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Impacts of the development of mineral metal resources on surface water quality in the Mongolian Plateau based on meta-analysis

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The mining of metal resources is one of the major sources of heavy metals in surface water, but studies on the different characteristics of the impact of the exploitation of mineral metal resources on surface water from a large-scale perspective are lacking. In the present study, we quantified the impacts of mineral metal resource development on As, Cu, Cr, Pb, Zn, Hg, Ni, Cd, Mn, and Fe in the overlying water and sediments of surface water under different scenarios (i.e., different geographic units and different mined metal types) using meta-analysis for the Mongolian Plateau of Mongolia and the Inner Mongolia Autonomous Region of China, which is rich in mineral metal resources and has high exploitation and use intensity. Finally, funnel plots and Egger's regression analysis were used to test the publication bias of the data. The results show that the order of heavy metal content in the overlying water of the Mongolian Plateau was Fe > Mn > As > Zn > Cu > Pb > Cr > Ni > Cd > Hg, and the order of heavy metal content in the sediment was Fe > Mn > Zn > Cr > Pb > Ni > Cu > As > Cd > Hg. In addition, As, Cr, Zn, Hg, Cd, and Pb in overlying water exceeded the standard to different degrees, among which the contents of As and Pb were 1.4 and 1.3 times higher than the World Health Organization guideline, and the contents of Cr, Pb, Hg, Cd were 1.5, 1.3, 25.4, 2.6 times Chinese environmental quality standards for surface water, and the contents of As, Pb, Zn, Hg were 1.4, 1.3, 4.7, 12.7 times Mongolian water quality standards, respectively. The content of As in sediments was 2.6 times the background value of soil environmental quality in Inner Mongolia. Significant differences existed in the content of heavy metal pollutants in surface water of different countries; the content of heavy metals in the overlying water was significantly higher in Inner Mongolia Autonomous Region of China than in Mongolia. Copper and molybdenum polymetallic mines significantly increased the content of Cd, Cr, Cu, Fe, Hg, Pb, and Zn in the overlying water, while the content of As, Cr, Pb, and Zn in overlying water increased significantly due to lead–zinc mining. However, the mining of gold–silver, lead–zinc, copper–molybdenum, and other polymetallic mines all significantly affected the concentration of As in sediments. The results of the present study can provide data support for environmental protection and the restoration of surface water in metal mining areas of the Mongolian Plateau.

KEYWORDS

mongolian plateau, metal mines, heavy metals, surface water, metaanalysis

1 Introduction

In the recent past, the exploitation of metal mining resources has not only brought considerable economic benefits to society but also exacerbated the problem of heavy metal pollution in a way that cannot be ignored. Heavy metals are defined as those elements having an atomic number greater than 20 and atomic density above 5 g/cm^3 and must exhibit the properties of metal (Ali and Khan, 2017; Raychaudhuri et al., 2021). These metals have adverse effects on living species and humans through various environmental segments (Yuksel and Arica, 2018; Narjala Rama, 2020). Mining creates a large amount of waste rock and tailings containing metal minerals that become exposed to the atmosphere; these are highly susceptible to oxidation and the formation of acid mine drainage when exposed to environmental conditions with abundant water and oxygen present (Akcil and Koldas, 2006). These heavy metal pollutants will also enter the surface runoff and groundwater environments through leaching and weathering (Punia, 2021). At the same time, physical and chemical conditions allow heavy metal pollutants in water bodies to easily become enriched in sediments where these metals will be re-released when external conditions change causing secondary pollution to the aquatic environment (Fu et al., 2014). Pollutants in sediments are the result of long-term accumulation and thus have a relatively lasting impact on water quality. Even if the external pollution sources are eliminated and cut off, the sediments will continue to have an impact on the quality of the overlying water for a long time, so the physical and chemical indices of the water body itself and sediments are important factors reflecting the quality and pollution status of surface water (Nguyen et al., 2016).

