

Occupational injury dynamics, accident causes, and risk factors at a mining and processing plant

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Abstract

Purpose. This study aims to analyze occupational injuries at a mining and processing plant over the period from 2009 to 2023, with particular attention to underground facilities as the most hazardous divisions of the enterprise.

Methods. The methodological basis of the study was a comprehensive statistical and analytical approach to assessing occupational injuries. The initial information base consisted of official occupational accident investigation records and enterprise statistical reporting data for 2009-2023. To quantify the level of occupational injuries, a system of indicators was used, including the injury frequency coefficient, injury severity coefficient, fatal injury coefficient, and overall injury rate. Time-series analysis with sixth-degree polynomial approximation was applied to identify long-term trends and nonlinear fluctuations in injury dynamics.

Findings. The analysis revealed pronounced nonlinear variability in occupational injury indicators over the fifteen-year period, with the most significant increases observed in 2011, 2014, 2021, and especially in 2022. A total of 227 occupational accidents involving 236 injured workers were recorded, including 19 fatal cases and 83 severe injuries. The results demonstrated a clear concentration of occupational risk in underground mining operations: facilities No. 1 and No. 2 accounted for approximately half of all accidents and 58% of fatal cases, with facility No. 2 showing the highest level of injury risk. The structure of accident causes was dominated by organizational and human-related factors, including inadequate work organization, unsafe worker behavior and other related causes, deficiencies in safety training, and unsatisfactory workplace conditions. Together, these factors accounted for approximately 81% of all recorded injury cases.

Originality. The study provides an integrated long-term assessment of occupational injuries by combining injury indicators, polynomial trend analysis, accident-cause assessment, division-level comparison, and worker-related risk analysis.

Practical implications. The findings support targeted improvements in occupational health and safety management, including stronger organizational control, enhanced training and mentoring, workplace modernization, equipment monitoring, and priority preventive measures at underground facilities No. 1 and No. 2.

Keywords: occupational injuries; underground mining; mining and processing plant; injury frequency; injury severity; accident causes; occupational risk; safety management

1. Introduction

The mining industry is traditionally classified as one of the most hazardous industrial sectors in terms of occupational injuries and fatalities [1]. Underground mining operations are characterized by a high concentration of hazardous factors, complex geological conditions, confined working spaces, and the extensive use of heavy machinery, all of which significantly complicate the provision of safe working conditions [2]-[4].

Recent studies also indicate that geomechanical processes developing during combined open-pit and underground mining can affect the stability of mining systems and increase the overall level of operational risk [5], [6]. Despite continuous

technological development and improvements in industrial safety systems, the reduction of occupational injury rates remains one of the most pressing challenges in the field of occupational health and safety. In reducing occupational injury rates remains one of the most pressing challenges in international studies consistently report that underground mines exhibit higher accident rates compared to surface operations. In contrast, the severity of accident consequences in underground conditions is generally considerably greater [7], [8].

The relevance of occupational safety analysis is further strengthened by the ongoing technological transformation of mining and metallurgical enterprises. Modern production systems increasingly involve complex material flows, pro-

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cessing of technogenic raw materials, utilization of industrial by-products, and the introduction of new technological solutions for resource efficiency and energy transition. Such changes expand the range of technical, organizational, and environmental interactions within mining and processing enterprises and require more systematic approaches to risk identification and occupational safety management [9]-[13]. At the same time, effective occupational safety management cannot be limited to the registration of accident cases alone. In modern industrial systems, managerial decisions increasingly rely on quantitative indicators, information-based analysis, investment prioritization, and evaluation of organizational effectiveness. Therefore, occupational injury data should be considered not only as retrospective statistics, but also as an analytical basis for selecting preventive measures, allocating resources, and improving the overall safety management system [14]-[18].

A review of the literature indicates that numerous studies confirm the exceptionally high level of occupational risk in the mining industry. Systematic reviews of recent studies show that the mining sector accounts for approximately 8% of all fatal occupational injuries worldwide, despite employing a substantially smaller proportion of the global workforce than many other industries [19]. Several studies emphasize that underground mining operations are associated with a significantly higher proportion of severe and fatal accidents compared to surface mining, making underground work particularly hazardous [7]. Similar conclusions have been reported for coal mines in Serbia, where a high frequency of injuries is characteristic of underground mining. At the same time, workers' age and length of service have a substantial influence on the duration of work disability and the probability of severe consequences [20].

According to the study reported in [21], accident statistics in underground mines indicate that 31% of occupational accidents are associated with rock falls and collapses, 29% with transportation and hoisting operations, 8% with the use of machinery, 3% with electrical current, 3% with sudden outbursts, 2.5% with falls from height, 2% with blasting operations, and 21.5% with gas and dust explosions and other causes. These data demonstrate the high risk associated with rock falls and collapses in underground workings and underscore the need to improve technologies and organizational procedures to prevent such incidents. In addition, the considerable proportion of injuries related to transportation and hoisting operations highlights the importance of proper work organization, technical control, and strict adherence to safety precautions.

A substantial body of scientific research is devoted to methods for analyzing occupational injuries, identifying accident causation, and developing preventive strategies. A comprehensive understanding of the conditions, circumstances, and causes of hazardous production situations can be achieved through a systems-based approach that assesses the implementation of safety principles and occupational health and safety management systems. In the international literature, review studies present a wide range of accident and incident investigation methods, reflecting the growing emphasis on systematic and multidisciplinary approaches to occupational safety analysis.

