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Long-term occupational risk assessment and injury severity analysis in municipal solid waste management: A 12-year Fine–Kinney study

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ABSTRACT

This study assessed heavy metal contamination in the Garan River's water and sediments to evaluate the impact of landfill leachate. Pollution levels and ecological risks were quantified using established indices, including the contamination factor (CF), pollution load index (PLI), geoaccumulation index (Igeo), enrichment factor (EF), and potential ecological risk index (PERI). Spatially, peak dissolved metal concentrations in water occurred at points S1 and S4, while maximum sediment concentrations were found at S3, directly downstream of the leachate outfall. Water quality analysis indicated that arsenic posed both acute and chronic human health risks at all stations, and chromium posed an acute risk at all stations. Sediment assessment revealed that barium, nickel, and mercury consistently exceeded the threshold effect concentration (TEC). Furthermore, nickel and mercury surpassed the probable effect concentration (PEC) at 100% and 85.71% of stations, respectively, signaling a significant potential for adverse effects on aquatic life. Index analysis showed higher CF values in sediments than in water. The PLI trend increased in sediments but decreased in water, whereas EF was higher in water and spatially stable. The average Igeo for all metals remained below zero, classifying the area as unpolluted. The PERI indicated medium ecological risk in sediments only at stations S3, S6, and S8. While the collective indices suggest that severe, widespread pollution is not present, the identified contamination hotspots and specific risks from metals like arsenic, nickel, and mercury warrant vigilant attention. Consequently, periodic monitoring of leachate-derived metals and proactive preventive measures are critically recommended to preserve aquatic ecosystem quality.

Highlights

- A decision matrix guided safety actions and resource allocation by injury severity.
- Fine-Kinney analysis assessed 84 accidents at a municipal waste management complex.
- Processing/transfer stations: risk (R = 540), intolerable; >60% of recorded accidents.
- Roads had a high-risk score (R = 450), with intolerable risk due to fatal outcomes.
- Lines, transfer stations, and roads were top priorities for immediate safety action.

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1. Introduction

Municipal solid waste management (MSWM) is a fundamental infrastructure of modern societies and plays a vital role in safeguarding public health and ensuring environmental sustainability. However, the operational nature of MSWM—encompassing waste collection, transportation, processing, recycling, and disposal—exposes workers to a

wide range of occupational hazards, including biological, chemical, and physical agents. If these hazards are not adequately managed, they can lead to irreversible health consequences for workers (Gowda et al., 2023). A systematic review by Thisakya and Dissanayake (2025) identified the MSWM sector as one of the most hazardous occupational settings worldwide, with an occupational accident rate of 35.5 per 100,000 workers (Thisakya & Dissanayake, 2025). However, this rate should be interpreted with caution because it is based on a specific study population and a particular definition of "accident"; therefore, it may not be directly generalizable to other national or regional contexts. Moreover, despite growing awareness of these occupational hazards, research on the root causes of occupational safety and health problems among MSWM workers remains scarce and, in many cases, outdated (Kuijer et al., 2010).

Numerous studies have investigated the occurrence of occupational injuries among waste workers; however, these studies differ substantially in study design, population, outcome definition, recall period, and denominator, limiting direct comparability. A cross-sectional study conducted in Karnataka, India, involving 313 solid waste management workers, reported a prevalence of occupational injuries of 73.2%, with falls accounting for 63.6% (Jayakrishnan et al., 2013). In Addis Ababa, Ethiopia, the 12-month prevalence of occupational injuries was reported as 43.7%, and non-use of personal protective equipment was associated with 2.62-fold increased odds of injury (Odo, 2012). A study by Abd El-Wahab et al. in Alexandria, Egypt, revealed that the prevalence of occupational accidents was 46.5% and that of needlestick injuries 32.7% (Abd El-Wahab et al., 2014). A global systematic review and meta-analysis encompassing 8,138 sanitation workers estimated the pooled prevalence of occupational injuries at 36.49% (Tolera et al., 2024). Furthermore, a study by Martins et al. at the largest landfill site in Latin America found that 68.7% of 999 waste pickers examined had a history of occupational accidents (Martins et al., 2026). It is important to note that these studies report worker-based prevalence estimates (i.e., the proportion of workers who experienced an injury during a defined period), whereas the present study analyzes recorded occupational accidents (i.e., event-based data from an accident registration system). These are conceptually different epidemiological measures and should not be directly compared. Collectively, these studies demonstrate the high occurrence of occupational injuries worldwide and underscore the role of environmental and behavioral factors, but they also highlight the need for event-based analyses that can inform intervention prioritization.

Risk assessment constitutes the core of safety management in occupational settings, and the selection of an appropriate method plays a decisive role in hazard identification and prioritization (Chen et al., 2025). Several semi-quantitative and qualitative methods are available, each with distinct strengths and limitations. The Fine-Kinney method, as one of the semi-quantitative risk assessment techniques, calculates risk as the product of probability (P), exposure, and consequence severity (S), and has been widely applied in occupational health and safety studies (Över Özçelik et al., 2025). However, like other semi-quantitative methods, Fine-Kinney is not inherently superior to alternative approaches such as Job Hazard Analysis (JHA) or Failure Mode and Effects Analysis (FMEA); rather, its appropriateness depends on the research question and available data. JHA is particularly useful for task-specific hazard identification, while FMEA is well-suited for systematic failure analysis of components and processes. Fine-Kinney, by contrast, is advantageous when the objective is to prioritize hazards or zones based on a combination of probability, exposure, and severity, particularly when retrospective accident data are available to inform scoring. Previous studies in the waste management sector have employed JHA (Jalali et al., 2025), FMEA (Babaei Masdaraghi et al., 2018), and FMEA (Keeshavarz Motamed et al., 2022), reflecting the diversity of methodological approaches in this field.

