

Chemical analysis and environmental assessment of snow cover pollution in urbanized territories

Inkar B. Dzhakupova¹, Zhanar B. Kudyarova^{2*}, Raushan Uazhanova^{3*}, Arman Zhylkaidar⁴, Sarzhan Sharipova⁵, Gabit Sharipov⁶, Gulmira Kassenova⁷, Kydyrbay Maikhin⁸

1. Department of Chemistry and Ecology, Almaty Technological University, Almaty, Kazakhstan

2. Department of Chemical Physics and Material Science, Al-Farabi Kazakh National University, Almaty, Kazakhstan

3. Department of Technology of Bakery Products and Processing Industries and Department of Food Safety and Quality, Almaty Technological University, Almaty, Kazakhstan

4. LLP "VITA", Almaty, Kazakhstan

5. Department of Pharmaceutical and Toxicological Chemistry, Asfendiyarov Kazakh National Medical University, Almaty, Kazakhstan

6. Department of Civil Defense and Military Training, Malik Gabdullin Academy of Civil Protection of the Ministry of Emergency Situations of the Republic of Kazakhstan, Kokshetau, Kazakhstan

7. Head of the Biotechnology Laboratory at the Research Institute of Biotechnology and Ecology; Zhetysu University named after I. Zhansugurov, Taldykorgan, Kazakhstan

8. Epizootic Monitoring Department, "National Reference Center for Veterinary Medicine", Almaty, Kazakhstan

* Corresponding author's E-mail: Zhanar.kudyarova@kaznu.edu.kz, uazhanova67@gmail.com

ABSTRACT

Pollution of snow cover in the urban environment is considered a cumulative indicator, which gives an exact representation of air quality and environmental risks. In this study, a chemical analysis and assessment of snow cover pollution in the urban environment of Kazakhstan have been conducted. An analytical and descriptive method with the cross-sectional design was used. Samples were taken from 45 sites in three cities with different industrial activity (mining, chemical, and coal industries) between January and February 2026. Sampling places were divided into five land use types, such as industrial, residential, commercial, roadside, and parks. Physicochemical characteristics, major anions, cations, and heavy metals were estimated through ion chromatography and atomic absorption spectroscopy methods. Statistical analyses were performed using ANOVA, PCA, and cluster analyses. It was revealed that the pH value reduced from 6.82 in the mining city to 6.38 in the coal-based city. The electrical conductivity increased from 48.6 to 78.2 $\mu\text{S cm}^{-1}$ and the TDS increased from 32.6 to 54.6 mg L^{-1} . The sulfate content increased from 8.42 to 16.82 mg L^{-1} . Lead content increased from 2.84 to 6.82 $\mu\text{g L}^{-1}$, while the cadmium content increased from 0.42 to 1.24 $\mu\text{g L}^{-1}$, exceeding the permissible limit of 1.0 $\mu\text{g L}^{-1}$. Cadmium had the maximum content of metal among all metals studied. The maximum concentration of zinc was 18.6 to 32.4 $\mu\text{g L}^{-1}$. The cadmium pollution index calculated was 1.24 and the environmental risk quotient for cadmium was 74.4, which put it in moderate-risk category. The results of Principal Component Analysis indicate that there are three major sources of pollution, industrial, traffic and urban (42.6%, 24.8% and 12.4% respectively). The total variance of 79.8% validated the model. A correlation matrix identified a positive correlation of 0.84 between the concentrations of sulfate and nitrate ions, as well as a correlation of 0.78 between the concentrations of lead and cadmium ions. Moreover, there was a negative correlation between the concentration of pH and heavy metal ions. It may be concluded that the most important pollutant in the snow cover of cities in Kazakhstan is cadmium, and lowering its emissions from the industries is the most effective way to reduce the risks of environmental pollution.

Keywords: Snow cover pollution, Heavy metals, Environmental risk assessment, Principal Component Analysis.

Article type: Research Article.