In 2020, researchers from the China University of Mining and Technology published a study in *Process Safety and*

Environmental Protection that reviewed 24 accident analysis methods and classified them according to the proposed framework [22]. It has also been noted that, as production processes become increasingly complex, it becomes more difficult to identify a single root cause of an incident; therefore, accidents should be considered as a sequence of interconnected events rather than isolated failures [23]. Consequently, systemic causation models have increasingly come into focus, including approaches such as AcciMap, which are widely applied to the analysis of accidents and incidents in complex sociotechnical systems. Causation models, ranging from qualitative and quantitative approaches to dynamic analysis, have gradually evolved within the framework of scientific methods aimed at improving occupational and industrial safety [24]-[29].

In international practice, risk analysis methods play a significant role in ensuring industrial safety by enabling a systematic assessment of the influence of technical, organizational, and human factors on the probability of occupational accidents. In the mining industry, the Haddon matrix, Fine-Kinney, and Kinney models are among the widely applied approaches, as they provide a structured framework for accident causation analysis and risk reduction measure prioritization. The Haddon matrix conceptualizes an accident as the result of interactions among the human, technical, and environmental components of a system. It is commonly applied to the analysis of underground mining accidents involving rock falls, gas explosions, and injuries involving mobile equipment. The Fine-Kinney method, based on an integrated risk index, is used to rank hazards in underground mining operations, including those associated with ground instability and transportation processes. The effectiveness of this approach has been demonstrated in studies focused on risk assessment and accident forecasting in coal mines [30], [31].

In Kazakhstan, as in many other mining-oriented countries, occupational injuries in the mining sector continue to demonstrate a persistent pattern. This issue is particularly relevant for mining and processing enterprises in Kazakhstan, where industrial risk assessment is increasingly considered in relation to both production safety and health-related impacts of mining and metallurgical activities [32]. Accident causation is dominated by organizational, technical, and behavioral factors, while underground mining facilities are consistently identified as the most injury-prone units. Although several previous studies addressed injury rate calculations, forecasting, and mathematical modeling of occupational injuries at mining and processing enterprises, more recent periods remain insufficiently explored [33], [34]. In particular, there is a lack of comprehensive scientific studies covering the period from 2009 to 2023, despite this timeframe being marked by substantial changes in production organization, workforce structure, technological modernization, and occupational safety management approaches.

The absence of up-to-date research integrating long-term statistical analysis of occupational injuries, accident causation assessment, and the distribution of injured workers by key demographic and professional characteristics represents a significant scientific and practical gap. Addressing this gap would enable a more evidence-based approach to developing injury prevention measures in underground mining operations.

This study aims to conduct a comprehensive analysis of occupational injuries at a mining and processing plant from

2009 to 2023, identify accident causes and risk factors, assess injury dynamics, and develop scientifically grounded recommendations for injury prevention and reduction in underground mining operations.

To achieve this aim, the following objectives were defined:

- to calculate and analyze key occupational injury indicators at the mining and processing plant over the period from 2009 to 2023;

- to construct time series of occupational injury indicators and approximate them using sixth-degree polynomial functions to identify long-term trends and nonlinear fluctuations in injury dynamics;

- to investigate the structure of occupational accident causes and determine the dominant organizational, technical, and human-related risk factors;

- to compare occupational injury levels at the mining and processing plant as a whole and at underground facilities No. 1 and No. 2;

- to analyze injured workers by age, length of service, and occupational category to identify high-risk groups and substantiate preventive measures for underground.

2. Materials and methods

The study used occupational injury data from a mining and processing plant for the period 2009 to 2023. The enterprise includes underground mining facilities, an open-pit mine, ore processing and crushing plants, and auxiliary divisions responsible for transportation, maintenance, repair, and automation services. Particular attention was paid to underground facilities No. 1 and No. 2, as these units pose the highest occupational risk.

The study's methodological framework was based on the analysis of official occupational accident investigation records and statistical reporting data. The research included calculating key occupational injury indicators, constructing time series for the analyzed period, approximating injury dynamics using polynomial functions, and structurally analyzing accidents by cause, enterprise division, age, length of service, and occupational category of injured workers.

This approach enabled assessment of both the general dynamics of occupational injuries at the enterprise and the specific contribution of underground mining operations to the overall injury level. The combination of quantitative injury indicators and structural accident analysis provided a basis for identifying dominant risk factors and developing evidence-based directions for injury prevention.

2.1. Calculation of key occupational injury indicators

The study focused on a mining and processing plant (MPP) comprising 27 structural divisions and a total workforce exceeding 7000 employees. The enterprise includes underground mining facilities Nos. 1 and 2, an open-pit mine, ore processing and crushing plants, as well as auxiliary divisions responsible for transportation, maintenance, repair, and automation support for the production process. The study covered the period from 2009 to 2023, enabling evaluation of long-term occupational injury trends under changing production, organizational, and technological conditions. During the analyzed period, a total of 227 occupational accidents involving 236 injured workers were officially registered at the enterprise, including 19 fatal cases and 83 severe injuries. In addition, nine group accidents were recorded during the study period.

The research was based on the analysis of official occupational accident investigation records, enterprise statistical reporting materials, and occupational safety documentation related to injury registration and investigation procedures. The collected data included the number of occupational accidents, injury severity, fatal cases, accident causes, the enterprise divisions where accidents occurred, and the demographic and professional characteristics of injured workers, including age, length of service, and occupational category.

Particular attention in the study was devoted to underground facilities No. 1 and No. 2, since underground mining operations are characterized by the highest concentration of occupational hazards and the greatest injury risk within the enterprise structure.