In Iran, concomitant with the ever-increasing urban population and rising waste generation, the development of waste processing and recycling facilities has accelerated considerably in recent years. However, parallel to this expansion, the rate of occupational accidents in this industry has also increased. A review of occupational accident studies in Iran indicates that the waste industry is among those with a high risk of accidents (Mehrifar et al., 2022). Nevertheless, only a limited number of studies have systematically and quantitatively assessed accident risk in waste facilities, and even fewer have covered accident trends over extended time periods. Although the severity of consequences is one of the key components of risk assessment methods such as the Fine-Kinney method, few studies in Iran have analyzed accidents based on injury severity and presented a corresponding prioritization framework. Most studies have confined themselves to hazard identification and risk prioritization, with less attention given to developing an operational framework for optimal resource allocation and safety intervention prioritization grounded in injury severity. To the best of our knowledge, no study in Iran has systematically analyzed occupational accidents in municipal solid waste management facilities based on injury severity over a long-term (12-year) period. This claim is based on our review of the available literature; however, we acknowledge that the absence of evidence is not definitive evidence of absence.

The present study was conducted at a single municipal solid waste management facility in Iran, which includes processing and sorting lines, transfer stations, a maintenance workshop, internal roadways, and administrative sections. This facility was selected because it represents a typical MSWM complex in Iran, with operational characteristics such as mechanical processing, manual sorting, and vehicle traffic that are common to similar facilities in the country. Conventional accident analysis often relies on frequency-based prioritization, which may overlook zones where severe but infrequent events occur. For example, a zone with a high number of minor injuries may receive greater attention than a zone with fewer accidents but more fatalities, even though the latter may pose a greater threat to worker safety. Incorporating injury severity into risk assessment is therefore expected to provide a more informative basis for intervention prioritization, particularly in contexts where resources are limited and must be allocated strategically. This study adopts a reactive approach—analyzing actual occurred accidents rather than relying solely on preventive assessments—to complement existing proactive risk assessment efforts.

However, it is important to clarify that this study does not directly compare reactive and proactive methods, nor does it claim that reactive analysis can identify hazards that proactive assessments cannot detect. Rather, it aims to demonstrate how retrospective accident data, when integrated with severity classification, can inform practical prioritization decisions.

The present study, therefore, seeks to analyze occupational accidents recorded over 12 years at the study facility, classify them by location and injury severity, apply the Fine-Kinney method to calculate risk scores, and develop a prioritization framework to assist managers in allocating limited safety resources. The intended contribution of this study is practical and context-based: it demonstrates how existing tools, when applied systematically to longitudinal accident data, can yield actionable insights for resource allocation in waste management facilities. This study does not claim to introduce a new methodological innovation; rather, it aims to provide a transparent and reproducible framework that may be adapted by similar facilities in other developing countries, with appropriate localization. Whether the proposed framework improves resource allocation compared with existing methods remains an empirical question that requires further validation in future studies.

2. Materials and Methods

2.1 Study Design

The present study is a retrospective, record-based observational study that examined and analyzed occupational accidents recorded at a municipal solid waste management facility in Iran over 12 years (2010–2022). The study was designed with a combined approach encompassing descriptive analysis and semi-quantitative risk assessment.

2.2 Study Population and Sample

A total of 102 accident records were initially identified in the facility's accident registration system for the period 2010–2022. Of these, 18 records were excluded for the following reasons:

- 9 records lacked sufficient detail on the accident description or injury outcome.
- 5 records were duplicates (same accident reported twice)
- 4 records were incomplete (missing date, location, or severity information).

The final sample therefore comprised 84 accidents (82.4% of the initial records). A flow diagram illustrating the record selection process is presented in Figure S1 (Supplementary Material).

2.3 Variable Classification and Operationalization

Two occupational health and safety (OHS) specialists independently coded location and injury severity. Inter-rater agreement was assessed using Cohen's kappa, yielding $\kappa = 0.87$ for location classification and $\kappa = 0.82$ for severity classification, indicating strong agreement. We resolved disagreements through discussion until consensus was reached.

a) Classification of the accident location variable

Based on the operational nature of the facility and the geographical distribution of accidents, locations were disaggregated into five zones (Table 1).

