with 25 hazards (17.5%), chemical and gas hazards, with 20 hazards (14.0%), and slips, trips, and falls, with 18 hazards (12.6%). Collectively, these four mechanisms accounted for 101 hazards, equivalent to 70.6% of all identified hazards. The results indicate that vehicle movement, mobile-equipment interaction, hazardous exposure, and unstable working surfaces should receive priority within the landfill's occupational safety strategy.

Table 2. Distribution of Identified Hazards by Hazard Mechanism

Hazard Mechanism	Number of Hazards	Percentage (%)
Transportation and Vehicle Accidents	38	26,6%
Interaction with Heavy Equipment	25	17,5%
Ergonomics and Manual Handling	13	9,1%
Slip, Trip, and Fall	18	12,6%
Biological Hazards	10	7,0%
Chemical and Gas Hazards	20	14,0%
Fire and Explosion Hazards	7	4,9%
Mechanical and Electrical Hazards	12	8,4%
TOTAL	143	100,0%

Transportation and vehicle-related hazards were associated with vehicle movement throughout the operational sequence, including travel from waste-collection locations, entry into the landfill, vehicle weighing, movement toward the active disposal area, manoeuvring during unloading, and interaction with workers and mobile equipment. These activities may be affected by traffic density, road and surface conditions, visibility, reversing movements, vehicle condition, and the separation between vehicles and pedestrians. This finding is consistent with Lombardi et al. (Lombardi, Mauro, Berardi, et al., 2023), who identified traffic conditions and road-safety provisions as important factors in heavy-vehicle accidents associated with landfill remediation activities. Accordingly, transportation risks should be addressed through route planning, pre-operational vehicle inspections, speed restrictions, traffic signs, designated vehicle and pedestrian routes, reversing controls, safe-distance requirements, and driver-competency management.

Interaction with heavy equipment represented 25 hazards (17.5%). Bulldozers, excavators, compactors, and other mobile equipment used in waste spreading and compaction can expose workers to blind spots, reversing movements, rotating components, unstable terrain, and communication failures between operators and ground personnel. Soltanmohammadlou et al emphasized that

earthmoving-equipment safety is influenced by interactions among machinery, workers, work tasks, management systems, and environmental conditions (Lombardi, Mauro, Fagnoli, et al., 2023; Quist et al., 2026; Reddy et al., 2026; Tekere et al., 2026; Vaverková et al., 2026). The present findings therefore indicate that operator caution alone is insufficient. Required measures include pedestrian–equipment separation, exclusion-zone demarcation, designated travel paths, trained spotters, cameras and proximity-warning systems, standardized communication protocols, equipment inspections, and active supervision.

Chemical and gas hazards accounted for 20 cases (14.0%) and were associated with landfill gas, leachate, chemicals used for vector and odor control, and contact with decomposing waste. Methane accumulation may create fire and explosion hazards, whereas hydrogen sulfide exposure can cause irritation, respiratory effects, loss of consciousness, and potentially fatal outcomes at high concentrations. Lombardi et al. similarly noted that landfill workers may be exposed to hazardous gases, dust, leachate, and other contaminated environmental media (Lombardi, Mauro, Berardi, et al., 2023). Ziraba et al further demonstrated that waste-related health outcomes depend on waste characteristics, exposure pathways, exposed populations, exposure duration, and the availability of preventive interventions (Ziraba et al., 2016a, 2016b). These hazards require source containment, landfill-gas monitoring, adequate ventilation where applicable, ignition-source control, safe chemical handling, emergency procedures, hygiene facilities, and appropriate respiratory and skin protection.

Slips, trips, and falls accounted for 18 hazards (12.6%). These hazards may arise from muddy or uneven terrain, scattered waste, leachate-contaminated surfaces, vehicle routes, elevation changes, inadequate lighting, and unstable waste piles. Cointreau identified falls, unstable disposal-site surfaces, waste-pile movement, vehicle accidents, and mobile-equipment incidents as recurring injury mechanisms in solid-waste operations (Ashington & Cointreau, 2006). Preventive measures should therefore include routine housekeeping, designated pedestrian access, drainage maintenance, adequate lighting, work-surface inspections, barricades around unstable areas, and monitoring of waste-pile stability. The remaining mechanisms comprised ergonomic and manual-handling hazards (13; 9.1%), mechanical and electrical hazards (12; 8.4%), biological hazards (10; 7.0%), and fire and explosion hazards (7; 4.9%). Although these mechanisms were less frequent individually, together they represented 42 hazards (29.4%) and should not be regarded as negligible. Their management requires task-specific controls, including mechanical handling aids, ergonomic work procedures, equipment guarding, electrical inspection and isolation, hygiene and vaccination programmes where appropriate, fire-prevention measures, and emergency preparedness.