The Mongolian Plateau is located in the central part of Eurasia and mainly includes Mongolia and the Inner Mongolia Autonomous Region of China (Fang et al., 2015). This region features a typical arid and semi-arid climate with an area of about 2.75 × 10^6 km^2 and supports a population of about 28 million (Tao et al., 2015). For thousands of years, herdsmen have lived here surviving on water and the resources of this grassland area. As one of the most important sources of water resources, surface water is the most indispensable substance in the Mongolian Plateau. This plateau is rich in mineral resources and has great potential. At present, more than 100 kinds of mineral products have been found here, including coal, copper, fluorite, gold, iron ore, and lead. As one of the main industries of the Mongolian Plateau, the mining industry provides the main source of income and stimulates regional development (Geng et al., 2006; Damba, 2014). However, in recent years, the depletion and pollution of rivers and lakes on the Mongolian Plateau have been closely related to the irrational exploitation and use of mining activities (Han et al., 2021). A survey of surface water in Mongolia conducted in 2003 showed that at least 23 rivers in eight provinces were polluted to varying degrees due to mining activities (Batbayar et al., 2017). Therefore, it is necessary to investigate the environmental quality of surface water in metal mining and surrounding areas to provide effective decision-making support for the protection of water resources in these areas on the Mongolian Plateau.

Previous studies on the impact of metal mining on surface water have mainly focused on a single or a few metal mining areas (Thorslund et al., 2012; Batsaikhan et al., 2017). However, these research results cannot provide a theoretical basis for the control of surface water pollution in metal mining areas from a large-scale perspective. Meta-analysis is suitable for the study of large-scale ecological phenomena, because in most cases, limitations of funds and energy make it difficult to carry out large-scale research. However, the accumulation and integrated use of individual research information provide a better analysis method for large-scale ecological and environmental research (Osenberg et al., 1999). Based on this, the present study is based on a meta-analysis study designed to quantitatively assess the heavy metal content in water bodies and sediments on the Mongolian Plateau, aiming to provide an important scientific basis for the treatment of the surface water environment in metal mining areas of the Mongolian Plateau. In summary, the assessment results of the present study can basically reflect the status of heavy metal pollution in surface water from metal mine resource development under different scenarios across the Mongolian Plateau, mainly because: 1) the number of included research papers is moderate, the questions are clear, and the classification of the study subgroups (different geographic units and different metal mine types) is reasonable, which can meet the requirements of the aggregated results; and 2) the included articles include all types of surface water (rivers, lakes, streams) and cover the main existing interfaces of heavy metals in water bodies (overlying water, sediments), which is comprehensive and representative.

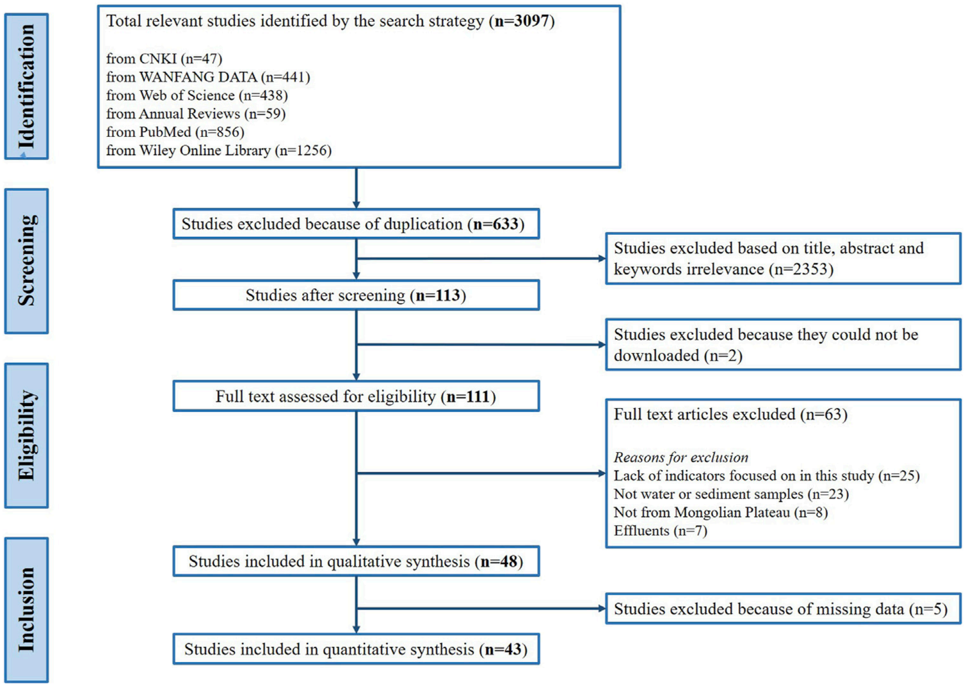

FIGURE 1
The PRISMA flow diagram for the selection and extraction of relevant studies.