Table 1 Classification of location zones

Zone Code	Zone Name	Description of Included Locations
Z1	Processing and sorting lines	Screen, conveyor belt, sorting lines, granulated fertilizer line, secondary fermentation, sorting room
Z2	Transfer stations and platforms	Khalkhabad, Hesarak, waste reception hall, weighbridge, dog shelter, reject
Z3	Workshop and warehouse	Central workshop, car wash, warehouse, fuel station
Z4	Road, yard, and traffic	Halgheh Darreh road, underpasses, line yard, streets leading to the facility
Z5	Other and administrative sections	Physicians' building, administrative office, administrative staircase, administrative floors, green space

b) Classification of the severity variable

Based on the ultimate consequence of the accident to the injured individual's health, and with reference to standard severity criteria used in risk assessment methods, injury severity was divided into four levels (Table 2). It should be noted that the severity scores assigned in this study (100, 50, 15, and 5) represent a modified version of the standard Fine-Kinney severity scale, adapted to the specific context of occupational accidents in waste management facilities. In the standard Fine-Kinney scale, severity scores range from 1 to 100, with specific anchors for catastrophe, disaster, very serious, serious, important, and noticeable consequences. However, because the standard scale is primarily designed for industrial incidents with property damage components, we adapted the severity anchors to focus exclusively on human health consequences, as follows:

- **S4 (Catastrophic):** Fatality → Score 100 (consistent with standard Fine-Kinney "catastrophe")
- **S3 (Very serious):** Amputation or severe fracture → Score 50 (modified; standard Fine-Kinney assigns 40 for "disaster" and 15 for "very serious")
- **S2 (Serious):** Injury requiring medical treatment and absence from work → Score 15 (consistent with standard Fine-Kinney "very serious")
- **S1 (Minor):** Superficial injury without absence → Score 5 (modified; standard Fine-Kinney assigns 1 for "noticeable")

The rationale for this modification is that the standard Fine-Kinney severity scale includes monetary damage thresholds that are not applicable to occupational accident records in this

context. We therefore retained the human-health anchors and adapted the intermediate scores to reflect the severity gradient observed in our dataset. This modification is explicitly acknowledged as a deviation from the standard method, and its implications for risk scores are discussed in the Limitations section.

2.4 Aggregation rule for zone-level severity

Because each zone contained accidents of varying severity, a single severity score (S) had to be assigned to each zone for the Fine-Kinney calculation. The following aggregation rule was applied consistently across all zones: the severity score corresponding to the most severe accident recorded in that zone was used. This rule was chosen because the objective of the study was to prioritize interventions based on the potential for severe harm, and using the most severe outcome ensures that zones with rare but catastrophic events are not underestimated. Applying this rule:

- Z1 (processing lines): most severe = 1 fatality (S4) → S = 100
- Z2 (transfer stations): most severe = 1 fatality (S4) → S = 100
- Z3 (workshop): most severe = 1 amputation (S3) → S = 50
- Z4 (roadway): most severe = 2 fatalities (S4) → S = 100
- Z5 (administrative): most severe = 1 amputation (S3) → S = 50

Table 2 Classification of Injury Severity

Severity Level	Title	Operational Definition	S Score
S4	Catastrophic	Resulted in death (explicit mention of death or fatality)	100
S3	Very serious (Critical)	Amputation, severe fracture (explicit mention of amputation or fracture)	50
S2	Serious	Injury requiring sutures, dressing, transfer to hospital, and absence from work	15
S1	Minor	Superficial abrasion, contusion, scraping, no need for absence from work	5

2.5 Risk Assessment Method

2.5.1 The Semi-Quantitative Fine-Kinney Technique

To numerically calculate risk and prioritize the different zones, the Fine-Kinney method was employed (Eq. 1). This technique is one of the most comprehensive semi-quantitative risk assessment methods, calculating the risk score (R) by considering three components: probability of occurrence (P), exposure frequency (E), and consequence severity (S) (Gul et al., 2021).

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

The evaluation tables for the concepts used to calculate the risk score in the Fine-Kinney method are presented in Tables 3 to 5 (Gul et al., 2021), and the risk score itself is shown in Table 6 (Moloudi et al., 2021).

Table 3 Probability of Occurrence (P)

Rating/Value	Probability of occurrence (P)
10	Might well be expected
6	Quite possible
3	Unusual but possible
1	Only remotely possible
0.5	Conceivable but very unlikely
0.2	Practically impossible
0.1	Virtually impossible

Table 4 Exposure

Exposure	Rating/Value
Continuous	10
Frequent (daily)	6
Occasional (weekly)	3
Unusual (monthly)	2
Rare (a few per year)	1
Very rare (yearly)	0.5

Table 5 Severity of the Consequence (Standard Fine-Kinney Scale)

Severity of the consequence	Rating/Value
Catastrophe (many fatalities, or >10^7 damage)	100
Disaster (few fatalities, or >10^6 damage)	40
Very serious (fatality, or >10^5 damage)	15
Serious (serious injury, or 10^4 damage)	7
Important (disability, or 10^3 damage)	3
Noticeable (minor first aid accident, or >$100 damage)	1

2.5.2 Determination of Probability (P)

The probability score was determined by the expert panel based on the observed frequency of accidents in each zone over the 12-year study period, combined with the operational nature of the zone. It is important to clarify that accident frequency was not equated with probability; rather, it served as one input among several. The following quantitative criteria (Table 7) were used to translate accident frequency into the categorical P score:

Table 6 Interpretation of Risk Levels in the Fine-Kinney Method

Risk score	Risk level	Suggested action
>400	Very high	Activity should not be performed until corrective action is taken.
200–400	High	Corrective action must be taken immediately.
70–200	Medium	Corrective action is required.
20–70	Low	Attention should be paid as soon as possible.
<20	Acceptable	No corrective action is required.

