



Public Health Risk Assessment of Quantitative Emission from a Molybdenum Production Plant: Case Study of Kazakhstan

Gulmira Kezembayeva,¹ Kanay Rysbekov,^{1,*} Zhuldyz Dyussenova,² Almas Zhumagulov,¹ Umbetaly Sarsembin,¹ Madina Barmenshinova,¹ Yerkezhan Begimzhanova¹ and Yryszhan Zhakypbek^{1,*}

Abstract

As is well known, one of the key problems facing modern humanity is atmospheric pollution caused by harmful industrial emissions, which negatively affect both the environment and public health. The main goal of this study is to conduct an analytical assessment of the impact of atmospheric air pollution on public health, using molybdenum production as an example. The evaluation includes an analysis of the acute toxic effects of pollutants on public health resulting from emissions of a molybdenum enterprise. The assessment of health risks caused by exposure to chemical air pollutants in the emissions of molybdenum mining enterprises revealed that the individual carcinogenic risk associated with substances such as nitrogen dioxide, dust, ammonia, sodium sulfide, and benzo [a] pyrene (a total of 17 substances) is 0.999.

Keywords: Molybdenum; Pollution; Environmental impacts; Health risk; Ambient air.

Received: 16 January 2025; Revised: 19 February 2025; Accepted: 06 March 2025.

Article type: Research article.

1. Introduction

Recent studies emphasize the imperative need for comprehensive frameworks to assess and mitigate risks associated with industrial emissions systematically. Among environmental health concerns, air pollution remains one of the most critical factors.^[1-3] Evidence accumulated over the past decade indicates that its contribution to premature mortality has been substantially underestimated.^[4-11] According to the World Health Organization (WHO), air pollution from fine particulate matter (PM_{2.5}) causes 4.2 million premature deaths annually worldwide, with more than 90% of the global population being exposed to its harmful effects. Some scientific studies have shown that PM_{2.5} levels exceed WHO air quality guidelines by up to five times.^[12-15] The coverage of ground-based PM_{2.5} measurements compiled in the WHO database is uneven across the world and is primarily concentrated in high- and middle-income

countries, particularly in China, Europe, India, and North America (Fig. 1).^[16,17]

The public health risks associated with ambient air pollution influence policy acceptance and public awareness. This highlights the importance of effective communication strategies in addressing industrial pollution-related health issues.^[18] Therefore, immediate policy interventions are required to reduce air pollutant emissions and mitigate their impact on public health. For instance, advanced modeling techniques for seismoacoustic processes in poroelastic media have been proposed.^[19] Furthermore, studies conducted in regions with high industrial activity, such as China and India, have demonstrated a direct correlation between specific pollutants and adverse health outcomes, including respiratory and cardiovascular diseases.^[20,21] Similarly, the European Union has adopted advanced environmental risk assessment methodologies that integrate real-time monitoring systems with predictive modeling tools.^[22,23] These approaches have proven effective in identifying high-risk areas and implementing targeted mitigation strategies.

The study by Birmili *et al.*^[24-29] investigated the health risks associated with ultrafine solid particles (PM_{0.1}) in urban and industrial environments, emphasizing their disproportionate impact on vulnerable populations, including children and the

¹ Mining and Metallurgical Institute named after O.A. Baikonurov, Satbayev University, 22 Satbayev str., Almaty, 050013, Kazakhstan

² Kazakhstan Agency of Applied Ecology LLC, Lead Specialist, 157, Zhibek Zholy Ave., Almaty, 050000, Kazakhstan

*Email: k.rysbekov@satbayev.university (K. Rysbekov);
y.zhakypbek@satbayev.university (Y. Zhakypbek)

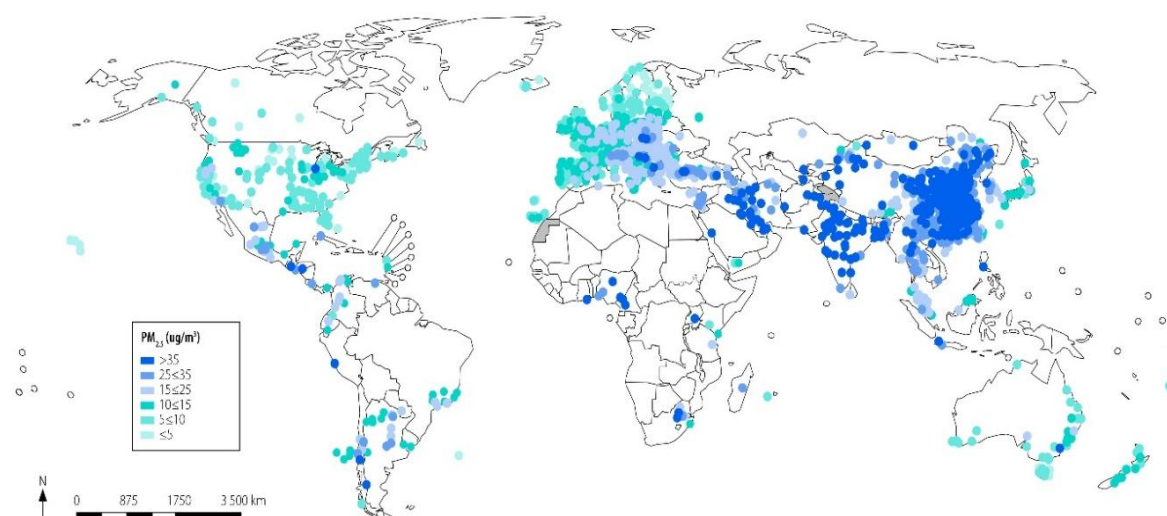


Fig. 1: Locations of settlements with data on PM_{2.5}, by number of ground measurements, 2010 to 2019. PM_{2.5}: Particulate matter with a diameter $\leq 2.5 \mu\text{m}$. Note: Some countries measure only or mainly PM₁₀ (particulate matter with a diameter $\leq 10 \mu\text{m}$) and are hence not reflected in this figure. Source: World Health Organization, 2022.^[16,17]

elderly. Additionally, substantial progress has been made in the quantitative assessment of health risks associated with specific industrial processes, including metal production. For instance, studies on the platinum mining sector in South Africa and the copper industry in Chile have identified elevated concentrations of heavy metals, such as arsenic and cadmium, in surrounding ecosystems, contributing to long-term health effects in local communities.^[30,31]