2 Materials and methods

2.1 Data source

As of March 2022, the author used ("Heavy metal" OR "Metal mine area "OR "Mining" or "Water pollution") AND ("Surface water" OR "River" OR "Lake" or "Stream") AND ("Mongolian Plateau" OR "Mongolia "OR "Inner Mongolia Autonomous Region") as keywords to search, collect, and collate articles about the influence of the exploitation of mineral metal resources on heavy metals in surface water on the Mongolian Plateau. The flow diagram of the "Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) (Moher et al., 2009)"and the exclusion reasons of screening articles are shown in Figure 1. Meta-analysis is the statistical combination of results from at least "two separate studies," of which 43 studies in our article are much more than the minimum required.

To ensure the accuracy of the study, the selection criteria for articles were as follows: 1) surface water samples were collected from areas affected by metal mining in the Mongolian Plateau region; 2) articles were selected that did not mention specific mining types around surface water that should be subject to the main metal minerals queried in the area; 3) surface water samples could be collected from perennial rivers, seasonal rivers, perennial lakes, seasonal lakes, or streams; 4) one or more of 10 heavy metals (As, Cu, Cr, Pb, Zn, Hg, Ni, Cd, Mn, Fe) were investigated; 5) data from man-made water bodies such as impoundments were excluded; 6) the present study included accurate information on sample size, sample type, heavy metal content (mean or minimum and maximum values), and standard deviation (*SD*), and was used only if standard error (*SE*) data were available in the paper; the standard deviation (*SD*) was calculated as follows (Du et al., 2020):

$$SD = SE\sqrt{N}$$

where N is the total number of samples in the article. If the standard deviation (*SD*) or standard error (*SE*) was missing in a paper, but the data range was given, the standard deviation (*SD*) could be approximated as follows to obtain as much available data as possible (Weir et al., 2018):

$$SD = 1/4(MAX - MIN)$$

where MAX and MIN are the maximum and minimum values of heavy metal content in the article, respectively. The mean and standard deviation (*SD*) of "below detection limit" or less than 0.0001 in articles were set as 0.0001 for meta-analysis (Umeoguaju et al., 2022).

The present study finally obtained 43 valid articles and extracted 21 sets of river and lake information, 2,255 sets of sample data, and three categories of mineral species from the charts of these articles. Figure 2 shows the main surface water resources, location of metal mining areas, and the number of included articles in different sub-regions of the Mongolian Plateau analyzed in the present study. The finalized Excel database included articles with background information (author, year of publication), the study area of each study (the whole or part of a river and lake basin), the country where the study areas were located, the type of sampling (overlying water, sediment), the type of metal mine, the type of heavy metal, along with the mean values, standard deviations, maximum and minimum values, and the number of samples of heavy metal content.

2.2 Meta-analysis of data

The R language vers. 4.1.3 (https://www.R-project.org/) was used for statistical analysis and plotting in the present study.

The mean and standard deviation (*SD*) of heavy metal content were the two statistical indicators used for the meta-analysis. The H and I^2 indices were first calculated using a Chi-square test to detect the heterogeneity between studies; based on the results of heterogeneity tests, the analytical model was selected including fixed-effects models (FEM) or random-effects model (REM) (Ravanipour et al., 2021). In the meta-analysis, an REM was used if heterogeneity existed among the original studies; otherwise, a FEM was used. Due to the high heterogeneity among studies on heavy metal content in surface water, the REM was used to evaluate the present study. Subgroup analysis was then performed for the countries where each study area was located (China, Mongolia) and different metal mine types (gold–silver, lead–zinc, copper–molybdenum, and other polymetallic mines).