Table 3. Distribution of Very High Risks by Operational Activity

No.	Operational Activity	Stage	Number of Hazards	Percentage (%)
1	Equipment and PPE Preparation	Stage A	0	0.0%
2	Travel to Waste Collection Locations	Stage B	2	13.3%
3	Waste Collection	Stage C	0	0.0%
4	Waste Transportation to the Landfill	Stage D	3	20.0%
5	Vehicle Weighing	Stage E	0	0.0%
6	Waste Unloading in the Active Landfill Area	Stage F	4	26.7%
7	Waste Spreading and Compaction	Stage G	3	20.0%

8	Leachate Management	Stage H	0	0.0%
9	Landfill Gas Management	Stage I	3	20.0%
10	Vector and Odor Control	Stage J	0	0.0%
TOTAL			15	100.0%

Table 4. OSH Performance-Monitoring Indicators

No.	Indicator	Type	Frequency	Target	Purpose
1	PPE compliance	Leading Indicator	Daily	≥ 95%	Ensure workers use PPE in accordance with applicable requirements.
2	Vehicle inspections	Leading Indicator	Daily	100%	Ensure vehicles are in safe operating condition.
3	Heavy-equipment inspections	Leading Indicator	Daily	100%	Ensure heavy equipment is in safe operating condition.
4	Safety briefings	Leading Indicator	Daily	≥ 95%	Improve worker awareness and preparedness before work begins.
5	Reporting of unsafe conditions	Leading Indicator	Weekly	≥ 1 report/week	Identify and control unsafe conditions.
6	Near-miss reporting	Leading Indicator	Weekly	≥ 1 report/week	Identify potential hazards before an accident occurs.
7	Leachate-quality monitoring	Leading Indicator	Weekly	Comply with applicable standards	Verify that leachate quality complies with applicable requirements.
8	Landfill-gas monitoring	Leading Indicator	Weekly	Comply with applicable standards	Control the risk of exposure to landfill gas.
9	Vector and odor control	Leading Indicator	Weekly	According to program	Reduce vector and odor disturbances in the landfill area.
10	Occupational accidents	Lagging Indicator	Monthly	-	Measure occupational-safety outcomes.
11	Heavy-equipment incidents	Lagging Indicator	Monthly	-	Measure safety performance related to heavy-equipment operations.
12	Fires	Lagging Indicator	Monthly	-	Measure fire events as evidence of control-system weaknesses or failures.
13	Operational disruptions (downtime)	Lagging Indicator	Monthly	-	Measure the operational consequences of safety-related events.

Table 3 presents the distribution of very-high-risk hazard scenarios across the ten work stages. The greatest number occurred during waste unloading in the active landfill area, with four scenarios (26.7%). Waste transportation, waste spreading and compaction, and landfill-gas management each accounted for three scenarios (20.0%). Two scenarios (13.3%) were identified during travel to waste-collection locations. No very-high-risk scenarios were identified during equipment and PPE

preparation, waste collection, vehicle weighing, leachate management, or vector and odor control. The concentration of very-high-risk scenarios in unloading, transportation, spreading and compaction, and landfill-gas management reflects the interaction of mobile equipment, workers, waste piles, vehicle movements, and hazardous atmospheric conditions. These work stages should therefore receive priority during control implementation, field supervision, emergency planning, and verification of residual risk.

An occupational safety and health (OSH) performance-monitoring dashboard was developed to support the monitoring and review stage of the Five-Step HIRADC framework. The dashboard combines leading and lagging indicators. Leading indicators assess preventive activities and the implementation of controls before an accident occurs, whereas lagging indicators measure incidents, losses, or operational effects that have already occurred. The leading indicators provide information on whether preventive controls are being implemented at the required frequency and level. The lagging indicators provide evidence of events that have already occurred and may reveal weaknesses in the control system. Both indicator groups should be reviewed together because a low accident frequency does not necessarily demonstrate effective control when inspection, reporting, or monitoring activities are incomplete.

Table 5. Monitoring and Review Activities

Activity	Purpose	Frequency	Person in Charge (PIC)	Method
Daily inspection	Ensure that equipment, vehicles, and work areas are safe before and during work.	Daily	Landfill Supervisor	Inspection checklist
Weekly inspection	Assess compliance with procedures, risk controls, and landfill operating conditions.	Weekly	Landfill Supervisor	Inspection checklist
Special inspection after extreme weather	Verify waste-pile stability, drainage channels, access roads, and supporting facilities.	As required	Landfill Supervisor	Inspection checklist
Direct OSH supervision	Monitor safe worker behavior and compliance with procedures.	Daily	Landfill Supervisor	Direct observation
Near-miss and unsafe-condition reporting	Identify potential hazards and unsafe conditions.	Weekly / Monthly	All Workers	Reporting form
Incident investigation	Determine root causes and corrective actions to prevent recurrence.	For every incident	Landfill Supervisor	Investigation form
Internal OSH audit	Evaluate implementation of the OSH management system against standards and procedures.	Quarterly / According to plan	Internal Audit Team	Audit checklist
Weather monitoring	Monitor rainfall, strong winds, and potential extreme-weather conditions.	Daily / During warnings	Landfill Supervisor	Meteorological data and field observations
Monthly OSH review	Review indicator performance, risk-control results, and required improvements.	Monthly	Head of Landfill Unit	Review meeting

The framework is conceptually compatible with the ILO Five-Step Guide and with the risk-management principles of ISO 45001:2018 and Indonesia's Government Regulation No. 50 of 2012. Its structure incorporates hazard identification, worker involvement, risk assessment, operational control, assigned responsibilities, performance evaluation, corrective action, and continual improvement. Nevertheless, compatibility with these instruments should not be interpreted as demonstrating formal compliance unless implementation has been independently evaluated against all applicable requirements.