Air pollution has a profound impact on human health and poses substantial economic consequences.^[32] Moreover, big data analytics can be utilized to predict potential health outcomes and mitigate associated risks.^[33] A 2016 study by the Global Burden of Disease program estimated that air pollution contributed to approximately 6.1 million deaths worldwide.^[34] By 2060, this number could double or even triple. According to the World Health Organization (WHO), up to 600,000 chemical compounds are used in practice out of more than 6 million known. Among these compounds, approximately 40,000 have harmful properties for humans, and 12,000 are classified as toxic.^[35]

The primary objective of this study is to conduct a comprehensive analytical assessment of the impact of atmospheric air pollution on public health, using molybdenum production as a case study. Existing research indicates that molybdenum production processes frequently emit hazardous pollutants, including sulfur oxides, nitrogen oxides, and particulate matter, which can have detrimental effects on both the environment and human health.^[36-42] This knowledge gap highlights the necessity of targeted risk assessments focused on emissions from molybdenum production facilities.

Similar studies conducted worldwide have identified concerning trends. For example, research in China, one of the leading producers of molybdenum, reported elevated concentrations of molybdenum and associated heavy metals in the surrounding soil and air, contributing to an increased incidence of respiratory diseases among the local population.^[43] In South Korea, the implementation of real-time air quality monitoring systems in industrial zones has provided critical insights into the correlation between metal refining activities and regional health outcomes.^[44] These studies underscore the critical importance of localized research in identifying specific pollutants and formulating effective mitigation strategies, as the composition of emissions and their dispersion patterns are influenced by multiple factors, including ore type, processing technologies, and regional climatic conditions. In Kazakhstan, where arid and semi-arid conditions prevail, particulate matter from mining and metallurgical activities can persist in the atmosphere for extended periods, increasing exposure risks for nearby populations. Furthermore, the socio-economic characteristics of communities located near industrial zones often include limited access to healthcare and a low level of awareness regarding environmental health risks, thereby emphasizing the necessity for targeted interventions.

Molybdenum production involves several stages, including ore mining, roasting, and refining, each of which contributes to the emission of various pollutants. Studies conducted in major molybdenum-producing countries have identified the emission of sulfur dioxide (SO₂), nitrogen oxides (NO_x), and particulate matter (PM₁₀, PM_{2.5}), as well as

trace amounts of heavy metals such as cadmium (Cd), lead (Pb), and mercury (Hg). These pollutants are known to have adverse effects on human health, ranging from respiratory diseases to cardiovascular conditions. For instance, studies conducted in China have shown that communities residing near molybdenum smelting plants experience higher rates of chronic obstructive pulmonary disease (COPD) and asthma due to prolonged exposure to airborne pollutants.^[36]

In addition to respiratory and cardiovascular effects, molybdenum-specific pollutants can impact ecosystems by altering the chemical composition of soil and water. A study conducted in Armenia, another major molybdenum producer, found that emissions from molybdenum plants led to elevated molybdenum concentrations in agricultural soils, resulting in bioaccumulation in crops and subsequent dietary exposure among the local population.^[45] These findings underscore the need for comprehensive risk assessments that consider both direct exposure through inhalation and indirect exposure through food and water.

Kazakhstan has yet to establish a regulatory framework for assessing public health risks associated with air pollution.^[46] In contrast, the Czech Republic has enacted laws that set public health targets. These targets primarily establish limit values, particularly for hazardous pollutants, based on annual reviews of health and environmental conditions, while also defining additional objectives for public health and environmental protection. Additional air quality targets are outlined in the National Emission Reduction Program. Furthermore, the reduction of environmental and occupational safety risks is a priority in the National Strategy for Health Protection, Promotion of Healthy Lifestyles, and Disease Prevention for 2021. According to Assanov *et al.*,^[47] Kazakhstan defines the total volume of pollutant emissions into the atmosphere as the sum of emissions from both stationary and mobile pollution sources.

For stationary sources, emissions include sulfur dioxide (SO₂), nitrogen oxides (NO_x, expressed as nitrogen dioxide), ammonia (NH₃), particulate matter (PM₁₀, PM_{2.5}, and total PM), carbon monoxide (CO), non-methane volatile organic compounds (NMVOCs), persistent organic pollutants (POPs, including polychlorinated biphenyls (PCBs), dioxins/furans, and polycyclic aromatic hydrocarbons (PAHs)), heavy metals (primarily cadmium (Cd), lead (Pb), and mercury (Hg)), and specific pollutants such as chlorine, phenol, benzene, and their derivatives. For mobile sources, emissions include carbon monoxide (CO), nitrogen oxides (NO_x, expressed as nitrogen dioxide), hydrocarbons (CH), soot, sulfur dioxide (SO₂), lead compounds, formaldehyde, and benzo(a)pyrene. These emissions are monitored both in general and by vehicle type

(*e.g.*, road, rail, air, water, and construction vehicles).