2.3 Publication bias

Publication bias refers to the phenomenon that statistically significant study results are more likely to be submitted and published than non-statistically significant study results (Marks-Anglin and Chen, 2020). Funnel plots were used to test for publication bias. A funnel plot can intuitively reflect whether the effect size of the original study is related to the sample size, and if all the studies are arranged symmetrically around the center line of a funnel plot, indicating that no publication bias existed; if they are asymmetrically distributed, publication bias is believed to exist (Zwetsloot et al., 2017). The quantitative test for the magnitude of funnel plot bias in the present study used Egger's regression analysis, with $p > 0.05$ or <0.05 suggesting no significant publication bias or some publication bias existed, respectively (Egger et al., 1997).

3 Results and analysis

3.1 Content and types of heavy metals in surface water of the Mongolian Plateau

The mean content of Pb in the overlying water of the Mongolian Plateau was 13.15 μg/L, which was the only heavy metal type in the present study that was simultaneously higher than the guideline values for drinking water quality standards specified by the United Nations World Health Organization (WHO) as well as the Mongolian and Chinese environmental quality standards for surface water (Tables 1, 2). In addition, the content of As, Cr, Zn, Hg, and Cd all exceeded the standards of these three organizations to different degrees, among which the contents of As was 1.4 times higher than the WHO guideline, and the contents of Cr, Hg, Cd were 1.5, 25.4, 2.6 times Chinese environmental quality standards for surface water, and the contents of As, Zn, Hg were 1.4, 4.7, 12.7 times Mongolian water quality standards, respectively. The average content of Cd in some surface water sediments was 0.64 mg/kg, which exceeded the risk screening values for soil contamination of agricultural land of China and was 17.1 times the background value of soil environment in Inner Mongolia; the average content of As was 16.64 mg/kg, which exceeded the soil quality standard of Mongolia and was 2.6 times the background value of soil environment quality in Inner Mongolia. Although the content of other heavy metals was not higher than the relevant standards, the results showed a trend of a substantial increase when compared with the background value of the soil environment in Inner Mongolia.

In the present study, H and I^2 statistics were selected for the heterogeneity tests. The two indices mentioned above were not affected by changes in the number of articles used in the analysis after a correction for degrees of freedom; the heterogeneity test was relatively robust (Wang et al., 2009). Tables 3, 4 present the I^2 and H indices used to quantify the heterogeneity of the studies. The results showed that heterogeneity existed among the original studies, so a random-effects model was used for meta-analysis (Tables 3, 4).

The meta-analysis showed that among all heavy metals in both the overlying water and sediment, the highest total mean concentrations were found for iron (Fe) with 102.25 (95% CI = 52.96–151.53 μg/L) and 27,303.04 (95% CI = 21,575.69–33,030.40 mg/kg), respectively, and Mercury (Hg) had the lowest total mean concentrations at 0.09 (95% CI = −0.02–0.21 μg/L) and 0.09 (95% CI = 0.06–0.12 mg/kg), respectively. The order of the content of heavy metals in the overlying water was Fe > Mn > As > Zn > Cu > Pb > Cr > Ni > Cd > Hg, and the order of the content of heavy metals in the sediment was Fe > Mn > Zn > Cr > Pb > Ni > Cu > As > Cd > Hg. According to the results of the aggregate estimates,

TABLE 1 Descriptive statistics of heavy metal content in overlying water of surface water in Mongolian Plateau (μg/L): a) World Health Organization (WHO) guidelines for drinking-water quality (World Health Organization, 2017); b) Chinese surface water environment quality, GB3838-2002 (The Ministry of Environmental Protection of the People's Republic of China, 2002); c) Mongolian surface water quality guideline, MNS 4586:1998 (Mongolian National Center for Standardization and Metrology, 1998).

	As	Cu	Cr	Pb	Zn	Hg	Ni	Cd	Mn	Fe
Mean	13.50	9.39	14.79	13.15	46.66	1.27	7.70	2.55	59.94	218.51
SE	6.44	4.01	6.73	5.32	18.98	1.05	3.85	1.65	18.39	118.06
SD	34.06	12.67	37.45	28.16	117.01	4.46	12.16	8.71	91.94	541.04
Max	134.68	37.60	189.40	122.90	658.00	19.00	40.00	36.40	428.75	2,530.00
Min	0.35	0.60	0.00	0.00	0.00	0.00	0.00	0.00	4.10	0.00
CV/%	252.29	134.89	253.16	214.11	250.77	351.36	158.02	342.02	153.40	247.60
WHO 2011 (a)	10.00	2000.00	50.00	10.00	—	6.00	70.00	3.00	400.00	300.00
GB3838-2002 (Class I) (b)	50.00	10.00	10.00	10.00	50.00	0.05	20.00	1.00	100.00	300.00
MNS 4586:1998 (c)	10.00	10.00	50.00	10.00	10.00	0.10	10.00	5.00	100.00	—