INTRODUCTION

The snow cover in urban zones can be regarded as an environmental matrix with special features of capturing and retaining pollutants from the atmosphere (Kujawska 2024; Sayed *et al.* 2026). Contrary to air, where pollutants are diluted, in snow, as mentioned by Vijayan *et al.* (2024) and Egamberdiyev *et al.* (2025) they accumulate. These features make snow an excellent instrument for the monitoring of pollution in space (Liu *et al.* 2025; Altufaili *et al.* 2025). The combination of pollutants that is formed as a result of the burning of fuel, industrial processes, and traffic puts a heavy burden on the snow cover in industrial cities (Faurat *et al.* 2025; Pedro *et al.* 2025). The chemical analysis of the snow cover gives information about the quality of air during snow cover formation (Moskovchenko *et al.* 2021; Arifin *et al.* 2021). The importance of this problem goes far beyond mere observation (Ali *et al.* 2019). Pollution of snow impacts the wellbeing of both aquatic and land ecosystems (Kaizal *et al.* 2024; Kotova *et al.* 2025). Melting of the contaminated snow in spring according to Starodymova *et al.* (2024) leads to contamination of surface water and ground water. The latter provokes a series of environmental effects, starting from degradation of water quality to pollution of food chains with heavy metals (Chand *et al.* 2024). Being a state with prolonged winter and year-round snow cover in most regions, Kazakhstan suffers from this problem quite vividly (Amangeldiev *et al.* 2025; Aliya *et al.* 2026; Pote *et al.* 2026). The accurate knowledge of chemical composition of snow based on Faurat *et al.* (2024) is an essential prerequisite for environmental risk evaluation and prevention measures. The relationship between the chemical composition of snow and the amount of air pollution is far more than just a connection (Jiang *et al.* 2024; Shuheil *et al.* 2026). In addition to absorbing pollutants from the atmosphere, as noted by Liu *et al.* (2024) snow can become a subject of atmospheric reactions like wet or dry deposition. The chemical composition of snow is determined by the interplay between sources of pollution, weather conditions, and physical-chemical properties of snow (Hu *et al.* 2025; Abu Shuheil *et al.* 2026). This interplay mentioned by Kakabayev (2023) turns into an increasingly complicated phenomenon in urban regions of Kazakhstan, suffering from pollution generated by burning of coal, mining industry, and automobile transport. For its evaluation, a multivariate method is required (Wang *et al.* 2025). On a theoretical level, combining environmental chemistry and environmental monitoring disciplines requires having a unified approach to their combination (Liu *et al.* 2023; Mohammad *et al.* 2026). The theories of environmental chemistry as discussed by Abdollahi *et al.* (2025) are centered around the issue of pollutant behavior in different matrices, while the literature on environmental monitoring deals with sampling networks and the spatial aspect of data interpretation. Nevertheless, this problem remains understudied from the perspective of applying to the developing countries such as Kazakhstan, as most researches concern the industrialized countries (Faurat *et al.* 2025; Jayabal *et al.* 2026). Practical need in carrying out this research concerns public health and environmental management (Ali *et al.* 2019). Snow pollution in urban areas as stated by Kujawska (2024) influences water purity and human health. Many industrial cities in Kazakhstan face air and water pollution, and snow covering in such cities, which may be considered a cumulative parameter, will reflect the degree of pollution (Aliya *et al.* 2026). It is impossible to develop environmental management programs without information on the chemical structure of snow (Faurat *et al.* 2024). This need demonstrates the necessity of this research (Farman *et al.* 2026). From the methodological point of view and as explained by Vijayan *et al.* (2024), the chemical analysis of snow needs multistage approach, when different stages of research, sampling, cold chain maintaining, laboratory analysis, and spatial data interpretation have particular requirements. The environmental monitoring system in Kazakhstan is under development, and this research will contribute to the development of environmental monitoring system (Kakabayev 2023). Additionally, the results of this research can be used for international cooperation in environmental chemistry. These considerations lead to this research into the chemical composition of polluted snowpacks in the cities of Kazakhstan and their environmental impact. It is aimed at providing a comprehensive methodology that will make it possible to examine the chemical composition of pollutants, determine the major pollution sources, and assess the potential environmental risks. The results of this work may be used in making decisions about environmental management and improving the effectiveness of pollution control policies. This research addresses some of the theoretical and empirical gaps in the field of developing countries.

MATERIALS AND METHODS

The present research is designed using a descriptive-analytical approach with a cross-sectional design aimed at conducting chemical analysis and an environmental evaluation of snowpack pollution in urbanized territories of Kazakhstan. In total, three cities that differ in the nature of their industrial activity were taken into consideration, including one city where mining and metallurgy prevail, another city where chemical and refining industries

operate, and another city characterized by intensive automobile traffic and consumption of coal fuel. Sampling took place in January and February 2026; these months were selected in order to ensure maximum snowfall before spring melting occurs. Each city had 15 sampling sites; these sites were chosen depending on land use (industrial, residential, commercial, roadside, and parks), proximity to pollution sources, and included a total of 45 samples. The sampling involved the entire thickness of the snow cover and used pre-cooled equipment. Samples were collected in sterile polyethylene containers and stored in the laboratory in a refrigerated chamber at -4°C . Melting took place under room temperature conditions. The chemical analysis of the samples was done in three sets of parameters. In the first place, the physiochemical parameters such as pH, conductivity, turbidity, total dissolved solids (TDS), and alkalinity were analyzed. Then the major anions and cations, such as sulfate, nitrate, chloride, calcium, magnesium, sodium, and potassium, were analyzed using ion chromatography and atomic absorption spectroscopy. Finally, heavy metals like lead, cadmium, zinc, copper, nickel, chromium, and arsenic were analyzed using graphite furnace atomic absorption spectroscopy. Detection limits of these heavy metals by the technique were from 0.1 to $1.0\ \mu\text{g L}^{-1}$. Accuracy of the data was ensured by the use of standard reference materials and control samples. Recovery of all metals from the samples by the technique was found between 92% and 106%. The following methodology was used in analyzing the collected data. Firstly, the calculations of descriptive statistics and normality of the parameters have been done. Secondly, the analysis of variance (ANOVA) was done for the comparison of parameters within three cities and five categories of land use. Finally, principal component analysis (PCA) was performed in order to define main sources of pollution, and cluster analysis was applied for defining clusters of sampling points by the chemical composition of soil. Indices of heavy metal pollution and indices of ecological risks were also calculated. The spatial analysis was made with the help of GIS software, and the interpolation was made with the help of kriging method. The analyses were performed in March-June 2026 with the help of statistical software.

