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Assessment and Forecasting of Occupational and Environmental risks in Industrial Enterprises based on Foresight

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Abstract

The expansion of production processes in industrial enterprises may result in the release of gases, dust, aerosols, and other pollutants into the atmosphere, as well as the generation of liquid and solid waste, which can contribute to the formation of environmental and occupational risks. Pollutants such as PM2.5, PM10, carbon monoxide (CO), nitrogen dioxide (NO_2), sulfur dioxide (SO_2), and ozone (O_3) play an important role in atmospheric air pollution[1]. The aim of this study is to systematically analyze the interrelationship between environmental and occupational risks in industrial enterprises and to develop a methodological approach for identifying and forecasting potential future hazards using foresight methods. The study examines the possibilities of using such methods as hazard source identification, retrospective analysis, expert assessment, Delphi, SWOT, PESTLE, and scenario analysis. In assessing environmental risks, impacts on atmospheric air, water, soil, flora, and fauna were identified as the main areas of focus, while in assessing occupational risks, the direct or indirect exposure of workers to hazardous and harmful factors was considered the primary focus. Certain types of occupational risks associated with chemicals, dust, noise, and vibration are related to occupational diseases recognized by the International Labour Organization.

Keywords: Industrial enterprise, environmental risk, occupational risk, industrial waste, emissions, atmospheric air, water, soil, toxic substances, occupational diseases, foresight, Delphi, SWOT, PESTLE, scenario analysis.

Introduction

The development of industrial production is one of the important factors of economic and technological progress, but it also leads to increased anthropogenic pressure on the environment. During raw material processing, fuel combustion, the operation of technological equipment, transportation processes, product manufacturing, as well as waste storage and disposal, various pollutants may enter the atmosphere, water, and soil[1]. Air pollution is one of the important environmental risk factors for human health and ecosystems. In its global air quality guidelines, the World Health Organization identifies PM2.5, PM10, O_3, NO_2, SO_2, and CO as major air pollutants. Long-term or high-level exposure to these substances may adversely affect the cardiovascular and respiratory systems.

The composition of gases generated at industrial enterprises depends on the production technology, raw materials used, energy source, temperature and pressure of the technological process, and the efficiency of gas purification. For example, CO may be formed during incomplete combustion processes. SO_2 and NO_2 are among the reactive gases that may affect the respiratory system. Volatile organic compounds (VOCs), benzene, hydrogen sulfide (H_2S), polycyclic aromatic hydrocarbons (PAHs), and other chemical substances may also be generated or released into the environment during industrial processes. The degree of hazard associated with such substances depends on their toxic properties, concentration, duration of exposure, conditions of dispersion, and route of entry into the body[2].

Environmental risk is not limited to atmospheric air. Industrial wastes and emissions may enter water and soil, alter their physicochemical properties, and affect living organisms. Chemical pollutants may enter biota through the food chain and, in some cases, cause bioaccumulation[3]. From this perspective, it is important to consider the chain of "pollutant source – environmental component – pathway of dispersion – biota – human" when assessing environmental risks. The interrelationship between the health of humans, animals, plants, and ecosystems is also specifically emphasized in the modern One Health approach[4].

Alongside environmental risks, occupational risks are also present in industrial enterprises. Workers may be exposed to dust, gases, vapors, aerosols, chemicals, noise, vibration, and other physical factors. The International Labour Organization's documents on occupational diseases specifically identify diseases associated with chemical, physical, and other factors in the workplace[5]. The identification of an occupational disease involves not only the presence of the disease itself, but also consideration of working conditions, the presence of the risk factor, the level and duration of exposure, and the causal relationship between the factor and the disease.

For example, exposure to mineral dust and crystalline silica may be associated with pneumoconioses, including silicosis; asbestos fibers may be associated with asbestosis, lung cancer, and mesothelioma; and benzene may be associated with certain hematological diseases and occupational cancer. Noise may cause hearing impairment, while vibration may cause diseases affecting the muscles, tendons, bones, joints, peripheral blood vessels, and nerves. Thus, the same industrial source may simultaneously constitute both an environmental and an occupational hazard. For example, dust may affect air quality while also being inhaled by workers, thereby increasing the risk of occupational respiratory diseases[6].