On January 2, 2021, a new Environmental Code (No. 400-VI ZRK) was adopted in Kazakhstan, addressing public health risk issues. In particular, Clause 5, "Fundamentals of Environmental Legislation of the Republic of Kazakhstan," establishes that the legal regulation of environmental relations is based on the precautionary principle and the "polluter pays" principle. These principles aim to prevent environmental damage in any form and to avoid harm to human life and health.^[48] Clause 55 "Criteria for Document Review" establishes that one of the criteria for document review is the assessment of environmental risks, including their impact on public health. Clause 70, "Criteria for Significance of Environmental Impact in Reviewing the Impact of Planned Activities" defines parameters that characterize planned activities and their potential impact on the environment. One of these parameters is the level of environmental pollution risk and the harm caused to human life and health.

When assessing the potential adverse effects of substances on the environment, the risk to public health is always considered a significant factor. Additionally, Clause 135 "Compensation for Environmental Damage to Land Resources" addresses environmental damage to land, while Clause 353 "General Requirements for Landfills for Hazardous Waste Disposal" specifies that the collection, processing, and utilization of landfill gas must minimize environmental degradation and risks to human health.^[20] Thus, it can be concluded that public health risks are assessed at all stages, including pre-project planning, design, commissioning, and operation of existing facilities. Through this study, we aim to bridge the knowledge gap and contribute to the growing body of literature on industrial emissions and public health.

2. Materials and methods

An assessment of the state of atmospheric air is essential for establishing causal relationships between indicators characterizing environmental and production conditions and the population's morbidity rate. This approach is also consistent with the principles of risk assessment. Several methods can be used to assess public health risks.^[35,49] Prediction methods, such as SARIMAX (Seasonal Auto Regressive Integrated Moving Average with Exogenous Variables),^[50] are employed to model the time series of pollution and its health effects. This model,^[51] developed by Prof. S. M. Novikov, Research Institute of Human Ecology and Environmental Hygiene named after A. N. Sysin, is based on two main principles:

- The health hazard associated with exceeding the

maximum permissible concentration (MPC_{ad}) is quantified by evaluating the relationship between risk and the severity of effects across all effective concentrations. These concentrations range from lethal levels to threshold values, below which no observable adverse effects occur.

- The health hazard caused by exposure to the i -th pollutant follows a power-law (logarithmic) dependence on the levels of exposure or the degree of excess over MPC_{ad} .^[52]

Industrial emissions, especially from metallurgical processes, make a significant contribution to environmental pollution, which requires a comprehensive risk assessment to protect public health.^[53]

To describe the risk of chronic intoxication (including carcinogenic risk) associated with atmospheric pollution, a linear-exponential (non-threshold) model is commonly used in Eq. (1):^[35]

$$R_3 = 1 - \exp \left[-0,174 \left(\frac{c}{MPC_{ad} * K_3} \right)^\beta * t \right] \quad (1)$$

where $1/K$ is the single risk coefficient, a proportionality constant linking risk and the concentration of a toxicant; β is the coefficient accounting for the peculiarities of the toxicological properties of substances; c is the concentration or dose of a substance that exerts an effect over time; and MPC_{ad} is the maximum permissible average daily concentration of a pollutant in the air in populated areas, expressed in mg/m^3 .

As applied to atmospheric pollution, this model can be generally described by Eq. (2):

$$RI_3 = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{a+b \lg c} \exp(-\tau^2/2) d\tau \quad (2)$$

where a and b are parameters dependent on the toxicological properties of the substance; c is the concentration of the pollutant in the air; and τ is the integration parameter.

The integral in Eq. (2) cannot be expressed in terms of elementary functions. To perform the calculations, computational methods or mathematical tables should be used. The values of the coefficients a and b in Eq. (1) are determined based on specialized toxicological studies of the properties of substances. For practical calculations, it is appropriate to relate the coefficients a and b to the values of traditional parameters used to characterize the toxicity of substances and normalize their concentrations in environmental media, such as the toxicity class of a substance, MPC , etc., RI_3 is calculated in Eq. (3):

$$RI_3 = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{a+b \lg (c/MPC_{m.s.})} \exp(-\tau^2/2) d\tau \quad (3)$$

where $MPC_{m.s.}$ is the maximum permissible single concentration of a pollutant in the air of populated areas, measured in mg/m^3 . This concentration, when inhaled for 20 minutes, should not induce reflex reactions in the human body.

The methodology under consideration is based on the following assumptions: The health hazards caused by exceeding the MPC_{ad} can be assessed in terms of risk and the severity of effects across the entire range of effective concentrations, from lethal levels to threshold or maximum inactivity. A measure of conditional risk (R) is defined as a function of the probability of the occurrence of an effect of a certain severity.

The health hazard caused by exposure to the i -th pollutant follows a power-law (logarithmic) dependence on the levels of exposure or the degree of exceedance of MPC_{ad} , Eqs. (4) and (5):

$$R_i = b \lg(C_i / MPC_{ad}) \quad (4)$$

$$R_i = a + b \lg(C_i) \quad (5)$$

where C_i is the actual concentration of the i -th pollutant, $a = -\lg(MPC_{ad})$, and b is the slope of the 'concentration-conditional risk' dependence, which integrally characterizes the hazard associated with exceeding the MPC concentration. The value of b indicates the degree of hazard increase when MPC s are exceeded and is determined by the slope of the risk versus exposure level dependence.