RESULTS

The data is tabulated and presented through six tables and four figures. The first table provides information on the sampling sites and the land-use aspects of the three cities. Thereafter, the physicochemical characteristics and ion contents of the snow samples are discussed. Afterwards, the concentrations of the heavy metals, as well as pollution and environment risk indices, are presented. Finally, the outcome of the principal component analysis conducted to detect the sources of pollution are presented. This sequence gives an overview of the process involved in the analysis of the data, from sample collection to pollution source detection. Table 1 shows the sampling points as well as land use description for the three cities. A total of forty-five sampling points have been set out within five categories of land use, which are industries, residential, commercial, roadside, and parks. The distance of these points from pollution sources varied between 0.3 to 6.0 km. These parameters of snow samples from the three cities are presented in Table 2. The pH values went down from 6.82 to 6.38 for the mining city to the coal city, respectively. The electrical conductivity was elevated from 48.6 to $78.2\ \mu\text{S cm}^{-1}$, while total dissolved solids increased from 32.6 to $54.6\ \text{mg L}^{-1}$. Thus, pollution increased in the city from mining to coal.

Table 1. Sampling sites and land-use characteristics across three cities.

City	Site code	Land-use type	Distance from Source (km)	Coordinates
City A (Mining)	A1–A5	Industrial	0.5–2.0	50.28°N, 57.17°E
City A (Mining)	A6–A10	Residential	2.5–5.0	50.30°N, 57.20°E
City A (Mining)	A11–A15	Traffic	1.0–3.0	50.25°N, 57.15°E
City B (Chemical)	B1–B5	Industrial	0.8–2.5	47.80°N, 67.70°E
City B (Chemical)	B6–B10	Commercial	2.0–4.5	47.82°N, 67.75°E
City B (Chemical)	B11–B15	Park	3.0–6.0	47.78°N, 67.68°E
City C (Coal)	C1–C5	Industrial	0.3–1.8	49.80°N, 73.10°E
City C (Coal)	C6–C10	Residential	2.0–4.0	49.82°N, 73.15°E
City C (Coal)	C11–C15	Traffic	1.5–3.5	49.79°N, 73.08°E

Table 2. Physicochemical parameters of snow cover samples across three cities.

Parameter	City A (Mining)	City B (Chemical)	City C (Coal)
pH	6.82 ± 0.24	6.54 ± 0.31	6.38 ± 0.28
Electrical Conductivity ($\mu\text{S cm}^{-1}$)	48.6 ± 8.2	62.4 ± 10.7	78.2 ± 12.4
Turbidity (NTU)	12.4 ± 2.8	18.6 ± 3.4	24.2 ± 4.1
Total Dissolved Solids (mg L^{-1})	32.6 ± 5.4	42.8 ± 7.2	54.6 ± 8.8
Alkalinity ($\text{mg CaCO}_3\ \text{L}^{-1}$)	14.2 ± 2.6	18.4 ± 3.2	22.8 ± 3.8

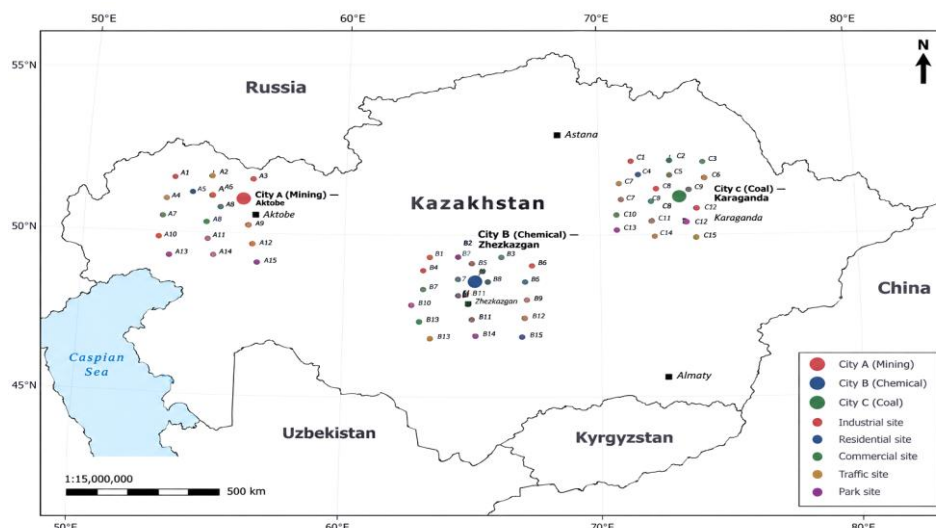


Fig. 1. Study area and sampling locations across three cities in Kazakhstan.

As shown in Fig. 1, there is a map showing the study area together with the sampling points in three different cities of Kazakhstan. The city of A has mining industries, the city of B has chemical industries, while the city of C has industries that rely on coal as their energy source. Sampling sites have been color coded based on the land use.

Table 3. Major anion and cation concentrations in snow cover samples.

