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Research Article

GEOCHEMICAL DISTRIBUTION OF PRECIOUS AND POTENTIALLY TOXIC ELEMENTS IN TECHNOGENIC WASTES FROM THE ANGREN GOLD PROCESSING PLANT

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ABSTRACT
This study is devoted to a comprehensive assessment of the geochemical characteristics, distribution patterns of elements, and environmental significance of technogenic wastes from the Angren Gold Processing Plant in Uzbekistan. These technogenic wastes were generated during the processing of gold-bearing ores delivered from the Kochbulak, Kyzylalmasay, Kauldy, Karakutan, and Akturpak deposits. Their elemental composition was formed under the influence of the mineralogical and geochemical characteristics of the primary ores as well as the applied beneficiation technology. During the study, the quantitative concentrations of As, Sb, Se, Cd, Tl, Bi, Te, In, Pb, Zn, Mo, U, and Th were determined using inductively coupled plasma mass spectrometry (ICP-MS) based on nine representative samples collected from the tailings storage facility. The degree of geochemical enrichment and environmental risk of the elements was assessed using the Clark concentration coefficient and maximum permissible concentration (MPC) values. The obtained results demonstrated significant accumulation of certain elements within the technogenic wastes. The highest enrichment levels were observed for tellurium (Te), bismuth (Bi), selenium (Se), antimony (Sb), arsenic (As), and molybdenum (Mo). Comparison with MPC values showed that As, Sb, Se, and Pb can be considered environmentally priority elements requiring enhanced monitoring. To determine the relationships between elements, Pearson correlation analysis was performed, and the results were visualized using a heatmap. Hierarchical cluster analysis revealed the separation of elements into three major geochemical associations: Sb–Cd, Se–Te–Zn–Th, and As–Tl–Bi–In–Pb–Mo–U groups. These associations reflect similar migration behavior of elements within technogenic wastes and their potential mineralogical relationships. Principal component analysis (PCA) showed that the first two principal components accounted for 88.07% of the total variance (PC1 – 64.20%, PC2 – 23.87%), confirming the statistical reliability of the identified geochemical associations. Based on the obtained ICP-MS data, Clark concentration coefficients, MPC assessments, and multivariate statistical analyses, it was established that the technogenic wastes of the Angren Gold Processing Plant represent not only an environmentally significant object requiring monitoring but also a promising secondary source of valuable, rare, and strategic elements. The results of this study provide an important scientific basis for environmental monitoring of technogenic wastes, determining element distribution mechanisms, and developing approaches for their efficient utilization as secondary mineral resources.

Keywords: *Technogenic Tailings, Potentially Toxic Elements, Tellurium (Te), Bismuth (Bi), Arsenic (As), Antimony (Sb), Environmental Assessment*

INTRODUCTION
As a result of the rapid development of the mining industry, the extraction and processing volumes of mineral resources have significantly increased worldwide. Although the development of mineral deposits plays an important role in economic growth, industrial progress, and ensuring raw material security, these processes inevitably lead to the formation of large volumes of technogenic wastes. Particularly, wastes generated during the processing of gold and other precious metal ores retain not only major metals but also numerous associated elements, including potentially toxic, rare, and strategically important components. During ore beneficiation, only a certain proportion of valuable components is recovered, while a significant part of the processed ore mass accumulates in tailings storage facilities. Since gold production requires the processing of large volumes of ore to obtain only