Table 7 Quantitative criteria for translating accident frequency into the categorical P score

Accident frequency (per zone over 12 years)	Assigned P score	Fine-Kinney description
>20 accidents	6	Quite possible
10–20 accidents	3	Unusual but possible
5–9 accidents	1	Only remotely possible
<5 accidents	0.5	Conceivable but very unlikely

It should be acknowledged that, because the number of exposure opportunities (e.g., number of workers, operating hours) was not available for all zones, the P scores represent expert judgment informed by accident frequency rather than a strictly quantitative probability calculation. This limitation is acknowledged in the Limitations section.

2.5.3 Determination of Exposure

The exposure score was determined based on the number of hours workers were exposed to hazards in each zone, as estimated from shift schedules and operational records. Specifically:

- Continuous exposure (E=10): Workers are present in the zone throughout the entire shift.
- Frequent/daily exposure (E=6): Workers enter the zone multiple times per day.
- Occasional/weekly exposure (E=3): Workers enter the zone a few times per week.
- Unusual/monthly exposure (E=2): Workers enter the zone a few times per month.
- Rare exposure (E=1): Workers enter the zone a few times per year.

We acknowledge that detailed worker-hour data were not available for all zones, and the E scores therefore represent expert estimates based on shift schedules and operational knowledge. This limitation is acknowledged in the Limitations section.

2.5.4 Expert Panel Composition and Procedure

The panel comprised three occupational health and safety (OHS) specialists with the following qualifications:

- **Expert 1:** PhD in Occupational Health, 15 years of experience, including 5 years in waste management facilities.
- **Expert 2:** MSc in Occupational Health, 10 years of experience, including 3 years in waste management.
- **Expert 3:** MSc in Safety Engineering, 8 years of experience, including 4 years in waste management.

Experts were selected based on their demonstrated expertise in occupational risk assessment and their familiarity with waste management operations. Each expert independently reviewed the zone descriptions, accident frequency data, and operational characteristics, and independently assigned P and E scores. Disagreements were resolved through a consensus meeting. The arithmetic mean of the three experts' ratings was used as the final P and E score for each zone, and scores were rounded to the nearest value in the Fine-Kinney scale.

2.5.5 Methodological Contribution and Innovation

While the present study applies the semi-quantitative Fine-Kinney method as its risk assessment framework, the methodological contribution lies in the systematic integration of 12-year longitudinal accident data with expert panel judgment to calibrate the probability (P) and exposure scores, rather than relying solely on expert opinion as in conventional applications of this method. The study does not introduce new weighting factors or a novel algorithmic validation process; rather, it adopts a practical, context-driven approach to risk prioritization. It must be acknowledged that no new weighting method was developed, and no formal inter-rater agreement index (such as ICC or Kendall's W) was calculated. The innovation of this study is therefore practical and context-based, rather than methodological.

2.6 Statistical Analysis Method

The collected data were analyzed after entry into SPSS software version 26 and Microsoft Excel 2019. Given the descriptive analytical nature of the study and the absence of a control group, inferential statistical tests (such as chi-square) were not employed for comparing proportions. Instead, the analysis was conducted based on descriptive indices and the risk score (Moloudi et al., 2022).

3. Results and Discussion

In this section, the results derived from the analysis of 84 occupational accidents recorded over 12 years (2010–2022) at

the municipal solid waste management facility under study are presented. The findings are organized into four sequential steps: descriptive data analysis, examination of the relationship between accident location and injury severity, quantitative risk calculations using the Fine-Kinney method, and finally, derivation of the intervention prioritization matrix.

The analysis of 84 recorded accidents over 12 years (2010–2022) revealed that the study facility faces a high risk of occupational accidents, with 11.9% of all accidents (10 cases) resulting in fatality or amputation. The highest accident frequency was observed in the processing line zone, with 27 cases (32.1%), followed by the transfer station zone with 24 cases (28.6%). According to the semi-quantitative Fine-Kinney method, the processing line and transfer station zones (R = 3600) and the roadway zone (R = 900) were classified as very high risk.

3.1 Descriptive Data Analysis

3.1.1 Frequency distribution of accidents by year of occurrence

The annual distribution of accidents, as shown in Fig. 1, revealed considerable fluctuations over the study period. The year 2019 had the highest number of accidents (21 cases; 25% of all accidents), whereas 2011 had the lowest (one case). In 2018 and 2020, 13 and 12 accidents were recorded, respectively, representing 15.5% and 14.3% of the total.