2.2. Calculation of occupational injury indicators

To assess the level and dynamics of occupational injuries at the mining and processing plant, a statistical analysis of official occupational accident records was conducted. Within the study, a system of occupational injury indicators commonly used in industrial safety practice was developed.

The injury frequency coefficient (C_f) characterizes the number of occupational accidents per 1000 employees over a specified period and was calculated as:

$$C_f = \frac{A \cdot 1000}{B}, \quad (1)$$

where:

A – number of occupational accidents;

B – average number of employees.

The injury severity coefficient (C_s) reflects the average number of lost workdays per injured worker and was determined as:

$$C_s = \frac{D}{A}, \quad (2)$$

where:

D – total number of workdays lost due to occupational injuries.

The overall injury rate (C_o) was used as an integrated indicator characterizing the general level of occupational injury risk and was calculated as:

$$C_o = C_f \cdot C_s. \quad (3)$$

The fatal injury coefficient (C_m) characterizes the number of fatal occupational accidents per 1000 employees and was calculated using the following Equation:

$$C_m = \frac{L \cdot 1000}{B}, \quad (4)$$

where:

L – the number of fatal occupational accidents.

The calculated indicators were used to evaluate long-term dynamics of occupational injuries, identify periods of increased occupational risk, and compare injury levels across the enterprise's divisions, including underground mining facilities No. 1 and No. 2.

2.3. Time-series and structural analysis methods

For each calculated occupational injury indicator, annual time series were constructed for the period 2009-2023. The time-series analysis was used to assess year-to-year changes

in occupational injury levels and to identify periods characterized by increased or decreased occupational risk.

To describe the nonlinear dynamics of injury indicators, a sixth-degree polynomial approximation was applied. This approach enabled reflecting fluctuations in the analyzed indicators over the 15 years and identifying characteristic long-term trends in occupational injury dynamics. The general form of the polynomial model was expressed as:

$$y = a_6x^6 + a_5x^5 + a_4x^4 + a_3x^3 + a_2x^2 + a_1x + a_0, \quad (5)$$

where:

- y – the value of the analyzed occupational injury indicator;
- x – the year of observation;
- a_0, a_1, \dots, a_6 – polynomial coefficients.

The quality of the approximation was evaluated using the coefficient of determination (R^2), which characterizes the degree of correspondence between the fitted polynomial and the empirical data. Higher R^2 values indicate a closer fit of the model to the observed injury dynamics.

In addition to time-series analysis, comparative and structural analytical methods were applied. Comparative analysis was used to evaluate differences in occupational injury levels between the mining and processing plant as a whole and underground facilities No. 1 and No. 2. Structural analysis was performed to determine the distribution of occupational accidents by causes, enterprise divisions, age groups, length of service, and occupational categories of injured workers.

The combined application of time-series approximation, comparative analysis, and structural grouping enabled the identification of dominant injury patterns, the determination of the most hazardous enterprise divisions, and the establishment of the main organizational, technical, and human-related risk factors affecting occupational injuries in underground mining operations.

3. Results

3.1. Dynamics of occupational injury indicators

A comparison of occupational injury indicators over the study period allows for an assessment of long-term injury dynamics at the mining and processing plant. Injury data obtained from official statistical sources are summarized in Table 1. Table presents the annual values of the injury frequency coefficient (C_f), injury severity coefficient (C_s), fatal injury coefficient (C_m), and overall injury rate (C_o) for the period from 2009 to 2023. Based on these data, trends of occupational injury indicators for the period 2009-2023 were constructed. Figure 1 illustrates the temporal distribution of the analyzed injury coefficients and overall injury indicators.

Figure 1a presents the dynamics of the number of occupational accidents recorded during the study period. The approximation of the time series using a sixth-degree polynomial function demonstrated a satisfactory agreement between the fitted curve and the empirical data ($R^2 = 0.626$). Pronounced peaks in the number of occupational accidents were observed in 2011, 2014, 2021, and particularly in 2022. The average annual number of occupational accidents during the analyzed period was 15.7 cases. Figure 1b illustrates the dynamics of the injury frequency coefficient (C_f). The polynomial approximation yielded a coefficient of determination (R^2) of 0.6328.

Table 1. Occupational injury indicators at the mining and processing plant

Year	Frequency coefficient, C_f	Severity coefficient, C_s	Coefficient of Mortality, C_m	Overall injury rate, C_o
2009	0.86	22.66	–	22.12
2010	1.71	33.80	0.30	58.08
2011	2.99	28.81	0.43	86.19
2012	2.70	19.42	0.43	52.50
2013	1.70	27.33	0.14	46.38
2014	2.82	22.95	0.28	64.67
2015	1.12	20.75	–	23.22
2016	1.81	23.23	0.14	41.95
2017	1.54	28.00	0.14	43.22
2018	2.37	24.8	0.14	58.90
2019	1.81	24.800	0.14	43.80
2020	1.66	22.00	0.14	36.8
2021	2.93	29.50	0.42	85.800
2022	4.04	43.60	–	17.70
2023	2.23	24.80	–	55.50

The highest frequency coefficient values were recorded in 2011, 2014, 2021, and 2022, with 2022 showing the highest value over the analyzed period. The average annual value of the injury frequency coefficient was $C_f = 2.15$. Figure 1c presents the dynamics of the injury severity coefficient (C_s). The sixth-degree polynomial approximation demonstrated a relatively high level of agreement with the observed data ($R^2 = 0.695$). Elevated values of the severity coefficient were observed in 2010-2011 and in 2022. During the period from 2015 to 2018, the coefficient remained comparatively stable. Figure 1d shows the dynamics of the fatal injury coefficient (C_m). The approximation model yielded a coefficient of determination (R^2) of 0.6498. The most pronounced increases in the fatal injury coefficient were recorded in 2011-2012 and 2021, while the absence of fatal occupational injuries characterized several years. The average value of the fatal injury coefficient during the analyzed period was $C_m = 0.18$. Figure 1e presents the dynamics of the overall injury rate (C_o). The fitted polynomial model demonstrated the highest coefficient of determination among the analyzed indicators ($R^2 = 0.7174$). The highest overall injury rate was observed in 2011, 2014, 2021, and especially in 2022, when the indicator reached its highest value during the entire study period. A decline in the indicator was observed in 2023. The average overall injury rate during the analyzed period was 59.7.