a few grams of metal, the resulting technogenic wastes represent a substantial mineral mass. The trace elements remaining in these wastes may migrate into environmental components, including soils, surface water, and groundwater, under the influence of long-term physicochemical weathering processes. Consequently, long-term environmental risks, biogeochemical migration, and potential bioaccumulation processes in living organisms may occur. Since the second half of the 20th century, considerable attention has been devoted to studying the environmental impacts of mining wastes, the accumulation of heavy metals in technogenic deposits, and their migration mechanisms. Adriano (1986) provided a detailed description of the accumulation of heavy metals in mining wastes, their environmental hazards, and their effects on biological systems. Later, Kabata-Pendias and Pendias (2001) comprehensively analyzed the geochemical characteristics, migration behavior, and bioaccumulation processes of heavy metals in soil and natural environmental systems. (Sanakulov, 2019). In Uzbekistan, considerable attention has also been paid to studying the geological, geochemical, and environmental characteristics of technogenic formations associated with the development of the mining industry. Turesbekov et al. (2019), The studies of Abdullayev (1985), Rafikov (1988), Mavlonov (1989), Zokirov (1972), Shukurov (1999–2023), Miraslanov and Zokirov (2003), Amanbayeva (2004), Nuradilov (2004), D. Barkovskaya (2008), Umarov (2008), Sharipov (2011; 2022), Petrov (2021), Fayziyev (2022), Sh. Shukurov (2022), and other researchers have provided important scientific foundations for assessing the formation patterns, element distribution, and environmental conditions of technogenic environments. Despite these studies, the comprehensive assessment of potentially toxic and rare elements in the technogenic wastes of the Angren Gold Processing Plant using modern high-precision analytical methods and multivariate statistical approaches remains insufficiently investigated (Makhammatov A., 2026). The Angren Gold Processing Plant, which is part of the Almalyk Mining and Metallurgical Complex (AMMC), processes gold-bearing ores supplied from the Kochbulak, Kyzylalmasay, Kauldy, Chatkal, Karakutan and Akturpak deposits. Due to the diverse geological structures, mineralogical compositions, and ore-forming characteristics of these deposits, the wastes generated at the plant represent a complex and heterogeneous geochemical system. The long-term accumulation of these technogenic deposits during continuous beneficiation processes has resulted in uneven distribution of various elements, their association with mineral phases, and potential secondary migration processes, which require modern geochemical investigations (Dunin-Barkovskaya E.A., 2008). In recent years, the application of multivariate statistical methods has become increasingly important for determining element distribution patterns, rather than limiting investigations only to concentration-based assessments. Correlation analysis allows the identification of relationships between elements, hierarchical cluster analysis enables the grouping of elements with similar geochemical characteristics, while principal component analysis (PCA) helps determine the main geochemical factors controlling the system. These approaches provide a deeper understanding of element sources, migration behavior, and potential mineralogical associations within technogenic wastes.

The main objective of this study is to determine the concentrations of As, Sb, Se, Cd, Ti, Bi, Te, In, Pb, Zn, Mo, U, and Th in technogenic wastes of the Angren Gold Processing Plant using inductively coupled plasma mass spectrometry (ICP-MS), to evaluate their degree of geochemical enrichment based on Clark concentration coefficients, and to assess their environmental risk through comparison with maximum permissible concentration (MPC) values. In addition, relationships between elements were evaluated using Pearson correlation analysis, hierarchical cluster analysis, and principal component analysis (PCA). The obtained results provide an important scientific basis for assessing the environmental status of technogenic wastes from the Angren Gold Processing Plant, determining the distribution patterns of potentially hazardous elements, developing long-term geochemical monitoring systems, and evaluating technogenic wastes as promising secondary sources of valuable and strategic elements.

MATERIALS AND METHODS

This study was conducted at the technogenic waste storage facility of the Angren Gold Processing Plant, which is part of the Almalyk Mining and Metallurgical Complex (AMMC), located in the Akhangaran district of Tashkent Region, Uzbekistan. (Figure 1).

To determine the spatial distribution characteristics of elements in technogenic wastes, nine representative samples were collected from different parts of the tailings storage facility. The sampling points were selected to reflect the overall geochemical characteristics of the technogenic waste mass. The collected samples underwent preliminary preparation procedures under laboratory conditions. Foreign impurities were removed from the samples, followed by drying and grinding to obtain a uniform granulometric composition. The prepared samples were used for subsequent geochemical analyses.

Geochemical analysis by ICP-MS

Inductively coupled plasma mass spectrometry (ICP-MS) was applied to determine the quantitative concentrations of trace elements in the technogenic wastes. This analytical method is widely used in modern geochemical and environmental studies due to its low detection limits, high sensitivity, and ability to simultaneously determine a large number of elements. To ensure the reliability of the obtained analytical results, laboratory analyses were performed in accordance with standard geochemical quality control and analytical verification procedures.

Geochemical assessment and statistical analysis

To evaluate the degree of element accumulation in technogenic wastes, their concentrations were compared with the average abundances of elements in the Earth's crust (Clark values). The Clark concentration coefficient (Kc) was calculated for each element to determine the degree of enrichment relative to natural background values. In addition, the determined element concentrations were compared with maximum permissible concentration (MPC) values to assess potential environmental risks. This approach allowed the evaluation of the hazard level of potentially toxic elements present in technogenic wastes and their possible impact on environmental components. The relationships between elements were assessed using Pearson correlation analysis, and the results were graphically presented as a heatmap. Hierarchical cluster analysis (HCA) was performed to identify elements with similar geochemical characteristics and possible common sources. Furthermore, principal component analysis (PCA) was applied to determine the major geochemical factors controlling the dataset and to evaluate element associations. All statistical analyses were performed to identify relationships between elements, grouping patterns, and the overall geochemical characteristics of technogenic wastes.