3. Results and discussion

To describe the negative impact of environmental pollution on health, which can manifest as immediate toxic or chronic effects (including carcinogenic and immunotoxic), two models are typically used: threshold and non-threshold. In our example, we focus on chronic health effects in the population. The use of remote sensing and climatic data enables a more accurate assessment of health risks.^[54,55]

Data on MPC_{ad} , hazard classes of pollutants, and risk calculations are provided in Table 1. The parameters β and K_p recommended for calculations based on an exposure time of 25 years are also listed in Table 1. Additionally, regardless of the hazard class, $R_p = 0$ for substances whose concentration is below the MPC .

Fig. 2 illustrates the relationship between hazard classes and two key parameters, β and K_p , over a 25-year period. In the first chart, the y-axis represents β , a coefficient reflecting the relative risk level, while the x-axis displays the hazard classes, ranging from the 1st (extremely dangerous) to the 4th (low danger). The second chart plots K_p , a proportionality parameter indicating cumulative risk over time, against the

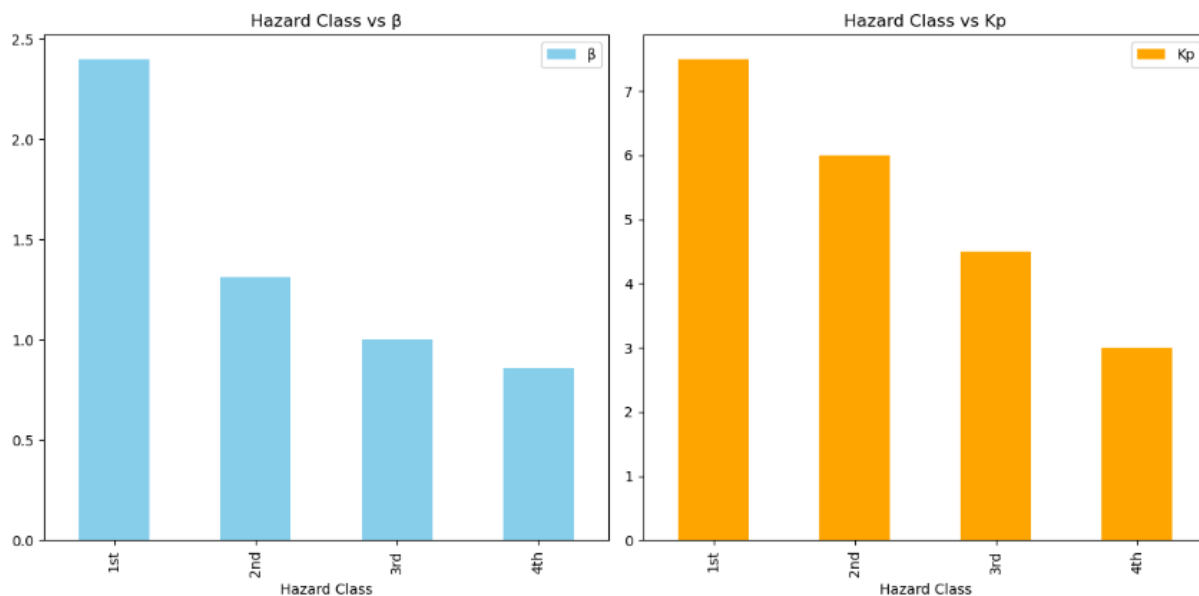


Fig. 2: Relationship between hazard class and parameters (β and K_p) for 25-year exposure time.

Table 1: Parameters for risk calculation.

Hazard class	Characteristics of substances	β	K_p
1st	Extremely dangerous	2.40	7.5
2nd	Highly dangerous	1.31	6.0
3rd	Moderately dangerous	1.00	4.5
4th	Low-dangerous	0.86	3.0

same hazard classes. Both β and K_p exhibit a decreasing trend as the hazard classes progress. Substances classified in the 1st hazard class are considered extremely dangerous, with the highest values of $\beta = 2.40$ and $K_p = 7.5$, signifying the greatest risk. In contrast, the 4th hazard class, considered low risk, shows the lowest values of $\beta = 0.86$ and $K_p = 3.0$, indicating significantly reduced risk levels. This pattern demonstrates that higher hazard classes correlate with greater risk parameters, while lower hazard classes correspond to reduced risk.

The consistent decline in both β and K_p across hazard classes underscores the clear differentiation in risk severity based on classification. This systematic reduction highlights the effectiveness of categorizing substances into hazard classes to prioritize regulatory actions and health interventions. The findings highlight that as the danger level of a substance decreases (from 1st to 4th class), both immediate and cumulative risks from long-term exposure diminish. This gradation enables a structured approach to risk management, ensuring that resources are allocated to address the most dangerous substances first. The cumulative risk assessment methodology aligns with recent meta-analyses

indicating that exposure to air pollutants, including those emitted from industrial plants, significantly contributes to cancer incidence rates.^[16] This underscores the necessity of adopting stringent regulatory policies to control emissions from molybdenum production facilities.

Furthermore, the study underscores the necessity of comprehensive air quality monitoring and effective pollution control measures to minimize exposure to harmful pollutants among both workers and local communities. The high carcinogenic risk and cumulative toxic effects highlight the urgent need for stricter regulations and enhanced safety protocols in molybdenum mining enterprises. Prioritizing the development of emission-reduction technologies and mitigation strategies is essential to reducing the health risks associated with industrial activities.^[56]

Recent analyses have also focused on the health risks associated with exposure to chemical pollutants, emphasizing the importance of evaluating both immediate and long-term health effects.^[57] Studies have shown that the development of metallurgical industries has led to complex environmental situations, necessitating the assessment of health risks due to atmospheric emissions.^[58] Additionally, research has been