3.2. Analysis of occupational accident causes

According to Figure 2, twelve categories of occupational accident causes were identified at the mining and processing plant during the study period. Four dominant categories accounted for the majority of occupational accidents:

- inadequate organization of work processes – 74 cases (31%);
- other causes – 68 cases (29%);
- deficiencies in safety training – 25 cases (11%);
- unsatisfactory workplace conditions – 24 cases (10%).

Overall, these four categories accounted for 191 out of 236 recorded occupational injury cases, representing approximately 81% of all accidents during the analyzed period.

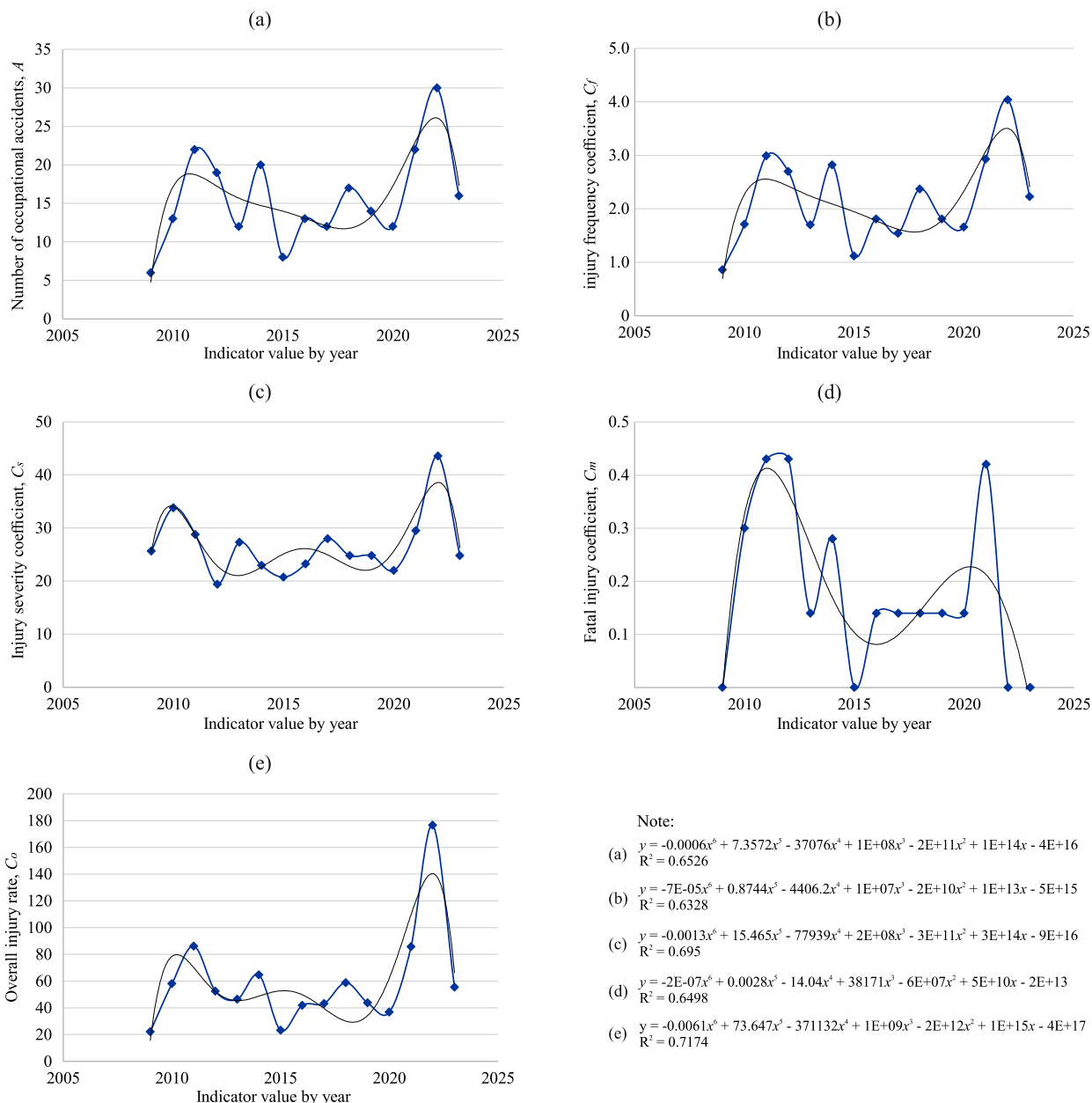


Figure 1. Dynamics of occupational injury indicators at the mining and processing plant in 2009-2023: (a) number of occupational accidents; (b) injury frequency coefficient; (c) injury severity coefficient; (d) fatal injury coefficient; (e) overall injury rate