RESULTS AND DISCUSSION

The ICP-MS analysis results demonstrated that technogenic wastes of the Angren Gold Processing Plant contain potentially toxic and economically significant trace elements accumulated in varying concentrations (Table 1) Shukurov Sh. et al.(2022). Comparison with the average abundances of elements in the Earth's crust revealed significant enrichment of certain elements within the technogenic wastes. The highest values of the Clark concentration coefficient were observed for Te (820.0), Bi (247.78), Sb (67.12), Se (30.80), and As (12.68). In addition, Mo (5.65), Pb (3.48), and Ti (1.72) also demonstrated enrichment relative to natural background values.

For the assessment of environmental risks, the concentrations of elements were compared with the maximum permissible concentration (MPC) values. The results showed that the concentrations of As (10.78 times), Sb (7.45 times), Zn (2.29 times), Pb (1.85 times), Ti (1.72 times), and Se (1.54 times) exceeded the established permissible limits. These findings indicate that As and Sb, in particular, require priority monitoring due to their potential environmental hazards within the technogenic wastes. When the Clark concentration coefficient and MPC values were evaluated together. it was found that although Te and Bi exhibited very high levels of geochemical enrichment. their environmental risk was relatively low. In contrast. As and Sb were identified as the most important indicator elements in terms of both geochemical enrichment and environmental hazard. This observation suggests that these elements are genetically associated with the original gold-polymetallic ores and were retained in the waste material during the beneficiation process. The relationships between elements were evaluated using Pearson correlation coefficients. and the results were presented in the form of a heatmap (Figure 2). As shown in Figure 2. strong positive correlations were observed among Ti. Bi. Mo. U. In. and Pb.

Figure 1. Study area: (a) Uzbekistan in the world map; (b) location of Tashkent Region within Uzbekistan; (c) sampling locations at the Angren Gold Processing Plant tailings storage facility.

Sample collection and preparation

Table 1. Clark concentration coefficient of the investigated elements in the technogenic tailingis of the angren gold processing plant. ICP-MS

Sample №	Chemical Elements	As	Sb	Se	Cd	Ti	Bi	Te	In	Pb	Zn	Mo	U	Th
1	AGPP Tailings	15.0	39	2.40	0.21	1.8	1.8	1.1	0.085	34	76	5.70	3	11
2	AGPP Tailings	29.0	35	2.70	0.12	2.2	3.3	1.1	0.1	70	101	10.10	4.5	14
3	AGPP Tailings	22.0	28	1.80	0.11	2.2	2.7	0.57	0.1	73	44	8.30	3.4	9.3
4	AGPP Tailings	24.0	36	1.40	0.1	1.5	2	0.66	0.093	45	62	4.60	3.2	9
5	AGPP Tailings	16.0	43	1.20	0.081	1	1.1	0.51	0.058	20	22	3.30	2.4	8.1
6	AGPP Tailings	14.0	33	1.00	0.16	1.4	1.5	0.72	0.071	50	46	5.60	2.6	8.7
7	AGPP Tailings	32.0	27	0.50	0.1	1.3	0.94	0.66	0.074	36	38	3.20	2.9	9.1
8	AGPP Tailings	7.0	30	1.40	0.11	1.7	2.5	0.87	0.066	53	41	6.40	2.6	8.9
9	AGPP Tailings	35.0	31	1.50	0.13	2.4	4.2	1.2	0.11	120	46	8.80	4.3	12
Total		194.0	302.0	13.9	1.1	15.5	20.0	7.4	0.8	501.0	476.0	56.0	28.9	90.1
Average concentration		21.56	33.56	1.54	0.12	1.72	2.23	0.82	0.08	55.67	52.89	6.22	3.21	10.01
Clarke value in the Earth's crust		1.7	0.5	0.05	0.13	1	0.009	0.001	0.25	16	83	1.1	2.5	13
Clarke concentration		12.68	67.12	30.80	0.92	1.72	247.78	820	0.32	3.48	0.64	5.65	1.28	0.77
MPC		2	4.5	1	1	1	3		2	30	23	10	5	
Exceedance of MPC (times)		10.78	7.45	1.54	0.12	1.72	0.74		0.04	1.85	2.29	0.62	0.64	

The element pairs exhibiting very high correlation coefficients indicate the presence of common geochemical sources or similar migration characteristics. Additionally. Se demonstrated positive correlations with Zn (r = 0.813). Th (r = 0.746). and Te (r = 0.595). These results suggest a genetic association of Se with sulfide-rich mineral phases (Shukurov Sh. et al.. 2022). In contrast. Sb showed negative or very weak correlations with most elements. indicating that Sb possesses relatively independent geochemical behavior compared to other elements. Overall. the correlation analysis confirms that the distribution of elements within the technogenic wastes is not random but occurs in the form of specific geochemical associations.