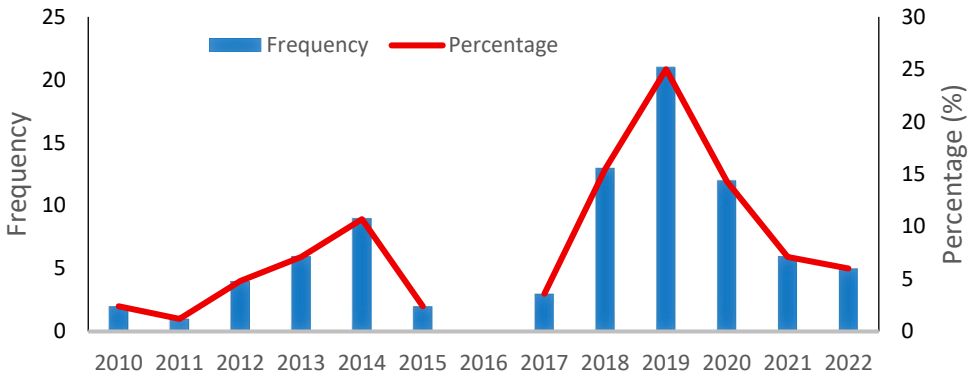


Fig.1 Annual frequency distribution of accidents

A noteworthy observation was the decline in accidents in 2021 and 2022 (6 and 5 cases, respectively) following the peak in 2019. Although this reduction may indicate the positive effect of control measures, it cannot be conclusively attributed to them, as decreased operational activity during the post-pandemic period or changes in the accident recording system may also have contributed to this decline.

3.1.2 Frequency distribution of accidents by accident type and location zone

Injury was the most common type of accident, with 41 cases (48.8%), followed by fire with 11 cases (13.1%) and traffic accidents with 9 cases (10.7%). Amputation, with 6 cases (7.1%), was among the high-severity accidents and occurred specifically in the processing line zone. Dog bites and needlestick injuries, each with 3 cases (3.6%), reflected the specific biological hazards characteristic of this sector. Falls from height, with 5 cases (6.0%), and myocardial infarction, with 2 cases (2.4%), were among the other types of recorded accidents (Fig. 2).

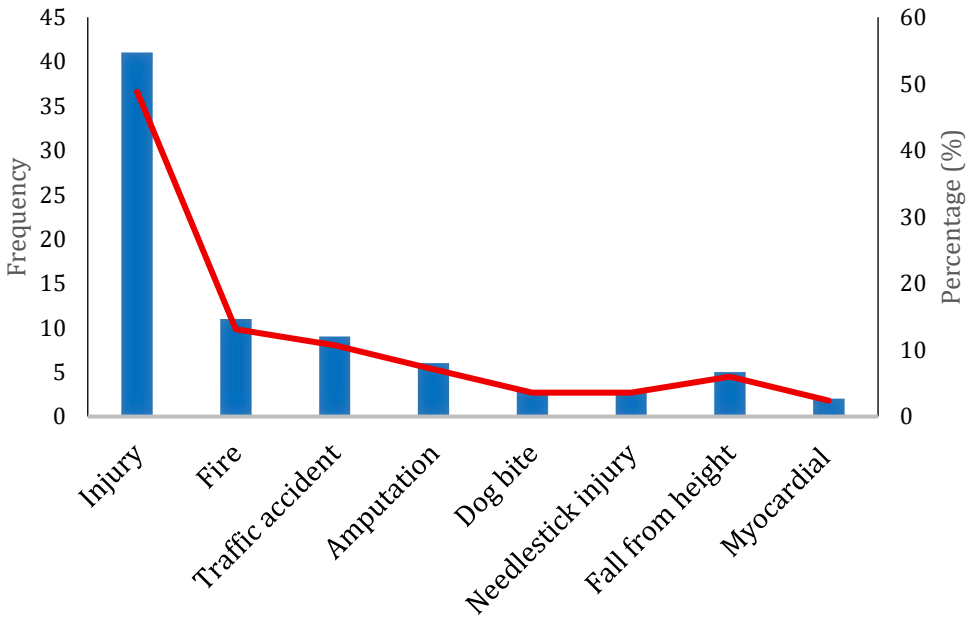
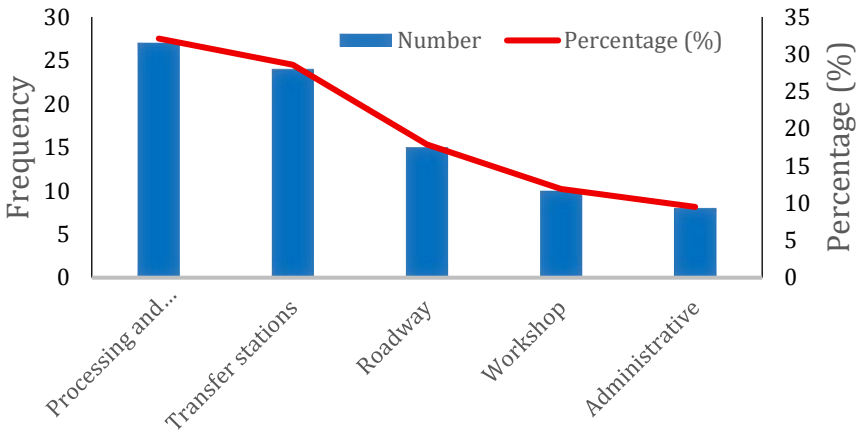


Fig. 2 Frequency distribution of accidents by accident type

A study by Abd El-Wahab et al. in Egypt demonstrated that workers in direct contact with waste were at greater risk of gastrointestinal, respiratory, and musculoskeletal disorders (Abd El-Wahab et al., 2014), This finding is comparable to the high proportion of injuries (48.8%) and the predominance of mechanical hazards observed in the present study. On the other hand, the meta-analysis by Tolera et al. (2024) reported a pooled prevalence of 36.49% for occupational injuries among sanitation workers, which is lower than the 48.8% observed in the present study (Tolera et al., 2024). This difference may be attributable to differences in services as well as in accident recording and reporting systems.