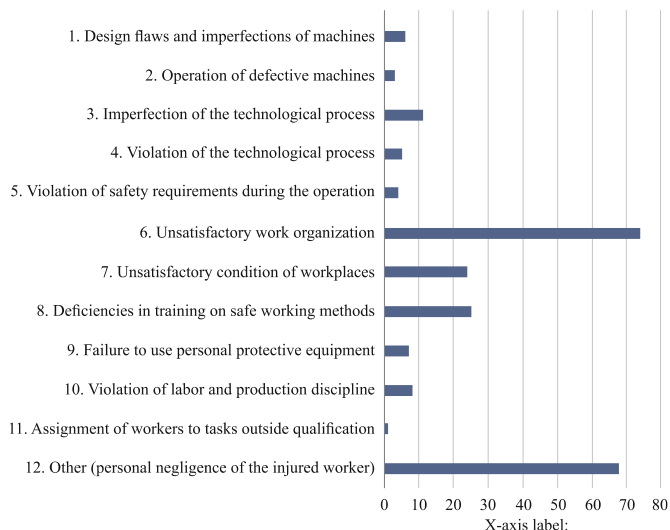


Figure 2. Distribution of accident causes at the mining and processing plant in 2009-2023

The results indicate that organizational factors played a dominant role in the structure of occupational accident causes. Inadequate organization of work processes represented the largest category of accidents, while deficiencies in training and unsatisfactory workplace conditions also accounted for a considerable proportion of injuries.

3.3. Comparative analysis of the mining and processing plant and underground facilities No. 1 and No. 2

Figure 3 illustrates the dynamics of occupational accidents at the mining and processing plant (MMP) as a whole and at underground facilities No. 1 and No. 2 during the period from 2009 to 2023.

The general trend for the enterprise demonstrated pronounced fluctuations in injury levels, with the highest values observed in 2011, 2014, 2021, and 2022. The combined indicator for underground facilities No. 1 and No. 2 generally followed the enterprise's overall trend.

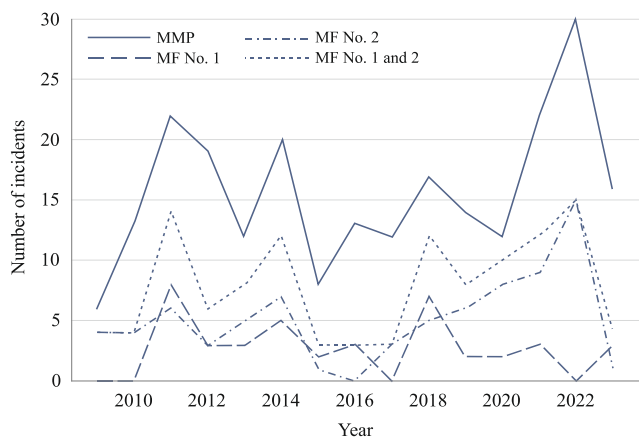


Figure 3. Dynamics of the number of occupational accidents at the mining and processing plant and underground facilities No. 1 and No. 2 in 2009-2023

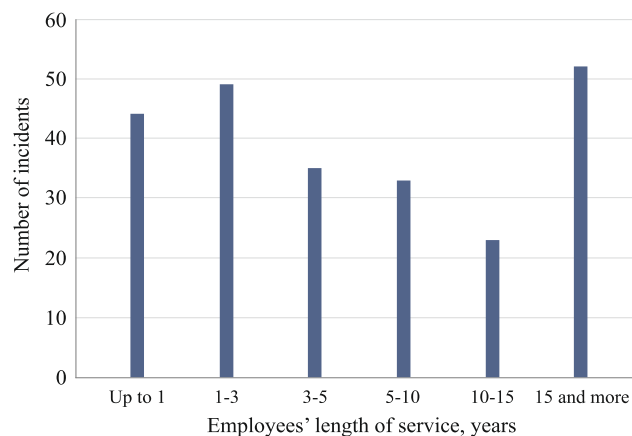


Figure 5. Histogram of the distribution of injured workers by length of service at the mining and processing plant in 2009-2023

According to the obtained results, approximately 50% of all occupational accidents recorded during the analyzed period occurred at underground facilities No. 1 and No. 2. These divisions also accounted for approximately 58% of all fatal occupational accidents registered between 2009 and 2023.

During the analyzed period, 41 occupational accidents, including two fatal cases, were recorded at underground facility No. 1. At underground facility No. 2, 77 occupational accidents and nine fatal cases were registered. The results indicate that underground facility No. 2 demonstrated the highest occupational injury level and the greatest severity of accident consequences among the analyzed enterprise divisions.

3.4. Analysis by age, length of service and occupation

A comprehensive analysis of occupational injuries by age, length of service, and occupational category was conducted for underground mining workers from 2009 to 2023.

Figure 4 presents the age distribution of injured workers. The highest number of occupational injuries was observed among workers aged 30-40 years and those aged 50 years or older. The age groups 40-50 years and 50+ years also demonstrated the highest proportion of fatal occupational injuries.

Figure 5 illustrates the distribution of occupational injuries according to length of service. The results revealed elevated injury rates among workers with less than 1 year of experience, those with 1-3 years of service, and those with more than 15 years of service. Workers with intermediate levels of experience demonstrated comparatively lower injury rates.