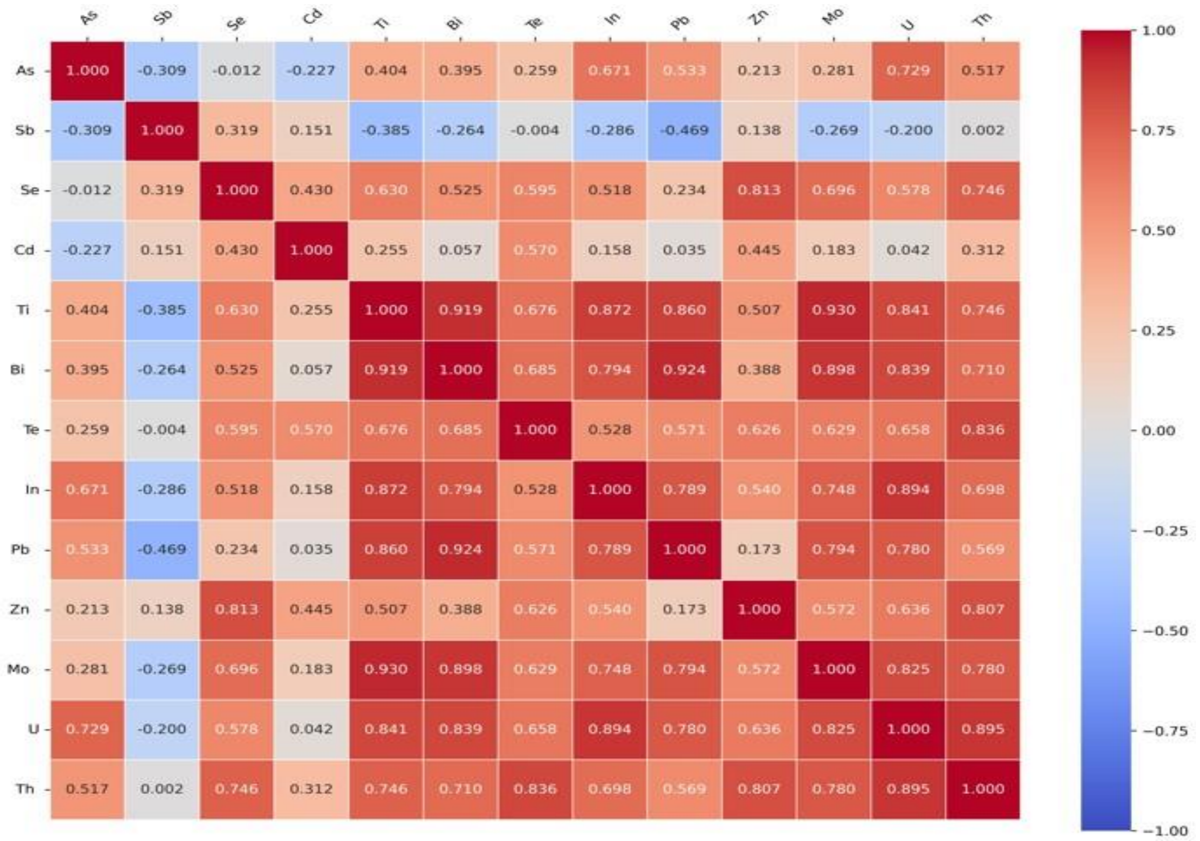

Figure 2. Pearson correlation heatmap of the investigated elements.

The color scale represents the Pearson correlation coefficient (r). ranging from −1.00 (strong negative correlation) to +1.00 (strong positive correlation). Hierarchical cluster analysis (HCA) complemented the results of Pearson correlation analysis and demonstrated that the investigated elements were divided into three main associations according to their degree of geochemical similarity. The first cluster included Sb and Cd elements. The formation of a separate group by these elements indicates that their geochemical behavior and migration characteristics differ to a certain extent from those of the other elements.