Traditional risk assessment approaches are often focused on assessing existing or observed conditions. However, changes in technologies, the use of new chemicals and materials, increases in production volumes, changes in climatic and meteorological conditions, and the emergence of new risk factors require consideration of future risks in advance. The foresight approach makes it possible to systematically examine new technologies, trends, and the potential impacts of future changes[7].

Research Objective: to identify the sources and interrelationships of environmental and occupational risks in industrial enterprises, systematize their potential impacts on the environment and human health, and develop methodological foundations for identifying and forecasting future hazards based on the foresight approach.

To achieve the research objective, the following tasks were defined: i. to classify environmental and occupational risk factors in industrial enterprises; ii. to identify the main types of industrial emissions and waste; iii. to analyze their impacts on atmospheric air, water, and soil; iv. to establish criteria for assessing their potential impacts on flora and fauna; v. to systematize risk factors associated with human health and occupational diseases; vi. to identify the interrelationships between environmental and occupational risks; vii. to identify future risk factors and develop scenarios using foresight methods; viii. to select appropriate risk assessment methods for managing and reducing environmental and occupational risks.

Methodology

The study was aimed at a comprehensive assessment of the effects of environmental and occupational hazards on human health in industrial enterprises. The research methodology considered the production environment, harmful and hazardous factors, their pathways of exposure to the human body, and potential occupational consequences as interconnected components. In this regard, the basic principles of the One Health concept, which takes into account the close interrelationship between human health and the environment, were applied.

The research materials included scientific and regulatory information on hazardous and harmful factors encountered in industrial enterprises, such as mineral and chemical dusts, asbestos fibers, coal dust, benzene, carbon monoxide (CO), hydrogen sulfide (H_2S), nitrogen oxides (NOx), sulfur oxides (SOx), lead, and chromium and nickel compounds. Each hazard factor was analyzed in relation to its main pathway of exposure and potential occupational consequences.

In assessing hazard factors, their physicochemical properties, toxicity, concentration in the air, particle size, duration of exposure, frequency of exposure, and route of entry into the human body were adopted as the main criteria. It was taken into account that hazardous substances can enter the body mainly through inhalation, through the skin, and through the consumption of contaminated water or food.

In assessing dust-related hazards, the composition and particle characteristics of the dust, its concentration in the air, duration of exposure, and the worker's level of protection were analyzed. Exposure to mineral dust and crystalline silica was assessed in relation to occupational diseases such as silicosis, pneumoconiosis, and silicotuberculosis, while asbestos fibers were assessed in relation to asbestosis, lung cancer, and mesothelioma. In addition, potential occupational respiratory diseases resulting from long-term inhalation of coal dust were also analyzed.

In assessing chemical hazards, the toxicity of the substance, exposure concentration, duration of exposure, and route of entry into the body were taken into account. The hematological effects and occupational cancer risk associated with benzene, the hypoxic and acute toxic effects of CO, the toxic effects of H_2S, the effects of NOx and SOx on the respiratory tract, and the systemic toxic, hematological, and neurological effects of heavy metal compounds were considered separately.

In assessing the relationship between occupational diseases and hazard factors, the principle of considering the worker's occupational history, exposure conditions at the workplace, type and intensity of the hazard factor, duration of exposure, and clinical and pathological data was applied. In this context, determining the causal relationship between the disease and occupational activity was adopted as an important methodological criterion[8].

An analytical approach based on the sequence of hazard factor — pathway of exposure — potential occupational consequence was used to systematize hazards in the study. Through this approach, the pathway through which each hazard factor affects the human body and the occupational consequences that it may cause were identified.

In the integrated assessment of environmental and occupational hazards, the potential impact of hazardous substances and emissions from industrial enterprises not only on workers but also on the population and the environment was taken into account. Potential indirect exposure pathways through ambient

air, water, soil, and the food chain were analyzed. This approach made it possible to consider the impact of industrial activities on human health and ecosystems within a unified system.