Ion	City A (Mining)	City B (Chemical)	City C (Coal)
Sulfate (mg L^{-1})	8.42 ± 1.24	12.64 ± 1.87	16.82 ± 2.34
Nitrate (mg L^{-1})	3.26 ± 0.58	4.82 ± 0.74	6.48 ± 0.92
Chloride (mg L^{-1})	4.18 ± 0.76	5.64 ± 0.91	7.82 ± 1.18
Calcium (mg L^{-1})	6.24 ± 1.02	8.46 ± 1.28	10.82 ± 1.54
Magnesium (mg L^{-1})	2.18 ± 0.42	3.26 ± 0.58	4.42 ± 0.72
Sodium (mg L^{-1})	3.42 ± 0.64	4.86 ± 0.82	6.24 ± 0.98
Potassium (mg L^{-1})	1.24 ± 0.28	1.86 ± 0.36	2.48 ± 0.44

The concentrations of the main anions and cations present in the snow collected in the three cities have been provided in Table 3. The concentration of sulfate has been observed to increase from 8.42 to 16.82 mg L^{-1} for the coal mining city. Nitrate has been observed to increase from 3.26 to 6.48 mg L^{-1} , and chloride from 4.18 to 7.82 mg L^{-1} .

Table 4. Heavy metal concentrations in snow cover samples across three cities.

Metal	City A (Mining)	City B (Chemical)	City C (Coal)	Maximum permissible concentration
Lead ($\mu\text{g L}^{-1}$)	2.84 ± 0.62	4.26 ± 0.84	6.82 ± 1.24	10.0
Cadmium ($\mu\text{g L}^{-1}$)	0.42 ± 0.12	0.68 ± 0.18	1.24 ± 0.28	1.0
Zinc ($\mu\text{g L}^{-1}$)	18.6 ± 3.4	24.8 ± 4.2	32.4 ± 5.6	50.0
Copper ($\mu\text{g L}^{-1}$)	4.82 ± 1.02	6.24 ± 1.28	8.46 ± 1.64	20.0
Nickel ($\mu\text{g L}^{-1}$)	3.26 ± 0.74	4.42 ± 0.92	5.86 ± 1.18	10.0
Chromium ($\mu\text{g L}^{-1}$)	2.48 ± 0.58	3.64 ± 0.76	4.82 ± 0.98	10.0
Arsenic ($\mu\text{g L}^{-1}$)	0.86 ± 0.22	1.24 ± 0.32	1.82 ± 0.42	5.0

The heavy metals in the snow samples taken from three cities have been presented in Table 4. The concentration of lead in the coal city increased from 2.84 to $6.82 \mu\text{g L}^{-1}$. Cadmium concentration also increased from 0.42 to $1.24 \mu\text{g L}^{-1}$, which is higher than the permitted limit of 1.0 . The highest concentration was of zinc, which increased from 18.6 to $32.4 \mu\text{g L}^{-1}$. Fig. 2 presents the spatial distribution of the concentration levels of heavy metals in the snow cover in four Figs. Panels A to D represent the distribution of lead, cadmium, zinc, and copper, respectively. The highest concentration is noted in City C which uses coal-based fuel, whereas the lowest concentration is recorded in City A which is mining-based. The pollution indices and environmental risks associated with heavy metals are presented in Table 5. The highest contamination value was observed for cadmium with the pollution index of 1.24 and contamination factor of 2.48 . Environmental risk factor was found to be 74.4 , which means that

it has moderate environmental risks, while other metals have low environmental risks. Thus, it can be concluded that cadmium is one of the main pollutants in the snow cover of cities in Kazakhstan.