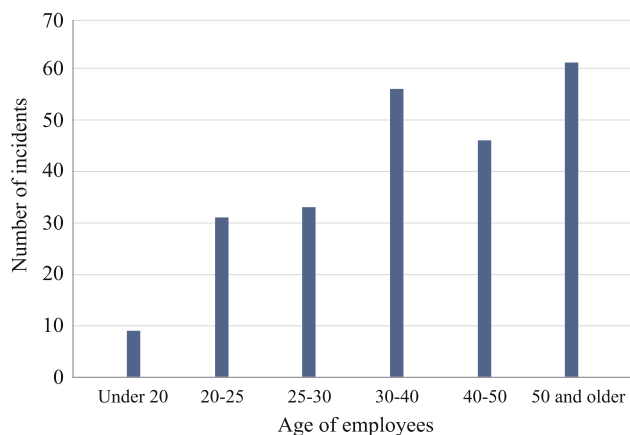


Figure 4. Histogram of the age distribution of injured workers at the mining and processing plant in 2009-2023

The occupational structure of injuries showed that the largest proportion of occupational accidents and fatal cases was associated with occupations directly involved in underground excavation and face operations, including miners, drifters, face workers, and auxiliary underground personnel.

Technical support occupations, including electrical fitters, gas welders, underground transport operators, and engineering personnel, had a lower proportion of occupational accidents than underground production workers.

4. Discussion

4.1. Interpretation of injury dynamics

The results confirm that underground mining operations are among the most injury-prone industrial activities, consistent with numerous international studies [1], [19]-[20]. The elevated risk level in underground mines is driven by the combined effects of complex geological conditions, confined working spaces, a high concentration of hazardous factors, and the use of heavy machinery in restricted workings. Under such conditions, even minor deviations from established safety requirements may lead to severe consequences, which is reflected in the higher frequency and severity of occupational accidents observed at underground facilities No. 1 and No. 2.

As shown in Table 1 and Figure 1, the dynamics of occupational injury indicators for the period 2009-2023 demonstrated alternating periods of increase and decrease, with pronounced peaks in 2011, 2014, 2021, and especially in 2022. Such fluctuations indicate that occupational injury risk at the enterprise is not constant, but depends on the interaction of production, organizational, technical, and human-related factors. The sharp increase in the overall injury rate in 2022, followed by a decline in 2023, suggests that short-term changes in working conditions, production intensity, or safety management effectiveness may significantly affect injury levels [35]-[38].

The polynomial approximation of the time series enabled the identification of nonlinear patterns in the dynamics of injury indicators. The coefficient of determination values presented for the analyzed indicators confirm that the observed trends can be used to interpret long-term changes in occupational injury levels. At the same time, the observed fluctuations also indicate that statistical trends should be interpreted together with the structure of accident causes and the characteristics of the most hazardous divisions of the enterprise.

4.2. Role of underground facilities in occupational injury formation

The comparative analysis presented in Figure 3 showed that underground facilities No. 1 and No. 2 largely determine the enterprise's overall occupational injury profile. These facilities accounted for approximately half of all occupational accidents and more than half of all fatal cases recorded during the study period. This confirms that underground mining operations form the main concentration of occupational risk within the enterprise structure.

Facility No. 2 demonstrated the highest number of accidents and fatal injuries, indicating that this division requires priority attention in the occupational health and safety management system. The higher injury level observed at facility No. 2 may be related to more complex mining conditions, higher production intensity, greater exposure to hazardous zones, or differences in the organization and control of underground operations.

This result confirms that analyzing occupational injuries at the enterprise level is insufficient without separate consideration of the most hazardous structural divisions. For mining and processing plants with underground operations, division-level analysis is necessary to identify local risk concentrations and develop targeted preventive measures. Therefore, the results shown in Figure 3 provide an important basis for prioritizing preventive actions at underground facilities No. 1 and No. 2, especially at facility No. 2.

4.3. Accident causes and risk-management interpretation

The structure of accident causes shown in Figure 2 indicates the dominance of organizational and human-related factors. The dominant causes included inadequate organization of work processes, unsafe worker behavior, deficiencies in safety training, and unsatisfactory workplace conditions. Together, these causes accounted for the majority of occupational injury cases during the analyzed period.

The structure of accident causes identified in this study is also consistent with global research findings [39]. According to the Haddon matrix, these causes reflect an imbalance among the human, technical, and environmental components of the safety system [30]. The observed distribution of causes also confirms the relevance of risk assessment and management approaches such as the Fine-Kinney and Kinney models, which allow hazards to be ranked and corrective measures to be prioritized [31]. The importance of integrated risk-management procedures is also supported by recent studies in industrial systems, where comprehensive quality assessment and risk management are considered essential for improving operational reliability and reducing the probability of failures [40].

The high proportion of accidents related to inadequate organization of work processes indicates systemic deficiencies in planning, coordination, supervision, and control of technological operations. In underground mining, where work is performed in confined, dynamically changing conditions, insufficient organization can quickly increase the likelihood of unsafe actions and hazardous situations. Therefore, regular internal audits, stricter control of workplace preparation before shifts, and compliance with the sequence of technological operations should be considered priority directions for prevention.

The significant share of accidents attributable to unsafe behavior and inadequate safety training underscores the importance of improving the enterprise's safety culture. These results suggest that formal compliance with safety procedures is insufficient without continuous training, practical simulation of emergency scenarios, and systematic behavioral safety audits. Particular attention should be paid to workers with limited experience, since this group is more vulnerable to errors caused by insufficient adaptation to underground conditions and incomplete formation of safe work skills.

Thus, the results presented in Figure 2 show that the greatest potential for reducing occupational injuries lies in strengthening organizational control, improving worker training, enhancing workplace conditions, and implementing risk-oriented safety management procedures.

4.4. Influence of age, length of service, and occupation

As demonstrated in Figure 4, age-related characteristics played an important role in the formation of occupational injury risk. The highest injury levels were observed among workers aged 30-40 years and workers older than 50 years, while the age groups 40-50 years and 50+ demonstrated the highest proportions of fatal injuries. This may be associated with age-related psychophysiological changes, including reduced reaction speed, slower information processing, accumulated fatigue, and increased vulnerability to severe accident consequences.