Based on the analysis of location of occurrence (Fig. 3), the processing and sorting line zone, with 27 cases (32.1%), and the transfer station zone, with 24 cases (28.6%), accounted for the highest accident frequencies. The roadway and maintenance workshop zones followed with 15 cases (17.9%) and 10 cases (11.9%), while the administrative sections had the smallest share, with 8 cases (9.5%).

Fig. 3 Frequency distribution of accidents by location zone

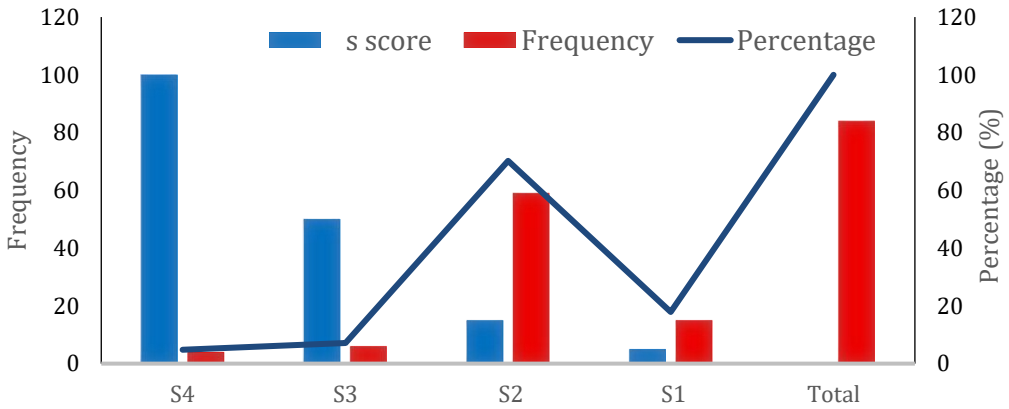


A comparison with previous studies reveals considerable consistency. In the study by Moussiopoulos and Kontogianni (2017), material recovery and composting facilities had the highest hazard levels (Moussiopoulos, 2017). This is consistent with our finding that the processing line zone accounted for 32.1% of all accidents and had an R value of 3600. The study by Moloudi et al. (2022) identified 485 HSE hazards, 38% of which were related to material recovery and composting facilities (Moloudi et al., 2022). Although that study focused on potential hazards, its findings are consistent with the present results.

3.1.3 Frequency distribution of accidents by injury severity

Based on the injury severity classification (Fig. 4), the highest frequency was associated with the serious level (S2), with 59 cases (70.2%). The minor level (S1) accounted for 15 cases (17.9%), the very serious level (S3) for 6 cases (7.1%), and the catastrophic level (S4) for 4 cases (4.8%). Although the S4 level had the lowest number of cases, the occurrence of four fatalities during the study period indicates the presence of severe hazards requiring immediate preventive action.

Fig. 4 Frequency distribution of accidents by injury severity



The proportion of severe accidents (S3 + S4) relative to all accidents was 11.9% (10 out of 84 cases). This high proportion underscores the necessity of devoting special attention to engineering control measures, since many severe accidents primarily arise from deficiencies in equipment design and inherent safety. The accident descriptions indicated that mechanical guards were absent and lockout/tagout procedures were not implemented in the affected zones, suggesting these as contributing factors. This highlights that investment in inherent equipment safety is among the most effective strategies for reducing severe accidents.

Table 8 Intersection Matrix of Location Zone and Injury Severity

Location Zone	S1 (Minor)	S2 (Serious)	S3 (Very serious)	S4 (Catastrophic)	Total
Z1 (Processing lines)	3	21	2	1	27
Z2 (Transfer stations)	5	17	1	1	24
Z3 (Workshop)	2	7	1	0	10
Z4 (Road)	3	9	1	2	15
Z5 (Other/Administrative)	2	5	1	0	8
Total	15	59	6	4	84

3.2 Intersection Analysis of Location Zone and Injury Severity

Based on Table 8, the processing line zone, with 2 cases of amputation (S3) and 1 fatality (S4), had the highest number of severe accidents (3 cases). The transfer station zone, despite its high accident frequency (24 cases), predominantly had S2-level injuries, with 1 amputation (S3) and 1 fatality (S4). The roadway zone, although having a lower frequency (15 cases), was critical because of 2 fatalities (S4). The administrative zone (Z5) recorded 1 amputation (S3) and had the lowest risk score.

3.3 Risk Assessment Results Using the Fine-Kinney Method

Based on the calculations, the processing line zone (Z1) and the transfer station zone (Z2), with a risk score of 3600, were classified at the very high level. This high score is primarily attributable to the combination of high probability, daily exposure, and high severity (fatality). The roadway zone (Z4), with a risk score of 900, was also classified at the very high level. Although the probability and exposure in this zone are lower, the high consequence severity due to 2 fatalities has substantially elevated the risk score. The maintenance workshop zone (Z3), with a risk score of 450, was also classified at the very high level due to the occurrence of one amputation. Finally, the administrative zone (Z5), with a risk score of 100, was identified at the medium level (Table 9).