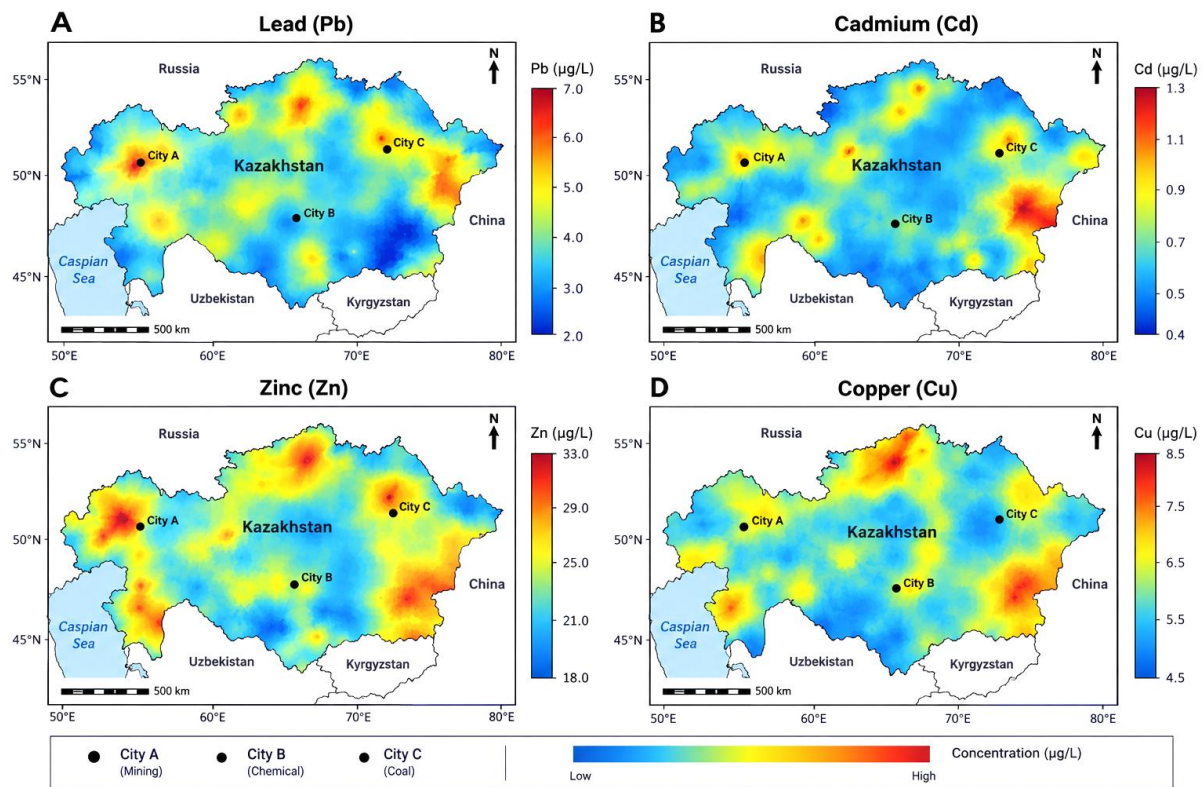


Fig. 2. Spatial distribution of heavy metal concentrations in snow cover.

Table 5. Pollution index and ecological risk assessment of heavy metals.

Metal	Pollution index (PI)	Contamination factor (CF)	Ecological risk factor (Er)	Risk level
Lead	0.68	1.24	12.4	Low
Cadmium	1.24	2.48	74.4	Moderate
Zinc	0.65	1.18	1.18	Low
Copper	0.42	0.86	4.30	Low
Nickel	0.59	1.08	5.40	Low
Chromium	0.48	0.92	1.84	Low
Arsenic	0.36	0.68	6.80	Low

Table 6. Principal component analysis results for pollution sources.

Variable	Component 1	Component 2	Component 3
Sulfate	0.84	0.12	0.08
Nitrate	0.78	0.24	0.14
Chloride	0.72	0.18	0.22
Lead	0.68	0.42	0.16
Cadmium	0.62	0.48	0.24
Zinc	0.58	0.52	0.18
Copper	0.54	0.46	0.28
Nickel	0.48	0.62	0.22
Chromium	0.42	0.58	0.26
Arsenic	0.38	0.54	0.32
Variance Explained (%)	42.6	24.8	12.4
Cumulative Variance (%)	42.6	67.4	79.8
Suggested Source	Industrial emissions	Traffic and urban activities	Crustal and natural sources

Table 6 shows the output of the principal component analysis conducted for pollution source identification. In all, three components were selected based on their ability to explain 79.8% cumulative variance. The first component explains 42.6% variance and consists of sulfates, nitrates, chlorides, and heavy metals, thus being related to

industrial pollution. The second component explains 24.8% variance and is represented by nickel, chromium, and arsenic – pollutants related to traffic and urban activities. The third component explains 12.4% variance and reflects natural crustal sources. Fig. 3 displays the box plot of heavy metals based on five land uses. Land use of an industrial type has the highest median concentration of all metals, whereas the land use of park type has the lowest median concentration of all metals. The metal with the highest median concentration is zinc, whereas cadmium has the lowest median concentration among all metals.

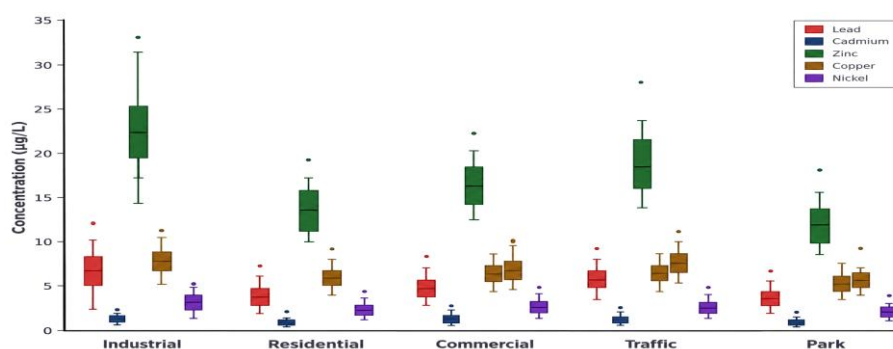


Fig. 3. Comparative box plot of heavy metal concentrations across land-use types.



Fig. 4. Heatmap of Correlation between Chemical Parameters and Pollution Sources.

In Fig. 4, the heatmap correlation of chemical parameters is depicted. The highest positive correlation was found between sulfate and nitrate (0.84) and lead and cadmium (0.78). The negative correlation was seen between pH and heavy metals. This finding proves the relationship between industrial contaminants and heavy metals.

DISCUSSION

The results of the research show that there is a certain trend in relation to snowpack pollution in the urbanized territories of Kazakhstan depending on the industry and land use. In the course of physicochemical analysis, it was found that the level of pollution load increases in comparison between the mining city and the coal-based city. Thus, the pH decreased from 6.82 in City A to 6.38 in City C, whereas the electrical conductivity increased from 48.6 to 78.2 $\mu\text{S cm}^{-1}$, and total dissolved solids increased from 32.6 to 54.6 mg L^{-1} . It should be noted that the changes in the parameters under consideration relate to the intensity of industrial activities in cities. This finding is consistent with Faurat *et al.* (2025), about similar spatial distribution and sources of heavy metal pollution in the snow cover of Pavlodar in northeastern Kazakhstan. There were significant disparities in ionic