The obtained data were grouped according to the exposure pathways, potential occupational consequences, and environmental impacts of the hazard factors. The results were used as a methodological basis for identifying hazard factors, assessing their significance for human health, and comprehensively managing occupational and environmental risks in industrial enterprises[9].

Results and Discussion

Classification of Environmental and Occupational Risk Factors. Considering risk factors in industrial enterprises solely within the workplace or solely within the environment does not fully reflect the interrelationship between risks. Therefore, this study adopted an approach that considers environmental and occupational risks as a unified system. This approach is consistent with the principle of integrated risk assessment, which is based on the joint consideration of risks to human health and the environment.

It can be seen from this classification that a single production process may generate several groups of hazards. For example, the generation of dust may lead to atmospheric air pollution while simultaneously causing direct inhalation exposure among workers.

Environmental Impact of Industrial Gases and Waste. In industrial production, gaseous substances, dust, aerosols, liquid waste, and solid waste may be released into the environment through various pathways. When assessing such hazards, it is not sufficient to identify only the name of the pollutant. Its source, formation process, pathway of release into the environment, dispersion mechanism, exposure, and biological effects should be considered together. Industrial emissions may contain substances such as CO, SO_2, NOx, VOCs, benzene, H_2S, PM2.5, and PM10. Their environmental and sanitary risks depend on concentration, duration of exposure, meteorological conditions, dispersion, chemical transformation, and the route of entry into the organism. Therefore, it is appropriate to consider industrial pollution based on the following chain.

This approach makes it possible to consider environmental and human health risks not separately, but as an interconnected system. The approach recommended for assessing chemical hazards from a human health perspective also implies consideration of the relationship between hazards, exposure, and health outcomes.

Impact of Industrial Pollutants on Flora and Fauna. Industrial pollutants may affect plants and animals through the atmosphere, water, and soil. Since plants are sensitive to certain pollutants in the air and soil, their condition can be used as an important indicator in environmental monitoring.

Certain gases and particles in the atmosphere may affect the leaf surface of plants, photosynthesis, growth, and development. Chemical pollution of water and soil may also affect plant root systems, soil microorganisms, and nutrient cycling.

Table-1: Classification of Environmental and Occupational Risk Factors in Industrial Enterprises.

Risk Factor Group	Main Factors	Exposure Environment	Potential Consequences
Chemical	CO, SO_2, NOx, VOCs, benzene, H_2S, and other toxic substances	Air, water, soil, workplace	Poisoning, respiratory diseases, environmental damage
Dust and aerosols	PM2.5, PM10, mineral and technological dust	Atmosphere, workplace	Respiratory diseases, pneumoconiosis
Liquid waste	Wastewater, chemical solutions, petroleum products	Water and soil	Water and soil pollution, harm to biota
Solid waste	Industrial residues, sludge, toxic residues	Soil and water	Soil degradation, secondary pollution
Physical	Noise, vibration, heat, radiation	Workplace and environment	Hearing, nervous system, vascular and functional disorders
Mechanical	Moving mechanisms, falls, impacts	Workplace	Injuries and accidents
Biological	Microorganisms and biological contamination	Air, water, soil, working environment	Biological and infectious hazards
Ergonomic and psychophysiological	Heavy physical work, awkward postures, high workload	Working environment	Fatigue, musculoskeletal disorders, reduced work capacity

Animals may be exposed to pollutants directly through the atmosphere, water, or soil, as well as through contaminated food chains. Certain chemical substances may accumulate in the food chain and affect various organisms within the ecosystem. In this regard, environmental risk can be expressed in the following sequence.

This approach is consistent with the One Health concept. Within this concept, the health of humans, animals, plants, and ecosystems is considered as an interconnected system[10].

Risks Associated with Human Health and Occupational Diseases. In industrial enterprises, workers may be directly exposed to hazardous substances at the workplace. In some cases, the population may be indirectly exposed through atmospheric air, water, soil, or the food chain.

When assessing chemical hazards, the toxicity of the substance, concentration, duration of exposure, frequency of exposure, and route of entry into the body should be taken into account.

In identifying an occupational disease, the causal relationship between occupational activity and the disease is of particular importance. According to ILO criteria, clinical and pathological data, occupational history, workplace assessment, identification and evaluation of occupational risk factors, and the role of other risk factors should be taken into account.