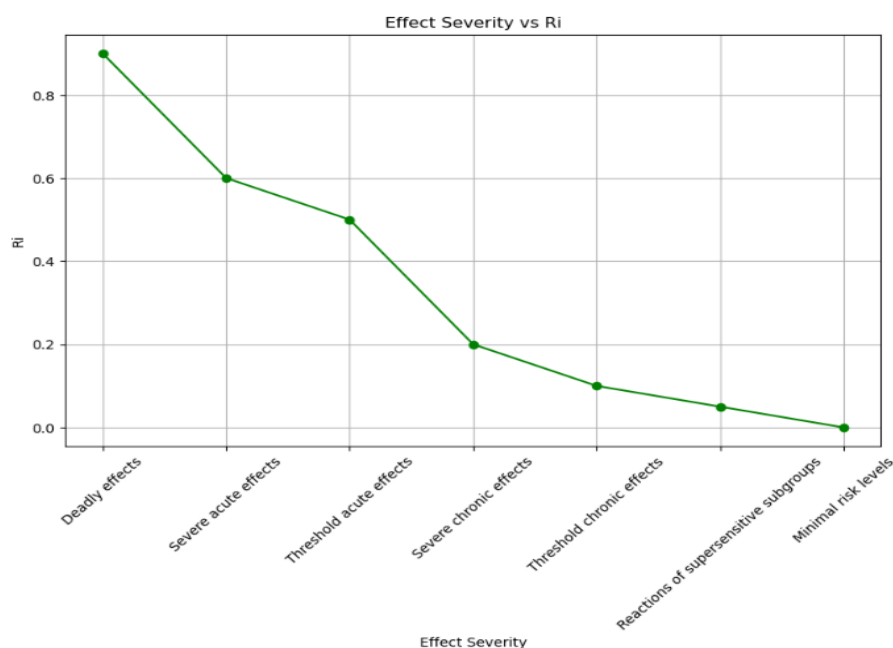


Fig. 3: Rank scale of effect severity levels and corresponding Ri values.

conducted to assess the health risks associated with exposure to chemical pollutants, highlighting the need for comprehensive evaluations of both immediate and long-term health effects.^[59] Overall, Fig. 2 underscores the importance of evaluating both β and K_p to comprehensively understand the health risks posed by hazardous substances across different hazard classes. This approach offers a robust framework for assessing and mitigating public health risks over extended periods.

As is well known, acute toxicity (immediate toxic manifestations) exhibits a pronounced threshold effect. An individual threshold model can be applied to assess the risk of immediate toxic effects. The risk of harmful effects is defined as conditional individual risk, representing the probability of death (or disease) resulting from the activation of the toxic mechanism. The health hazard associated with exceeding the MPC is not determined by general hazard classes but must be evaluated based on the specific characteristics of each substance. With prolonged exposure, the risk and severity of effects may either increase or remain consistent with those observed during initial exposure to a given concentration.

For instance, the spectral analysis method for modeling nonlinear equations has demonstrated high efficiency. If the pollutant concentration does not exceed the MPC, the relative risk is assumed to be zero.

When plotting graphs with coordinates $R_i - \lg(C_i/MPC_{ad})$ for the highest-priority air pollutants, linear dependencies of risk on the logarithm of the concentration-to-MPC ratio were observed in almost all cases. To assess the severity of the risk, the rank scale presented in Table 2 should be used.

Table 2: Rank scale of effect severity level.

Effect severity	R _i
Deadly effects	1.0 – 0.9
Severe acute effects	0.8 – 0.6
Threshold acute effects	0.6 – 0.5
Severe chronic effects	0.5 – 0.2
Threshold chronic effects	0.2 – 0.1
Reactions of supersensitive subgroups	0.1 – 0.3
Minimal risk levels	0 – 0.05

Fig. 3 illustrates the relationship between the rank scale of effect severity levels and the corresponding risk index (R_i) values, offering a systematic evaluation of health risks associated with priority air pollutants. The y-axis represents the risk index (R_i), ranging from 0 to 1, with higher values indicating more significant health risks. The x-axis categorizes the severity of effects into seven levels: deadly effects, severe acute effects, threshold acute effects, severe chronic effects, threshold chronic effects, reactions in supersensitive subgroups, and minimal risk levels.

The analysis reveals a linear decline in the risk index as the severity of effects decreases. For example, deadly effects exhibit the highest R_i values, ranging from 1.0 to 0.9, while minimal risk levels are associated with the lowest R_i values, between 0 and 0.05. Intermediate severity levels, such as severe chronic effects or threshold chronic effects, show

corresponding R_i values that progressively decrease along the scale. This proportional relationship highlights the connection between the severity of the effects and associated health risks. High-severity effects, such as deadly and severe acute effects, represent critical health risks that necessitate prioritized mitigation efforts. In contrast, lower severity effects, such as minimal risk levels, indicate reduced risks but remain important for comprehensive risk assessments.

Fig. 3 illustrates the utility of this rank scale in environmental and public health assessments, providing a clear framework for prioritizing actions to mitigate the adverse effects of pollutants based on their severity and associated

risks. For the mathematical description of the “concentration-effect” relationship, the individual threshold model is applicable. For practical use, this model can be divided into two formulas. The first describes this relationship as a straight line, assuming that the concentration is expressed in decimal logarithms and the probability of an adverse effect (risk) is given in “probits” (Prob), *i.e.*, on a normal probabilistic scale. The correspondence between “breakthroughs” and the probability of the effect is shown in Table 3.

Table 4 presents the results of calculating the risk to public health from emissions of pollutants from copper-molybdenum production. This calculation is performed using the individual

Table 3: Table of normal-probability distribution.