Table 9 Fine-Kinney Risk Scores and Calculations

Zone	P	Description	E	Description	S	Description	R	Risk Level
Z1	6	Quite possible	6	Daily	100	One fatality	3600	Very high
Z2	6	Quite possible	6	Daily	100	One fatality	3600	Very high
Z3	3	Possible	3	Weekly	50	One amputation	450	Very high
Z4	3	Possible	3	Weekly	100	Two fatalities	900	Very high
Z5	1	Unlikely	2	Monthly	50	One amputation	100	Medium

One of the prominent findings is the high-risk score of the roadway zone (900). This finding is comparable to the study by Demir et al. (2024), which identified 68 risks at a hazardous waste disposal facility in Turkey using the Fine-Kinney method (Demir et al., 2024). In Demir et al.'s study, most risks were classified at the "notable" level, whereas in the present study, four zones were identified at the "very high" level. The study by Jalali et al. (2025), conducted in the same geographical area, utilized the JHA method to identify 8 risk factors for Top Turn machine operators, of which 2 were at the unacceptable risk level (Jalali et al., 2025).

3.3.1 Addressing the Subjectivity of the Fine-Kinney Method

The authors acknowledge that the Fine-Kinney method is inherently susceptible to subjectivity. To mitigate this limitation, several strategies were employed. First, the expert panel comprised three OHS specialists, and the mean of their ratings was used as the final P and E score for each zone, thereby reducing individual bias. Second, the range of expert opinions was examined; however, a formal inter-rater agreement index was not calculated, which is acknowledged as a limitation. Third, the P and E scores were calibrated against 12-year empirical accident data. Fourth, the 12-year accident dataset itself served as a validation mechanism: the risk scores derived from the Fine-Kinney method were cross-checked against the actual distribution of severe accidents across zones. For instance, the processing line zone, which received the highest risk score (3600), also recorded the highest number of severe accidents (3 cases), providing empirical validation. While these measures do not eliminate the inherent subjectivity of the method, they represent a practical and transparent approach to reducing bias.

3.4 Final Decision Matrix for Intervention Prioritization

The decision matrix was constructed using the following explicit rules:

1. Primary criterion: Zones were ranked by their Fine-Kinney risk score (R) in descending order.
2. Tie-breaking criterion: When two zones had the same R value (e.g., Z1 and Z2 both with R=3600), the number of severe accidents (S3+S4) was used as a tie-breaker, with higher numbers receiving higher priority.
3. Action priority categories (Table 10):

- Immediate and emergency: R > 400 (Very high risk)
- High (within 6 months): R = 200–400 (High risk)
- Medium (within 1 year): R = 70–200 (Medium risk)
- Low (periodic review): R < 70 (Low/Acceptable risk)

While severity is already incorporated into R through the S component, the number of severe accidents provides additional information about the cumulative burden of severe events. A sensitivity analysis excluding the number of severe accidents as a criterion showed that the priority ranking remains unchanged.

Table 10 Final Decision Matrix for Intervention Prioritization

Priority	Zone	Risk Score (R)	Risk Level	Number of Severe Accidents	Action Priority
1	Z1 (Processing lines)	3600	Very high	3	Immediate and emergency
2	Z2 (Transfer stations)	3600	Very high	2	Immediate and emergency
3	Z4 (Road)	900	Very high	3	Immediate and emergency
4	Z3 (Workshop)	450	Very high	1	Immediate and emergency
5	Z5 (Other/Administrative)	100	Medium	1	Medium (within 1 year)

Based on the above matrix, four zones processing lines, transfer stations, roadways, and workshop are placed under immediate and urgent priority. In the processing line zone, the most critical action is the installation of standard mechanical guards on rotating machinery and the implementation of a lockout/tagout (LOTO) system. In the transfer station zone, there is a need for fire detection and suppression systems as well as infectious waste management. In the roadway zone, infrastructure improvements and installation of warning signs are prioritized. In the workshop zone, machine guarding and LOTO implementation during maintenance are prioritized.

In the Addis Ababa study, non-use of personal protective equipment was associated with 2.62-fold increased odds of injury (Odo, 2012), which is consistent with the findings of the present study regarding the role of carelessness and lack of safety equipment in accident occurrence. Furthermore, the study by Abib et al. (2024) in Ethiopia demonstrated that factors such as pre-employment safety training, sleep problems, and temporary workers were significantly associated with occupational injury occurrence (Abib et al., 2024). This finding aligns with the content analysis of accidents in the present study, as in many accident descriptions, drowsiness and carelessness were cited as contributing factors in road accidents.