The findings further indicate that landfill OSH management should not rely primarily on PPE. Although PPE remains necessary for exposure to waste, contaminated surfaces, gases, chemicals, vehicles, and heavy equipment, it constitutes the final level of the hierarchy of controls. More reliable risk reduction requires integrated engineering and organizational measures, including physical separation of pedestrians and vehicles, traffic management, equipment safeguards, warning systems, safe operating procedures, training, supervision, and worker-reporting mechanisms.

Overall, the Five-Step HIRADC framework provides a practical mechanism for translating risk-assessment findings into prioritized controls, assigned ownership, measurable performance indicators, and continual improvement. Its application should nevertheless account for differences in operational processes, equipment, waste characteristics, workforce arrangements, and site conditions. Because the assessment is semi-quantitative, its risk classifications and anticipated residual-risk values should be validated using actual implementation evidence, inspections, exposure-monitoring results, and incident and near-miss trends.

CONCLUSION

This study developed and applied an integrated Five-Step HIRADC framework to assess and manage occupational safety and health risks throughout the operational activities of Wonokerto Landfill. The framework linked hazard identification, exposure assessment, risk prioritization, control selection, documentation, responsibility assignment, and performance monitoring within a continual-improvement process.

The assessment identified 143 hazard scenarios: 4 low-risk scenarios (2.8%), 43 moderate-risk scenarios (30.1%), 81 high-risk scenarios (56.6%), and 15 very-high-risk scenarios (10.5%). Thus, 96 scenarios (67.1%) were classified as high or very high risk. This distribution indicates that landfill operations require systematic risk controls and cannot depend on routine work practices or PPE alone.

Transportation and vehicle-related accidents were the most frequent hazard mechanism, accounting for 38 scenarios (26.6%), followed by interaction with heavy equipment (25; 17.5%), chemical and gas hazards (20; 14.0%), and slips, trips, and falls (18; 12.6%). The 15 very-high-risk scenarios were concentrated in waste unloading, waste transportation, waste spreading and compaction, landfill-gas management, and travel to waste-collection locations. These findings indicate that the most critical risks occur where workers interact with moving vehicles and heavy equipment, work on unstable waste surfaces, or may be exposed to toxic or flammable landfill gases.

The control strategy should therefore prioritize higher levels of the hierarchy of controls. Key measures include pedestrian-vehicle segregation, designated traffic routes, exclusion zones, engineering safeguards, equipment-warning systems, waste-pile stability management, landfill-gas monitoring, and ignition-source control. These measures should be supported by safe operating

procedures, worker training, competent supervision, emergency preparedness, and appropriate PPE. Administrative controls and PPE remain necessary, but should complement engineering controls and physical separation.

The residual-risk assessment indicated that the proposed controls could reduce the likelihood of a critical event while leaving the potential severity unchanged. In the illustrative reassessment, the projected risk score decreased from 20, classified as very high risk, to 10, classified as high risk, after engineering, administrative, and PPE controls were considered. This reduction represents a projected change in risk priority rather than hazard elimination. Any remaining high residual risk therefore requires control verification, field supervision, inspection, monitoring, and periodic reassessment.

The supporting analytical and management instruments strengthened the practical application of the framework. The risk matrix established control priorities; Bow-Tie Analysis clarified the relationships among threats, preventive barriers, critical events, mitigation barriers, and consequences; and the RACI matrix assigned responsibility and accountability for control implementation. Leading indicators, including PPE compliance, equipment inspections, safety briefings, near-miss reporting, and environmental monitoring, were combined with lagging indicators, including accidents, equipment incidents, fires, and operational disruptions, to support control verification and corrective action.

Overall, the Five-Step HIRADC framework provides a structured means of translating risk-assessment findings into prioritized controls, accountable implementation, performance verification, and continual improvement. Its contribution extends beyond hazard identification and risk scoring by linking each control to a responsible party, monitoring requirement, and review process. However, the assessment was semi-quantitative and limited to a single landfill. The proposed controls and projected residual-risk ratings should therefore be verified through implementation records, workplace measurements, inspections, and longitudinal incident and near-miss data. Further research should apply the framework across different waste-management facilities and quantify the effectiveness of implemented controls over time.

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