Mineral, metallic, technological, and other types of dust may be generated in industrial enterprises. Their inhalation may cause damage to the respiratory system.

Occupational respiratory diseases recognized by the ILO include pneumoconioses caused by sclerogenic mineral dusts, including silicosis, anthracosilicosis, asbestosis, and silicotuberculosis, as well as occupational asthma, extrinsic allergic alveolitis, and chronic obstructive pulmonary diseases.

Therefore, when assessing dust-related risks, the composition of the dust, particle size, concentration in the air, duration of exposure, and the level of worker protection should be taken into account.

Chemicals may enter the body mainly through inhalation, through the skin, or through contaminated water and food. Their effects depend on the chemical form of the substance, its toxicity, concentration, and exposure conditions.

ILO documents identify diseases associated with benzene, sulfur oxides, certain metal compounds, organic solvents, and other chemicals. Benzene is listed among agents associated with occupational cancer. The diseases presented in this table should not automatically be considered occupational diseases in all cases. In determining their occupational status, a scientifically established causal relationship between working conditions, exposure, and the disease must be identified.

Table-2: Routes of Exposure and Potential Occupational Consequences of Hazardous and Harmful Factors Encountered in Industrial Enterprises.

Risk Factor	Main Route of Exposure	Potential Occupational Consequence
Mineral dust, crystalline silica	Inhalation	Silicosis, pneumoconiosis, silicotuberculosis
Asbestos fibers	Inhalation	Asbestosis, lung cancer, mesothelioma
Coal dust	Inhalation	Coal workers' pneumoconiosis
Dust and chemical aerosols	Inhalation	Occupational asthma, COPD, and other respiratory diseases
Benzene	Inhalation, dermal exposure	Hematological effects and risk of occupational cancer
CO	Inhalation	Acute toxic effects and hypoxia
H_2S	Inhalation	Acute poisoning and toxic effects
NOx	Inhalation	Respiratory tract irritation and respiratory risks
SOx	Inhalation	Respiratory tract irritation and respiratory diseases
Lead compounds	Inhalation, ingestion	Systemic toxic effects, hematological and neurological disorders
Chromium compounds	Inhalation, dermal exposure	Respiratory and dermatological effects; some forms are carcinogenic
Nickel compounds	Inhalation, dermal exposure	Respiratory and dermatological effects; some forms are carcinogenic

Industrial equipment, machinery, ventilation systems, vehicles, and other technical devices may generate noise and vibration. Long-term exposure to high levels of noise may be associated with a decline in hearing ability. Vibration, in turn, may cause occupational disorders affecting the muscles, tendons, bones, joints, peripheral blood vessels, and peripheral nerves.

Interrelationship between Environmental and Occupational Risks. Environmental and occupational risks in industrial enterprises are interrelated, and assessing them separately may lead to certain risk chains being overlooked. For example, dust generated during a technological process may, on the one hand, cause air pollution and, on the other hand, create an inhalation-related occupational risk for workers.

Similarly, gaseous pollutants may first be released into the atmosphere, subsequently enter water or soil, affect plants and animals, and under certain conditions contribute to human exposure.

Such an integrated approach makes it possible to consider together risks involving multiple substances, multiple environmental media, multiple pathways, and different biological systems.

Identification of Environmental and Occupational Risks Based on Foresight. The main objective of the foresight approach is not to define the future as a single predetermined scenario, but to systematically examine possible future changes, risks, and alternative development pathways. Research conducted on foresight technology and occupational risk analysis demonstrates the relevance of applying foresight methods to the identification, analysis, and forecasting of occupational risks[11].

In industrial enterprises, the following factors can be identified as the main objects of monitoring for future environmental and occupational risks in foresight analysis: changes in production volume; increasing complexity of technological processes; use of new chemical substances and materials; changes in the composition of emissions and waste; changes in waste management technologies; pollution trends in the atmosphere, water, and soil; emergence of new occupational risk factors; changes in climatic and meteorological conditions; new technologies and the level of automation; and development of occupational safety and environmental management systems.