A deeper interpretation of the findings reveals that the high-risk score of the processing line zone (3600) primarily stems from the combination of three factors: high probability (daily exposure to machinery), continuous exposure (workers are constantly active alongside conveyor belts and screens), and high severity (fatality). Analysis of accident descriptions in this zone indicates that most accidents resulted from workers' hands or clothing becoming caught in machinery and contact with sharp and cutting objects. This pattern points to the absence of standard mechanical guards and the failure to implement lockout/tagout (LOTO) procedures during maintenance and repair. Similar findings have been reported among municipal solid waste workers in India, where occupational health problems are frequently associated with inadequate engineering controls and limited use of personal protective equipment (Chinthapatla & Tiwari, 2024). In other words, despite the existence of international standards for machinery safety, these standards appear not to have been fully implemented in the facility under study. Regarding the transfer station zone, which is classified at the very high level with a risk score of 3600, the high diversity of hazards (fire, dog bites, needlestick injuries, accidents involving machinery, and falls) indicates the multidimensional nature of hazards in this zone. This diversity necessitates a variety of control approaches (technical, behavioral, and administrative) and cannot be addressed through a single control measure alone.

Comparison of the findings of the present study with the research by Imam and Rafizul (2025) at the Rajbandh landfill site in Khulna, Bangladesh, reveals considerable similarities in the vulnerability patterns of waste workers in developing countries (Imam & Rafizul, 2025). In the Khulna study, all informal waste workers surveyed reported that they lacked personal protective equipment. In contrast, in the present study, despite the data being extracted from formal workers at a municipal waste management facility, 15 minor accidents (17.9%) were still recorded, indicating deficiencies in the supply and monitoring system for personal protective equipment use.

The findings of Akyen et al. (2025) demonstrated that informal waste pickers, due to financial constraints, are unable to afford personal protective equipment, thereby endangering their health (Akyen et al., 2025). These findings are considerably consistent with the results of the present study, in which 15 minor accidents (17.9%) were recorded, indicating deficiencies in the supply and monitoring system for personal protective equipment use. Overall, both studies emphasize that safety interventions in the waste industry are not achieved through engineering measures alone, but must also consider the economic, social, and cultural dimensions of workers to bring about sustainable behavioral change.

3.5 Summary of Key Findings

The managerial implications of this study extend beyond the identification of high-risk zones and culminate in the provision of an operational prioritization framework that assists managers in allocating their limited resources in the most optimal manner. Based on this framework, four zones—processing lines, transfer stations, roadways, and workshop—are placed under immediate and urgent priority. For the processing line zone, proposed measures include installation of standard mechanical guards on all screens and conveyor belts, implementation of a lockout/tagout system with practical training for all operators, and installation of emergency stops within easy reach of all workstations. For the transfer station zone, installation of advanced fire detection and suppression systems (such as FM200 gas-based systems), establishment of a management system for infectious and sharps waste, workplace environmental safety measures against stray dogs, and firefighting training are recommended. For the roadway zone, installation of speed bumps and warning signs, improvement of roadway lighting, driver fatigue management programmes, and periodic vehicle technical inspections are prioritised. For the workshop zone, machine guarding and LOTO implementation during maintenance activities are prioritized.

3.6 Limitations

This study has several limitations. Its retrospective design, deficiencies in some recorded accident data, and lack of complete data on demographic characteristics, exposure levels, and organizational factors should be acknowledged. Because detailed denominator data (e.g., number of workers per zone, worker-hours, number of operations, traffic volume)

were not available for all zones, accident frequency could not be converted into incidence rates. Zones with larger workforces or longer operating hours would be expected to have more recorded accidents; therefore, accident counts alone cannot establish that a zone has higher occupational risk. Thus, the risk scores presented in this study should be interpreted as relative prioritization indicators rather than absolute risk measures. Future studies should collect denominator data to enable more precise risk estimation.

The proposed prioritization framework may help managers and safety professionals identify high-risk zones, allocate resources effectively, and plan preventive interventions. If validated in other facilities, it could serve as a model for enhancing occupational risk management systems in the MSWM sector.

4. Conclusion

Certain operational zones of MSWM facilities—particularly processing lines, transfer stations, internal roadways, and maintenance workshops—are exposed to high levels of occupational risk. The fatalities and amputations observed among the reviewed accidents, coupled with the classification of these zones as very high risk by the Fine-Kinney method, underscore the urgent need for immediate, targeted control measures. The prioritization framework developed in this study integrates consequence severity, accident frequency, and risk level to determine intervention priorities and may serve as a practical tool for targeted allocation of limited safety resources. Controlling mechanical hazards and implementing lockout/tagout (LOTO) systems in processing lines, strengthening fire prevention and suppression systems at transfer stations, improving traffic safety on internal roadways, and implementing machine guarding in maintenance workshops are among the highest-priority control measures. Therefore, adopting a risk- and severity-based approach can direct intervention resources toward hazards with potentially more severe consequences for the workforce, rather than focusing solely on accident frequency.

Statements and Declarations

Ethical considerations

Ethical issues (Including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, redundancy, etc.) have been completely observed by the author.

Data availability

Data will be made available on request.

Conflicts of interest

The author declares that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Author contribution

F. Jalali: Writing the main Draft; N. Ghobadi: Conceptualization; Writing – Review & Editing; and F. Ahmadi Zarajabad: Conceptualization, Methodology, Review, and Final Proof.

AI Use Declaration

During the preparation of this manuscript, the authors used artificial intelligence (AI) tools solely to assist in the design of the graphical abstract. The authors reviewed and approved the final graphical abstract and take full responsibility for the accuracy, integrity, and content of the manuscript.

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