Probability	Prob	Risk	Probability	Prob	Risk
1	-3.0	0.001	24	0.1	0.540
2	-2.5	0.006	25	0.2	0.579
3	- 2.0	0.023	26	0.3	0.618
4	- 1.9	0.029	27	0.4	0.655
5	- 1.8	0.036	28	0.5	0.692
6	- 1.7	0.045	29	0.6	0.726
7	- 1.6	0.055	30	0.7	0.758
8	- 1.5	0.067	31	0.8	0.788
9	- 1.4	0.081	32	0.9	0.816
10	- 1.3	0.097	33	1.0	0.841
11	- 1.2	0.115	34	1.1	0.864
12	- 1.1	0.136	35	1.2	0.885
13	- 1.0	0.157	36	1.3	0.903
14	- 0.9	0.184	37	1.4	0.919
15	- 0.8	0.212	38	1.5	0.933
16	- 0.7	0.242	39	1.6	0.945
17	- 0.6	0.274	40	1.7	0.955
18	- 0.5	0.309	41	1.8	0.964
19	- 0.4	0.345	42	1.9	0.971
20	- 0.3	0.382	43	2.0	0.977
21	- 0.2	0.421	44	2.5	0.994
22	- 0.1	0.460	45	3.0	0.999
23	0.0	0.50			

action threshold model, according to which the probability of toxic effects of a substance, accounting for the extent of exceeding the MPC_{m.s.} by the hazard class of the pollutant, can be determined using Eqs. (6)-(9) proposed in:

For substances of the 1st hazard class,

$$\text{Prob} = -9.15 + 11.66 \lg(C/\text{MPC}_{m.s.}) \quad (6)$$

For substances of the 2nd hazard class,

$$\text{Prob} = -5.51 + 7.49 \lg(C/\text{MPC}_{m.s.}) \quad (7)$$

For substances of the 3rd hazard class,

$$\text{Prob} = -2.35 + 3.73 \lg(C/\text{MPC}_{m.s.}) \quad (8)$$

For substances of the 4th hazard class,

$$\text{Prob} = -1.41 + 2.33 \lg(C/\text{MPC}_{m.s.}) \quad (9)$$

where Prob is the probability of the effect (risk), expressed in probits and calculated according to Table 3 of the normal probability distribution.

Fig. 4 illustrates the health risk assessment associated with pollutant emissions from copper-molybdenum production, highlighting the relationship between pollutant concentrations, their toxicity, and the corresponding

Table 4: Risk calculation.

Name of pollutant	Maximum ground concentration, mg/m ³	MPC/TSEL	Hazard class	Prob	Risk
Iron (II, III) oxides	0.4242	0.4000000*	3	-2.25485	0.0001
Quicklime	152.2599	0.3	2	14.75393	0.99999
Manganese and its compounds	1.1699	0.01	2	9.980434	0.99999
Chromium(VI) oxide	0.0172	0.0150000*	1	-8.45696	0.00001
Sodium sulfide	207.514	0.01	2	26.82214	0.99999
Nitrogen(IV) dioxide	173.5143	0.2	2	16.49791	0.9999
Nitric acid	0.0019	0.4	2	-22.9116	0.0001
Ammonia	0.0004	0.2	4	-25.7253	0.00001
Nitrogen (II) oxide	22.2299	0.4	3	4.158	0.9999
Hydrochloric acid	0.3815	0.2	2	-3.4093	0.0001
Sulphuric acid	0.0015	0.3	2	-22.7447	0.00001
Soot	49.2116	0.15	3	7.034591	0.9999
Sulfur dioxide	10.3981	0.5	3	2.56608	0.9999
Hydrogen sulfide	30.2247	0.008	2	21.28377	0.99999
Carbon disulfide	0.0002	0.03	2	-21.8089	0.0001
Carbon oxide	5.687	5	4	-1.27972	0.115
Fluorine gaseous compounds	0.8783	0.02	2	6.793171	0.99999
Inorganic fluorides, poorly soluble	0.0265	0.2	2	-12.0846	0.00011
Xylene	35.9646	0.2	3	6.060573	0.99999
Toluene	0.0002	0.6	3	-15.3197	0.9999
Benzo/a/pyrene (C ₂₀ H ₁₂)	15.1667	0.0000100	1	62.91919	0.9999
Ethylene glycol	1.9843	1	3	-1.23992	0.115

Name of pollutant	Maximum ground concentration, mg/m ³	MPC/ TSEL	Hazard class	Prob	Risk
Formaldehyde	10.5706	0.05	2	11.9052	0.9999
Potassium xanthate butyl	0.6663	0.1	3	0.722288	0.758
Petroleum low-sulphur gasoline	0.5357	5	4	-3.67021	0.001
Kerosene	0.3314	1.2	3	-4.43443	0.001
Mineral petroleum oil	282.5577	0.05	3	11.64547	0.9999
White spirit	3.46	1	4	-0.15395	0.460
Hydrocarbons C12-C19	36.0188	1	4	2.216713	0.982
Suspended solids	109.8959	0.5	3	6.385703	0.9999
Inorganic dust: more than 70% SiO ₂	51.4318	0.15	3	7.106074	0.9999
Inorganic dust: 70-20% SiO ₂	9794.046	0.3	3	14.48663	0.99999
Abrasive dust	33.8995	0.04	3	8.571937	0.99999
Dust from rubber waste	21.9061	0.1	3	6.380308	0.99999