In studying these factors, retrospective analysis can be used to identify existing trends; SWOT analysis can be used to systematize internal and external factors; PESTLE analysis can be used to assess political, economic, social, technological, legal, and environmental factors in the external environment; and the Delphi method can be used to systematically collect expert opinions on future risks. The application and classification of foresight methods provide a methodological basis for selecting appropriate analytical approaches for future risk assessment[12].

At the final stage of the foresight process, several development scenarios for future risks can be developed. In this case, the scenarios are considered not as precise predictions of the future, but as possible development options that serve to prepare management decisions. The use of foresight technology in occupational safety allows possible future hazards to be identified before they develop into significant workplace risks[13].

Methods for Assessing Environmental and Occupational Risks. When selecting a method for assessing environmental and occupational risks, the source of the hazard, exposure, likelihood of occurrence, severity of consequences, impact on human health, environmental consequences, and effectiveness of existing protective measures should be taken into account. The analysis of foresight methods demonstrates that their application can contribute to the assessment and forecasting of probable hazards under changing industrial conditions[14].

The integration of foresight approaches with occupational safety management makes it possible to improve the identification of potential hazards and strengthen preventive risk management in industrial enterprises[15]. Foresight-based assessment can also be used for evaluating probable hazards and determining their levels under conditions of uncertainty[16].

Table-2: Hazardous and Harmful Factors, Their Exposure Pathways, and Occupational Consequences.

Method	Main Objective	Key Issues to Be Considered
Risk Matrix	Expressing the level of risk through likelihood and consequences	Event likelihood, severity of consequences, human health, environmental damage
Fine–Kinney	Quantitative assessment of the level of risk	Frequency of exposure, likelihood, severity of consequences
HAZOP	Identifying deviations in the technological process	Deviations in pressure, temperature, flow, concentration, and other parameters
LOPA	Analyzing the adequacy of protection layers	Independent protection layers, their reliability, and probability of failure
Bow-Tie	Presenting the causes and consequences of hazards within a unified system	Initiating event, barriers, control measures, and final consequences

Therefore, the use of foresight technology in occupational safety can be considered an important methodological direction for identifying emerging hazards, forecasting their possible consequences, and developing preventive measures. Recent studies have emphasized the importance of foresight technology and its application in the field of occupational safety, particularly for improving the ability to anticipate future occupational hazards[17].

Therefore, in this study, the main methodological requirement in selecting risk assessment methods is to consider environmental and occupational risks within the same system, distinguish between existing and future risks, and link the foresight results with the risk assessment process.

Conclusion

Within the framework of the study, the formation of environmental and occupational risks in industrial enterprises through common sources and interconnected impact pathways was scientifically and methodologically substantiated. Emissions, toxic gases, dust and aerosols, liquid and solid waste, noise, and vibration were systematized as the main groups of environmental and occupational hazards.

Industrial waste and emissions may affect the quality of ambient air, water, and soil, subsequently pass to plants and wildlife, and affect human health through the food chain or direct exposure. Therefore, it is appropriate to consider environmental and occupational risks within the unified system of "industrial source – environment – biota – human – occupational risk".

From the perspective of occupational risks, mineral dusts may be associated with pneumoconiosis and silicosis; asbestos fibers with asbestosis and mesothelioma; benzene with certain hematological disorders and occupational cancer; noise with hearing impairment; and vibration with the risk of disorders associated with peripheral blood vessels and nerves, as well as the musculoskeletal system.

An important methodological result of the study is that, alongside the assessment of existing risks, it is necessary to identify potential future risks in advance. For this purpose, it was proposed to integrate a foresight approach, including retrospective analysis, SWOT, PESTLE, Delphi, and scenario analysis, into the environmental and occupational risk management system.

At the risk management stage, the possibilities of using methods such as Risk Matrix, Fine–Kinney, HAZOP, LOPA, and Bow-Tie were identified. When selecting these methods, it is necessary to take into account such criteria as the hazard source, exposure, likelihood, severity of consequences, protection layers, and environmental damage. The proposed approach can serve as a methodological basis for integrated risk management in industrial enterprises aimed at reducing environmental risks, protecting workers' health, and preparing in advance for emerging future risks.

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