composition between the three cities. The concentrations of sulfate ions increased from 8.42 to 16.82 mg L⁻¹ in the coal-powered city, whereas nitrate and chloride ion concentrations increased from 3.26 to 6.48 mg L⁻¹ and 4.18 to 7.82 mg L⁻¹, respectively. Calcium ions had the highest concentration of all cations with an increase of concentration from 6.24 to 10.82 mg L⁻¹. This is due to fossil fuel burning, leading to release of SO₂ and NO_x. The ratios of sulfate to nitrate ions were 2.59 for City C and 2.58 for City A, indicating more contribution from industries than from traffic. Metal concentrations gave a more accurate estimation of the pollutants, where the lead concentration ranged between 2.84 and 6.82 µg L⁻¹ in the coal mining city. The cadmium concentration ranged between 0.42 and 1.24 µg L⁻¹, which was higher than the allowed limit of 1.0. The zinc metal concentration was found to be the highest amongst all other metals and ranged between 18.6 to 32.4 µg L⁻¹. The copper and nickel concentrations were found to be 4.82 to 8.46 µg L⁻¹ and 3.26 to 5.86 µg L⁻¹, respectively. All metals had the highest concentration in the coal-mining city. This finding aligns with Aliya *et al.* (2026), about snow cover contamination in Pavlodar, Kazakhstan, and identified cadmium as a key pollutant according to elemental analysis and pollution indices. Pollution and environmental risk indices allowed assessing the degree of contamination. The most polluted was cadmium with a pollution index of 1.24 and contamination factor of 2.48. The environmental risk factor for cadmium was 74.4 making it an element from the moderate risk group. Lead (risk factor of 12.4) and arsenic (6.80) were elements from the low risk group, and zinc was an element with the lowest risk (1.18). Thus, cadmium is found to be one of the major pollutants in the snow cover of urban areas in Kazakhstan. The sources of pollution by cadmium are coal burning and metallurgy. According to principal component analysis, there are three pollution sources identified. The first one, which explains 42.6% of variance, consists of sulfates, nitrates, chlorides, and heavy metals, thus reflecting the industrial emissions as a source of pollution. The second source (24.8% of variance) includes nickel, chromium, and arsenic, and represents the source related to traffic and urban activities. The third source of pollution (12.4% of variance) is represented by crustal sources of contamination. The total explained variance of 79.8% makes the model suitable for explanation of sources of pollution. This finding is consistent with Liu *et al.* (2023), about multiple models for source apportionment of heavy metals in wet deposition in a typical industrial city. Differences in pollution were found between various land use areas using the box plot. Industrial zones exhibited the highest median values for all metals, while parks had the lowest values. Among all land uses, zinc had the highest median value of pollution and cadmium had the lowest. Dispersion of data was higher in industrial zones compared to other land use zones, which suggests heterogeneity in sources of pollution in industrial zones. Lower dispersion in parks indicates stability in the quality of snow. Correlation matrix showed the relationship between chemical parameters. The most intense correlation was positive correlation between sulfate and nitrate with the coefficient of 0.84, as well as positive correlation between lead and cadmium with the coefficient of 0.78. The parameter pH negatively correlated with heavy metals; the correlation coefficients were -0.56 and -0.62 respectively. These results are in line with Vijayan *et al.* (2024), about traffic-related metals in urban snow cover that emphasized the role of industrial and traffic sources in heavy metal accumulation. These results confirm the relationship between industrial pollution and heavy metals. Decrease in pH increases mobility of heavy metals and poses an environmental risk.

CONCLUSION

The aim of this study is to carry out the chemical analysis and environmental assessment of snow cover pollution in the urban areas of Kazakhstan. Snow samples were taken from 45 points in three cities with different industrial profile such as mining, chemical and coal-based. The analyses include three groups: physicochemical indexes, ionic composition and heavy metals. It was found out that the values of pH changed from 6.82 to 6.38 and electrical conductivity from 48.6 to 78.2 µS cm⁻¹ in the coal-based city. The concentration of sulfate increased from 8.42 to 16.82 mg L⁻¹. The concentration of heavy metals was the highest in the coal-based city; the lead increased from 2.84 to 6.82 µg L⁻¹, the cadmium – from 0.42 to 1.24 µg L⁻¹. The cadmium poses the highest danger as the value of pollution index is 1.24 and risk factor is 74.4. Principal component analysis revealed three types of pollution sources: industrial emissions (42.6%), traffic and urban activity (24.8%) and natural sources (12.4%). The total variance of 79.8% proves the reliability of the model. Policy implications of the study can be summarized in three points: firstly, paying special attention to reducing cadmium emissions from industry; secondly, improving snow quality monitoring in industrial areas and roadways; thirdly, including snow monitoring in air quality management systems. In this way, the problem is analyzed from industrial, urban and natural perspectives. Future research may include this approach with data collected over several years.