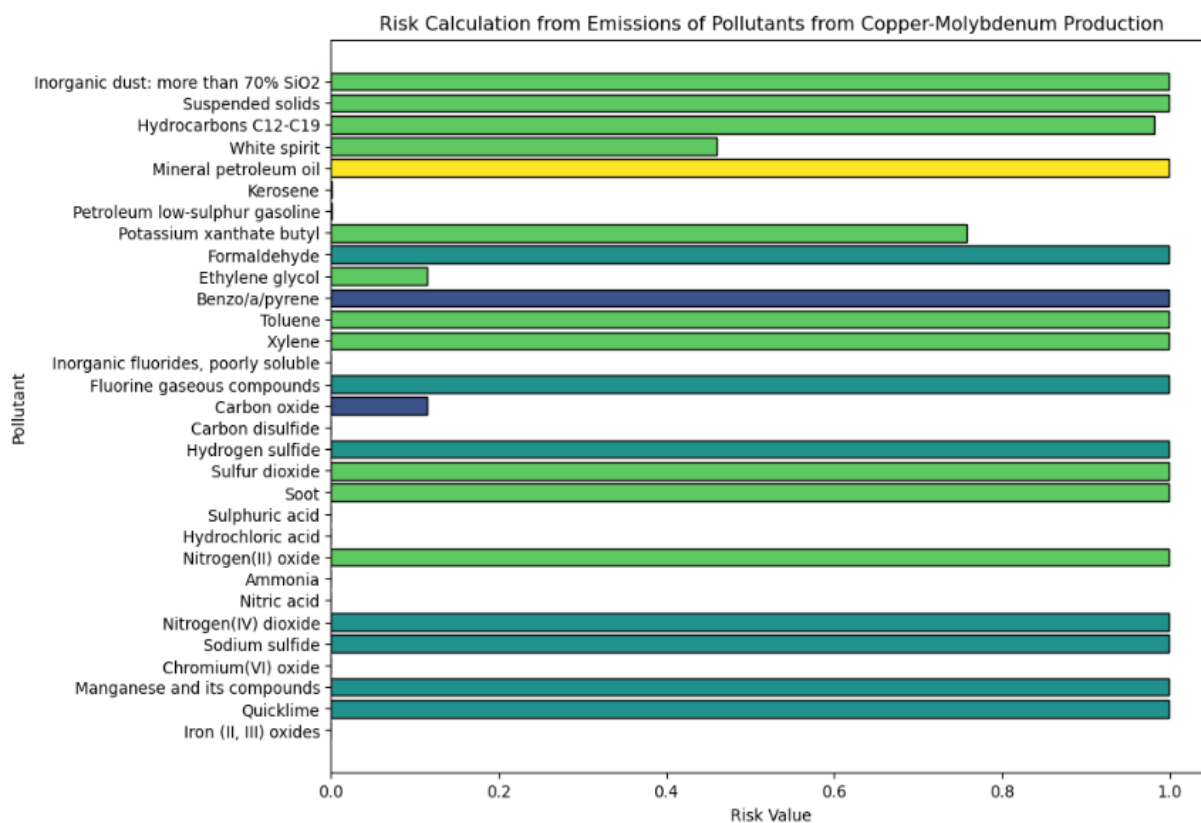


Fig. 4: Public health risk assessment from pollutant emissions of copper-molybdenum production.

risk levels. The x-axis represents risk values, ranging from 0 to 1, where 0 indicates no risk and 1 signifies maximum risk. The y-axis lists the pollutants, including both inorganic substances (e.g., iron and chromium oxides) and organic

compounds (e.g., benzene, xylene).

As the concentration of a pollutant and its hazard class increase, the associated risk rises significantly. Substances classified as hazard class 1, such as nitric acid and sulfur

dioxide, with high concentrations, exhibit nearly maximum risk. In contrast, substances of hazard class 4, such as toluene and benzene, even at low concentrations, present minimal risk. Notably, even substances like carbon dioxide, which can exceed the maximum allowable concentration, pose a high risk despite their relatively low toxicity.

Thus, Fig. 4 underscores the importance of monitoring pollutants with high concentrations and low maximum allowable levels, as they present the greatest health risks. This analysis aids in identifying priority pollutants that require stringent regulation and control to minimize health risks to the

population.

To obtain reliable risk assessment data, it is essential to consider the cumulative effect of specific substances. According to the applied methodology, the risk resulting from the combined action of pollutants is determined by the following Eq. (10):

$$Risk_{tot} = 1 - (1-Risk_1) \times (1-Risk_2) \times (1-Risk_3) \times \dots \times (1-Risk_n) \tag{10}$$

where Risk_{tot} is the risk of the combined action of impurities, Risk₁ - Risk_n is the risk of action of each individual impurity.

Table 5: Risk calculation for substances with a summation effect.

Summation group number	Name of substances	Total maximum surface concentration	Risk _{sum}
1	Ammonia and formaldehyde	211.414	0.999900001
2	Ammonia, hydrogen sulfide, formaldehyde	3989.502	0.999999999
3	Hydrogen sulfide and formaldehyde	3989.5	0.999999999
4	Ammonia and hydrogen sulfide	3778.09	0.99999
5	Sulfur dioxide and hydrogen sulfide	3798.884	0.999999999
6	Sulfur dioxide and sulfuric acid	20.8012	0.999900001
7	Hydrogen sulfide and carbon disulfide	3778.094	0.99990001
8	Nitrogen dioxide and sulfur dioxide	888.3677	0.99999999
9	Strong mineral acids (sulphuric, hydrochloric and nitric)	1.91725	0.000209988
10	Formaldehyde and hydrochloride (hydrochloric acid)	213.3195	0.0001
11	Carbon oxide, nitrogen oxides, formaldehyde	268.1242	0.999999991