The second cluster consisted of Se. Te. Zn. and Th elements. The close geochemical similarity among these elements indicates that they exhibit similar distribution patterns and may be associated with common geochemical processes or mineral phases within the technogenic environment. The third cluster combined As. Ti. Bi. In. Pb. Mo. and U elements. These elements also demonstrated strong positive correlations in the Pearson correlation analysis. and their grouping within a single cluster confirms their belonging to a common geochemical association. This group can be characterized as an elemental assemblage typical of gold-polymetallic mineralization. Overall. the results of hierarchical cluster analysis demonstrated that the investigated elements are distributed within the technogenic wastes in the form of three relatively independent geochemical associations. These results are consistent with the element groupings identified through Pearson correlation analysis and principal component analysis (PCA). further strengthening the reliability of the obtained geochemical interpretations.

Principal Component Analysis (PCA)

Principal component analysis (PCA) was performed to evaluate the overall geochemical structure of the investigated elements (Figure 3). The first two principal components explained 88.07% of the total variance. Specifically. PC1 accounted for 64.20% of the variance. whereas PC2 explained 23.87%. These results indicate that the major geochemical characteristics of the dataset are effectively represented by the first two principal components.

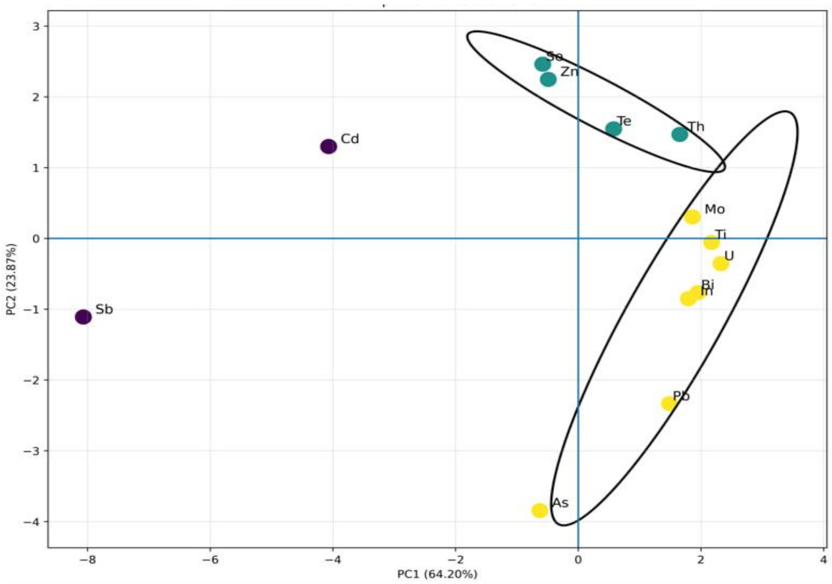

Figure 3. Principal component analysis (PCA) of the investigated elements.

The PCA score plot shows that Ti. Bi. In. Pb. Mo. and U are closely clustered. forming the principal geochemical association. In contrast. Se. Zn. Te. and Th constitute a second distinct group. Conversely. Sb and Cd are located considerably farther from the major groups. indicating that their geochemical characteristics are relatively independent. Although As is also separated to some extent from the main cluster. it remains associated with the third geochemical group in terms of its overall geochemical relationships. The PCA results are in full agreement with those obtained from Pearson correlation analysis and hierarchical cluster analysis. further confirming the presence of three major geochemical associations within the technogenic wastes.

CONCLUSION

This study provided a comprehensive assessment of the geochemical composition and environmental significance of the technogenic wastes from the Angren Gold Processing Plant using modern analytical and statistical approaches. Based on ICP-MS analyses. Clark concentration coefficients. and comparisons with maximum permissible concentration (MPC) values. it was established that the degree of geochemical enrichment and environmental risk varies considerably among the investigated elements. In particular. As. Sb. Se. and Pb were identified as the principal elements requiring priority environmental monitoring. The results of Pearson correlation analysis. hierarchical cluster analysis. and principal component analysis (PCA) were mutually consistent. demonstrating that the investigated elements are distributed within the technogenic wastes in the form of three major geochemical associations. The agreement among the results obtained using different statistical approaches increased the reliability of the identified geochemical patterns and confirmed that the distribution of elements is controlled by specific geochemical processes rather than occurring randomly. The findings indicate that the technogenic wastes of the Angren Gold Processing Plant should be regarded not only as a technogenic object requiring continuous environmental monitoring but also as a promising secondary source of valuable. rare. and strategically important elements with significant scientific and practical potential. Therefore. comprehensive geochemical assessment of these wastes. regular environmental monitoring. and investigation of the feasibility of recovering valuable components should remain among the major priorities of future research. The results of this study contribute to a better understanding of the distribution patterns of elements in technogenic wastes and provide a reliable geochemical basis for environmental risk assessment. sustainable resource utilization. and the development of scientific and practical strategies for the sustainable management of mining wastes.

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