REFERENCES

- Abdollahi, S, Hassanzadeh, N, Sohrabi, M & Loppi, S 2025, Biomonitoring of potentially toxic elements in the urban atmosphere of Tehran metropolis using the lichen *Anaptychia setifera* (Mereschk.) Räsänen. *Atmosphere*, 16: 206. <https://doi.org/10.3390/atmos16020206>.
- Abu Shuheil, M, Hussein Ismael, S, Ganesan, S, Ray, S, Basheer, NM, Jayabalan, K, Pramanik, A, Gautam, A & Sarhan, N 2026, Engineering MXene quantum dots: From quantum confinement and interfacial charge transfer to multifunctional environmental technologies. *International Journal of Environmental Analytical Chemistry*, pp. 1–43. <https://doi.org/10.1080/03067319.2026.2645938>.
- Ali, H, Khan, E & Ilahi, I 2019, Environmental chemistry and ecotoxicology of hazardous heavy metals: Environmental persistence, toxicity, and bioaccumulation. *Journal of Chemistry*, 2019: 1–14. <https://doi.org/10.1155/2019/6730305>.
- Aliya, Z, Zhanat, B, Nursultan, A, Nurlan, M, Kassym, Z, Yelena, P, Sayan, S & Medet, A 2026, Assessment of snow cover contamination in Pavlodar, Kazakhstan, based on elemental analysis and pollution indices. *Atmosphere*, 17(6): 583. <https://doi.org/10.3390/atmos17060583>.
- Altufaili, MA, Kadhim, RE & Merhij, EI 2025, Determination of effectiveness of certain chemical compounds in *Lactuca sativa* L. under cobalt salt stress. *Procedia Environmental Science, Engineering and Management*, 12(1): 237–242.
- Amangeldiev, D, Kozhoshev, A, Shadybekov, KB, Kadyrov, AA & Bekov, AT 2025, Sustainable innovations in management information systems for ensuring Quality 5.0 in local governance of smart cities. *Proceedings on Engineering Sciences*, 7(1): 177–188. <https://doi.org/10.24874/PES07.01A.009>.
- Arifin, Y, Putra, W, Maslikhah, Tongli, B & Sholeh, M 2023, Green supply chain management and environmental performance of small and medium enterprises. *Economic Annals-XXI*, 205(9–10): 34–38. <https://doi.org/10.21003/ea.V205-031>.
- Chand, R, Putna-Nîmane, I, Vecmane, E, Lykkemark, J, Dencker, J, Nielsen, AH, Vollertsen, J & Liu, F 2024, Snow dumping station – A considerable source of tyre wear, microplastics, and heavy metal pollution. *Environment International*, 188: 108782. <https://doi.org/10.1016/j.envint.2024.108782>.
- Egamberdiyev, EA, Turabdjanyov, S, Azimov, D, Tashmatova, U, Ergashev, Y, Mukhiddinova, K, Azimova, S, Rakhimov, K, Igamkulova, N & Mengliev, S 2025, Study of mine water and soil of the Almalyk mining and metallurgical plant: Composition, risks and methods of water and soil purification. *Procedia Environmental Science, Engineering and Management*, 12(1): 261–267.
- Farman, M, Jamil, K, Jamil, S, Nisar, KS, Smerat, A & Hafez, M 2026, Mathematical analysis of air pollution dynamics system for emission controls and air filtration technologies with Caputo derivative. *Modeling Earth Systems and Environment*, 12(2): Article 105. <https://doi.org/10.1007/s40808-026-02750-7>.
- Faurat, A, Yessimova, D, Satybaldiyeva, G, Kuatbayev, A, Utarbayeva, A, Kaliyeva, A, Akhmetov, K, Khan, SM, Ahmad, Z & Rakhmanov, S 2025, Assessing the spatial distribution and sources of heavy metal pollution in the snow cover: A case study from Pavlodar, northeastern Kazakhstan. *PLoS ONE*, 20(5): e0322300. <https://doi.org/10.1371/journal.pone.0322300>.
- Faurat, AA, Azhayev, GS, Shupshibayev, K, Akhmetov, K, Boribay, E & Abylkhasanov, T 2024, Assessment of heavy metal contamination and health risks in ‘snow cover–soil cover–vegetation system’ of urban and rural gardens of an industrial city in Kazakhstan. *International Journal of Environmental Research and Public Health*, 21(8): 1002. <https://doi.org/10.3390/ijerph21081002>.
- Hu, Q, Zhang, C, Chen, Y, Pei, N, Zhao, Y, Sun, L, Lan, J, Liu, F, Guo, Z & Mu, L 2025, Concentration characteristics, source analysis, and health risk assessment of water-soluble heavy metals in PM_{2.5} during winter in Taiyuan, China. *Atmosphere*, 16: 980. <https://doi.org/10.3390/atmos16080980>.
- Jayabal, R, Subbiah, G, Nandan, K, Selvarajan, S, Pampania, JB, GM, S, Tripathy, S, Smerat, A & Priya K, K 2026, Process-safe circular valorization of industrial side streams in hard-to-abate sectors: A risk-TEA-LCA decision framework. *Journal of Loss Prevention in the Process Industries*, 102: 106038. <https://doi.org/10.1016/j.jlp.2026.106038>.
- Jiang, S, Dong, X, Han, Z, Zhao, J & Zhang, Y 2024, Emissions and atmospheric dry and wet deposition of trace metals from natural and anthropogenic sources in mainland China. *Atmosphere*, 15: 402. <https://doi.org/10.3390/atmos15040402>.