At the same time, elevated injury levels among younger workers may be explained by limited work experience, lower resistance to stress factors, and insufficient skills for orientation and safe behavior in underground environments. Overall, age can be considered an important component of individual occupational risk, as it amplifies the effects of production workload and the specific nature of underground mining tasks.

The distribution of injured workers by length of service, presented in Figure 5, revealed a U-shaped relationship between work experience and injury risk. Workers with less than 1 year of service and those with 1-3 years of experience are at increased risk due to insufficient adaptation, underdeveloped professional skills, and higher psychophysiological workload. In contrast, employees with more than 15 years of service may face an elevated risk due to prolonged exposure to hazardous factors, accumulated fatigue, high workload, and age-related changes that affect reaction speed and resilience in emergencies.

Workers with intermediate experience, particularly those with 3-10 years of service, demonstrated comparatively lower injury levels. However, this group may remain vulnerable when performing complex, non-standard, or high-risk technological operations. These findings are consistent with international studies emphasizing the nonlinear relationship between occupational injury risk, age, and work experience [41].

The occupational structure of accidents confirms that the highest level of risk is associated with occupations directly involved in underground excavation and face operations, including miners, drifters, face workers, and auxiliary underground personnel. These occupational groups are continuously exposed to rock pressure, manual and semi-mechanized operations, confined spaces, and zones with a high probability of rock falls and collapses.

Technical support occupations, such as electrical fitters, gas welders, underground transport operators, and engineering personnel, demonstrated a lower proportion of accidents, but still maintain a persistent level of occupational risk. This risk is primarily associated with equipment operation, maintenance activities, adjustment and repair work, and the need to perform technical tasks in restricted underground conditions.

4.5. Practical implications and preventive measures

The practical significance of the results lies in their direct applicability to the enterprise's occupational health and safety management system. In accordance with the regulatory framework of the Republic of Kazakhstan, preventive recommendations are developed based on accident investigations, scheduled workplace inspections, statistical analyses of injuries, and occupational risk assessments. The patterns identified in this study, including dominant accident causes, high-risk age and experience groups, and the specific role of underground facilities No. 1 and No. 2, provide a basis for targeted preventive measures. Since preventive measures may differ in urgency, expected effectiveness, cost, and implementation complexity, their prioritization can be supported by multi-criteria evaluation approaches, which are used for selecting and ranking complex industrial and regional projects [42].

Based on the results presented in Figure 2, organizational measures should focus on improving the quality of work organization, strengthening control over workplace preparation before shifts, ensuring compliance with technological procedures, and minimizing non-standard or unplanned actions. Regular internal audits of compliance with established regulations can support the timely identification and elimination of systemic deficiencies in work planning and process control.

Considering the considerable role of deficiencies in safety training and unsafe worker behavior shown in Figure 2, worker training systems should be modernized through regular instruction in safe work practices, simulation of emergency scenarios, periodic recertification and mentoring programs for employees with less than three years of experience. These measures are particularly important for workers with limited underground experience, whose increased vulnerability is reflected in the distribution of injuries by length of service shown in Figure 5.

To reduce behavioral risks, it is advisable to introduce behavioral safety audits, visual safety reminders, pre-shift safety briefings, and fatigue monitoring during high-intensity shifts. Such measures are aimed not only at formal compliance with safety rules, but also at strengthening safety-oriented behavior and improving workers' readiness to respond to emergencies.

Technical measures should focus on improving workplace conditions, especially in high-risk underground areas. This includes modernizing ground support systems, improving temporary support structures, installing enhanced lighting, and mechanizing manual operations. These directions are particularly relevant because unsatisfactory workplace conditions were identified as a dominant cause of accidents in Figure 2.

The technical condition of equipment should be controlled through digital inspection logs, mandatory pre-shift checks, scheduled diagnostics of mobile machinery, and automated condition-monitoring systems capable of detec-

ting deviations in equipment operation in real time. Early identification of technical faults is especially important in underground workings, where equipment failure can rapidly create hazardous situations.

For underground facilities No. 1 and No. 2, targeted measures are required due to their high contribution to overall and fatal injury levels, as shown in Figure 3. These measures should include additional safety control points at entrances, shafts, and main transport routes; advanced emergency response drills; modernization of excavation and ground support equipment; phased replacement of mobile equipment and auxiliary machinery; optimization of shift schedules; and improvement of communication and dispatch control systems at underground levels.

Thus, the results obtained not only align with previous international studies but also demonstrate substantial practical relevance for improving occupational safety in underground mining operations. The integration of statistical injury analysis, structural assessment of accident causes, and worker-related risk characteristics allows preventive measures to be formulated on a more evidence-based basis.

4.6. Study limitations and future research

At the same time, the present study has certain limitations. The analysis is based mainly on official accident records and statistical reporting data; therefore, it primarily reflects registered occupational accidents and documented causes. Some latent factors, including informal work practices, individual perception of risk, fatigue levels, stress resistance, and attention stability, could not be fully assessed within the available dataset.

Therefore, future research should focus on the psychophysiological characteristics of underground workers, including attention, fatigue, stress resistance, and individual risk patterns. Combining statistical injury analysis with psychophysiological assessment would enable the development of a more personalized and effective framework for preventing occupational injuries in underground mining environments.