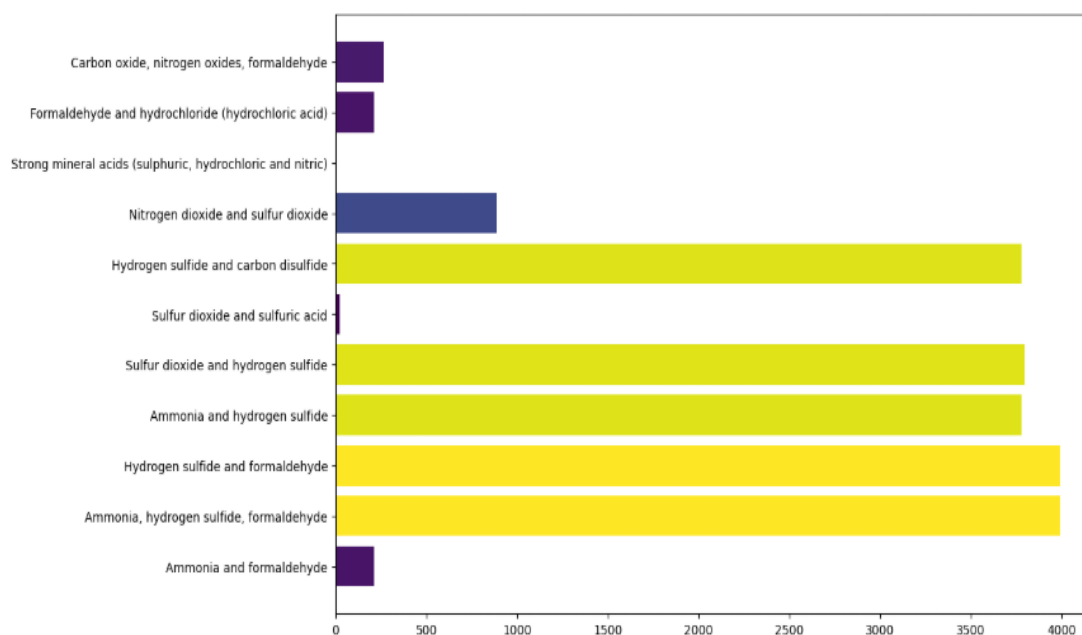


Fig. 5: Total maximum surface concentration and risk assessment for summation groups of pollutants.

Table 5 shows the results of the risk calculation for substances with a summation effect. Fig. 5 presents the results of a risk assessment for substance groups exhibiting a combined effect. The graph illustrates the total maximum surface concentration and the corresponding cumulative risk ($Risk_{sum}$) for each substance group. The x-axis represents the total maximum surface concentration of pollutants (mg/m^3), with higher values corresponding to increased exposure. The y-axis lists the names of the substance groups, categorized based on their combined effects, such as "Ammonia and Formaldehyde" or "Ammonia, Hydrogen Sulfide, Formaldehyde."

As the concentration of pollutants increases, the associated risk also rises. For example, substance groups with high concentrations, such as group 2 with a concentration of $3989.502 mg/m^3$, exhibit maximum risk values ($Risk_{sum} = 0.9999$). In contrast, groups with lower concentrations, like group 10 ($1.91725 mg/m^3$), show a significant reduction in risk ($Risk_{sum} = 0.000209988$). Generally, substance groups with highly toxic substances tend to have maximum risk levels (0.9999 and above), regardless of concentration. An exception to this pattern is observed in strong mineral acids (group 9), which show relatively low risk despite their toxicity ($Risk_{sum} = 0.0020$).

The analysis highlights that groups with the highest concentrations, such as 'Ammonia, Hydrogen Sulfide, Formaldehyde,' present the greatest health risks, with values approaching 1. This underscores the importance of monitoring the combined toxic effects of pollutants, as even substances with moderate toxicity can pose significant health risks when concentrations increase, as demonstrated in previous studies on ambient air pollution health risk assessment tools.^[60] Conversely, group 10 ("Formaldehyde and Hydrogen Chloride") demonstrates the lowest risk (0.000209988), indicating relatively safe exposure at the given concentration. This analysis emphasizes the importance of monitoring the combined toxic effects of pollutants, as substances with moderate toxicity can pose significant health risks when their concentrations increase. It is essential to prioritize the control of emissions from the most dangerous substances.

4. Conclusion

The study quantified the acute toxic effects of pollutants on public health resulting from emissions of a molybdenum production enterprise. The risk assessment revealed that individual carcinogenic risks associated with airborne chemical pollutants, including nitrogen dioxide, particulate matter, ammonia, sodium sulfide, and benzo/a/pyrene (a total of 17 substances), reach a critical value of 0.999. The

assessment of the combined risk from pollutants showed that among 11 combinations of substances emitted by molybdenum production, 9 pose a risk with a probability of 99%. These findings indicate that both enterprise employees and residents of nearby settlements are exposed to acute toxic effects from all emitted substances. Furthermore, the study underscores the necessity of comprehensive air quality monitoring and effective pollution control measures to minimize exposure to harmful pollutants among both workers and local communities. The high carcinogenic risk and cumulative toxic effects highlight the urgent need for stricter regulations and enhanced safety protocols in molybdenum mining enterprises. Prioritizing the development of emission-reduction technologies and mitigation strategies is essential to reducing the health risks associated with industrial activities. Public health policies should be adapted accordingly to address these risks and safeguard the long-term well-being of affected populations.

Acknowledgments

This research has been funded by the Committee of Science of the Ministry of Science and Higher Education of the Republic of Kazakhstan MGrant No. BR21881939 "Development of resource-saving energy generating technologies for the mining and metallurgical complex and creation of an innovative engineering center"

Conflict of Interest

There is no conflict of interest.

Supporting Information

Not applicable.

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