- Kaizal, AF, Algburi, JB & Al-Haidarey, MJ 2024, Heavy metal bioaccumulation in the blood and lungs of white albino rats exposed to welding fume. *Procedia Environmental Science, Engineering and Management*, 11(1): 83–89.
- Kakabayev, A 2023, Technogenic impact assessment on the environment of Pavlodar region using GIS technologies. *E3S Web of Conferences*, 38: 06001. <https://doi.org/10.1051/e3sconf/202338606001>.
- Kotova, EI, Shevchenko, VP, Lukyanova, ON, Titova, KV & Starodymova, DP 2025, Geochemical characteristics of the snow cover of the western territory of the Far North of Russia: The example of the Kola Peninsula and Karelian Coast. *Russian Journal of Earth Sciences*, 25: ES6015. <https://doi.org/10.2205/2025ES000977>.
- Kujawska, J 2024, Concentration and risk assessment of metals in snow cover monitoring in urban and rural areas. *Annals of Agricultural and Environmental Medicine*, 31: 205–211. <https://doi.org/10.26444/aaem/178399>.
- Liu, J, Sun, Z, Lei, W, Xu, J, Sun, Q, Shen, Z, Lyu, Y, Shi, H, Zhou, Y & Zhang, L 2025, A reliable medium for monitoring atmospheric deposition near emission sources by using snow from agricultural areas. *Atmosphere*, 16: 26. <https://doi.org/10.3390/atmos16010026>.
- Liu, Y, Gao, W & Chai, S 2024, Assessment of fluxes and ecological and health risks of toxic trace elements in atmospheric deposition from the Baicheng–Songyuan area, Jilin Province, northeast China. *Atmosphere*, 15: 744. <https://doi.org/10.3390/atmos15070744>.
- Liu, Z, Zhan, C, Liu, H, Liu, S, Quan, J, Liu, X, Zhang, J & Qu, C 2023, Source-specific health risk of PM_{2.5}-bound metals in a typical industrial city, central China, 2021–2022. *Atmosphere*, 14: 1406. <https://doi.org/10.3390/atmos14091406>.
- Mohammad, SI, Vasudevan, A, Oriquat, G & Qian, C 2026, Polymeric nanoparticles for modulating reactive oxygen species in the periodontitis microenvironment. *Journal of Biochemical and Molecular Toxicology*, 40(5): Article e70900. <https://doi.org/10.1002/jbt.70900>.
- Moskovchenko, D, Pozhitkov, R, Zakharchenko, A & Tigeev, A 2021, Concentrations of major and trace elements within the snowpack of Tyumen, Russia. *Minerals*, 11: 709. <https://doi.org/10.3390/min11070709>.
- Pedro, E, Capucho, J & coauthors 2025, Study concerning the environmental impact of higher-education institutions and quality of life. *International Journal for Quality Research*, 19(1): 13–32. <https://doi.org/10.24874/IJQR19.01-02>.
- Pote, XR, Doifode, VR, Patil, SD, Patil, PS, Marve, SR, Meghare, P, Yadav, LN, Kakade, NT, Puri, N, Pinjarkar, L, Smerat, A & Vairagade, VS 2026, Techno-economic evaluation and environmental impact analysis of sustainable energy systems using power to X technologies. *Process Integration and Optimization for Sustainability*, 10(2): 567–585. <https://doi.org/10.1007/s41660-026-00765-2>.
- Sayed, U, Naser, ST, Ganesan, S, Ray, S, Basheer, NM, Jayabalan, K, Pramanik, A, Gautam, A & Nooriadeh, H 2026, MXene quantum dots as multifunctional nanostructures for enhanced mass spectrometry: Mechanistic profiling and real-time monitoring of environmental pollutants. *Chemical Papers*. <https://doi.org/10.1007/s11696-026-04850-1>.
- Shuheil, MA, Zalov, AZ, Imanov, HA, Huseynova, AT, Majeed Alrifaie, MM & Sarvestani, MRJ 2026, Electrochemical determination of Ag⁺ in industrial effluents by coated graphite potentiometric sensor based on phenothiazine-based ligand as the ionophore: DFT and experimental studies. *International Journal of Environmental Analytical Chemistry*: 1–17. <https://doi.org/10.1080/03067319.2026.2666865>.
- Starodymova, DP, Kotova, EI, Shevchenko, VP, Titova, KV & Lukyanova, ON 2024, Winter atmospheric deposition of trace elements in the Arkhangelsk region (NW Russia): Insights into environmental effects. *Atmospheric Pollution Research*, 15: 102310. <https://doi.org/10.1016/j.apr.2024.102310>.
- Vijayan, A, Österlund, H, Marsalek, J & Viklander, M 2024, Traffic-related metals in urban snow cover: A review of the literature data and the feasibility of filling gaps by field data collection. *Science of the Total Environment*, 920: 170640. <https://doi.org/10.1016/j.scitotenv.2024.170640>.
- Wang, Y, Hou, Z, Ma, J, Zhang, X, Liu, X, Wang, Q, Chen, C, Yang, K & Meng, J 2025, Seasonal variations and health risk evaluation of trace elements in atmospheric PM_{2.5} in Liaocheng, the North China Plain. *Atmosphere*, 16: 72. <https://doi.org/10.3390/atmos16010072>.

Bibliographic information of this paper for citing:

Dzhakupova, IB, Kudyarova, ZB, Uazhanova, R, Zhylkaidar, A, Sharipova, S, Sharipov, G, Kassenova, G, Maikhin, K 2026, Chemical analysis and environmental assessment of snow cover pollution in urbanized territories, *Caspian Journal of Environmental Sciences*, 24: 1157-1165.