5. Conclusions

The analysis of occupational injuries at the mining and processing plant over the period from 2009 to 2023 enabled the identification of stable, long-term patterns in injury dynamics, the determination of the dominant causes of accidents, and the establishment of the main groups of workers exposed to elevated occupational risk.

The dynamics of occupational injury indicators demonstrated pronounced fluctuations during the analyzed period, with the highest values recorded in 2011, 2014, 2021, and especially in 2022. The polynomial approximation of the time series confirmed the nonlinear nature of injury dynamics and demonstrated satisfactory agreement between the fitted models and the empirical data. The overall injury rate reached its maximum value in 2022, followed by a decline in 2023.

Underground facilities No. 1 and No. 2 were found to be the most injury-prone divisions of the enterprise. These facilities accounted for approximately half of all occupational accidents and 58% of fatal cases recorded during the study period. Facility No. 2 demonstrated the highest level of occupational risk, with 77 accidents and 9 fatalities, indicating the need for priority preventive measures at this site.

The structure of accident causes showed the dominance of organizational and human-related factors. The largest share of accidents was associated with inadequate organization of work processes, unsafe worker behavior, deficiencies in safety training, and unsatisfactory workplace conditions. Together, these four categories accounted for approximately 81% of all recorded occupational injury cases.

The analysis of injured workers by age, length of service, and occupational category showed that increased injury risk was characteristic of workers aged 30-40 years and over 50 years, of employees with less than 3 years of service, and of workers with more than 15 years of service. The highest proportion of accidents was associated with occupations directly involved in underground excavation and face operations, including miners, drifters, face workers, and auxiliary underground personnel.

The obtained results confirm the need for a comprehensive approach to reducing occupational injuries in underground mining operations. Priority directions include strengthening organizational control, improving worker training and mentoring systems, enhancing workplace conditions, modernizing ground support and equipment monitoring systems, and implementing targeted preventive measures at underground facilities No. 1 and No. 2.

Further research should focus on the psychophysiological characteristics of underground workers, including attention, fatigue, stress resistance, and individual risk patterns. The integration of statistical injury analysis with psychophysiological assessment would provide a stronger basis for developing personalized and more effective occupational injury prevention measures.

Author contributions

Conceptualization: DZ, MI; Data curation: UB; Formal analysis: LR, RU; Funding acquisition: DZ; Investigation: UB, SS; Methodology: UB, SU; Project administration: MI, RU; Resources: LR; Software: UB, DZ; Validation: DZ, MI, SU; Visualization: UB, RU; Writing – original draft: DZ, MI, LR; Writing – review & editing: UB, SS, RU, SU. All authors have read and agreed to the published version of the manuscript.

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Conflicts of interest

The authors declare no conflict of interest.

Data availability statement

The original contributions presented in the study are included in the article, further inquiries can be directed to the corresponding author.

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Динаміка виробничого травматизму, причини нещасних випадків та чинники ризику на гірничо-збагачувальному комбінаті

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Мета. Метою дослідження є аналіз виробничого травматизму на гірничо-збагачувальному комбінаті за період з 2009 по 2023 рр. з особливою увагою до підземних об'єктів як найбільш небезпечних структурних підрозділів підприємства.

Методика. Методичну основу дослідження становив комплексний статистико-аналітичний підхід до оцінювання виробничого травматизму. Вихідною інформаційною базою слугували офіційні матеріали розслідування нещасних випадків на виробництві та дані статистичної звітності підприємства за 2009-2023 рр. Для кількісної оцінки рівня травматизму використано систему показників, що включала коефіцієнт частоти травматизму, коефіцієнт тяжкості травматизму, коефіцієнт смертельного травматизму та загальний показник травматизму. Для виявлення довгострокових тенденцій застосовано аналіз часових рядів із поліноміальною апроксимацією шостого ступеня.

Результати. Аналіз виявив виражену нелінійну мінливість показників виробничого травматизму протягом п'ятнадцятирічного періоду, з найбільш істотними зростаннями у 2011, 2014, 2021 та особливо у 2022 році. Загалом було зареєстровано 227 нещасних випадків на виробництві, унаслідок яких травмовано 236 працівників, зокрема зафіксовано 19 смертельних випадків і 83 тяжкі травми. Отримані результати засвідчили чітку концентрацію професійного ризику в підземних гірничих роботах: об'єкти №1 і №2 забезпечили близько половини всіх нещасних випадків і 58% смертельних випадків, причому об'єкт №2 характеризувався найвищим рівнем травматизму. Структура причин нещасних випадків засвідчила домінування організаційних і людських чинників, зокрема незадовільної організації робіт, небезпечної поведінки працівників та інших пов'язаних причин, недоліків у навчанні з питань безпеки, а також незадовільних умов праці. Сукупно ці чинники становили близько 81% усіх зареєстрованих випадків травматизму.

Наукова новизна. Дослідження забезпечує комплексну довгострокову оцінку виробничого травматизму шляхом поєднання розрахунку показників травматизму, поліноміального аналізу трендів, оцінки причин нещасних випадків, порівняння рівнів травматизму між підрозділами підприємства та аналізу ризиків, пов'язаних із характеристиками працівників.

Практична значимість. Отримані результати можуть бути використані для цільового вдосконалення системи управління охороною праці, зокрема шляхом посилення організаційного контролю, покращення навчання та наставництва працівників, модернізації робочих місць, моніторингу технічного стану обладнання та впровадження пріоритетних профілактичних заходів на підземних об'єктах №1 і №2.

Ключові слова: *виробничий травматизм; підземні гірничі роботи; гірничо-збагачувальний комбінат; частота травматизму; тяжкість травматизму; причини нещасних випадків; професійний ризик*

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