TABLE 2 Descriptive statistics of heavy metal content in sediments of surface water in the Mongolian Plateau (mg/kg): a) Inner Mongolian soil background values (China National Environmental Monitoring Centre, 1990); b) Chinese soil environmental quality—Risk control standard for soil contamination of agricultural land, GB 15618–2018 (Ministry of Ecology and Environment of the People's Republic of China 2018); c) Mongolian soil environment quality standard, MNS 5850:2019 (Mongolian National Center for Standardization and Metrology, 2019).

	As	Cu	Cr	Pb	Zn	Hg	Ni	Cd	Mn	Fe
Mean	16.64	55.93	47.21	25.48	85.13	0.10	25.21	0.64	552.78	27,154.88
SE	5.73	24.13	10.11	3.77	17.62	0.02	3.66	0.31	45.78	2,875.86
SD	28.09	125.40	48.49	18.84	93.22	0.08	14.16	1.34	129.50	9,094.26
Max	143.23	619.00	234.67	78.26	547.50	0.30	61.50	5.65	765.14	46,040.00
Min	2.61	0.16	0.01	0.18	8.83	0.02	3.90	0.02	422.56	18,250.00
CV/%	168.80	224.20	102.70	73.95	109.51	82.42	56.15	207.95	23.43	33.49
BCG-IM (a)	6.30	12.90	36.50	15.00	48.60	0.03	17.30	0.04	446.00	21,200.00
GB 15618-2018 (b)	25.00	100.00	250.00	170.00	300.00	3.40	190.00	0.60	—	—
MNS 5850:2019 (c)	6.00	100.00	150.00	100.00	300.00	2.00	150.00	3.00	—	—

TABLE 3 Meta-analysis results of heavy metal content in overlying water of surface water in Mongolian Plateau. n, the number of data points collected in the articles.

Heavy metals	n	Estimate (μg/L)	I^2	H	Egger's test (p)
As	436	13.39 (0.84, 25.93)	99.7	18.96	0.0577
Cu	546	10.81 (4.61, 17.01)	99.7	19.01	<0.0001
Cr	455	8.19 (1.64, 14.73)	99.8	21.05	0.0017
Pb	456	10.23 (2.86, 17.59)	100.0	530.42	0.4584
Zn	548	12.01 (8.11, 15.91)	98.9	9.76	<0.0001
Hg	303	0.09 (−0.02, 0.21)	99.7	19.03	0.0101
Ni	228	7.45 (−0.14, 15.05)	99.6	16.18	0.02
Cd	362	1.79 (−0.57, 4.14)	99.9	28.28	0.0145
Mn	293	21.52 (14.97, 28.08)	90.3	3.21	<0.0001
Fe	440	102.25 (52.96, 151.53)	99.8	22.89	0.0041

TABLE 4 Meta-analysis results of heavy metal content in sediments of surface water in Mongolian Plateau. *n*, the number of data points collected in the articles.

Heavy metals	*n*	Estimate (mg/kg)	I^2	H	Egger's test (*p*)
As	302	15.89 (5.94, 25.84)	99.6	15.80	0.2827
Cu	1,062	23.32 (18.80, 27.83)	100.0	78.21	0.1303
Cr	368	38.56 (27.99, 49.14)	99.6	16.08	<0.0001
Pb	935	24.47 (17.82, 31.12)	100.0	47.87	0.4634
Zn	1,068	67.16 (58.30, 76.03)	99.9	29.94	0.0168
Hg	218	0.09 (0.06, 0.12)	97.2	6.02	<0.0001
Ni	855	24.20 (18.04, 30.36)	99.9	27.91	0.0316
Cd	224	0.32 (0.16, 0.47)	99.1	10.31	0.0005
Mn	206	548.33 (461.42, 635.25)	93.6	3.97	–
Fe	1,030	27,303.04 (21,575.69, 33,030.40)	99.4	13.22	0.1188

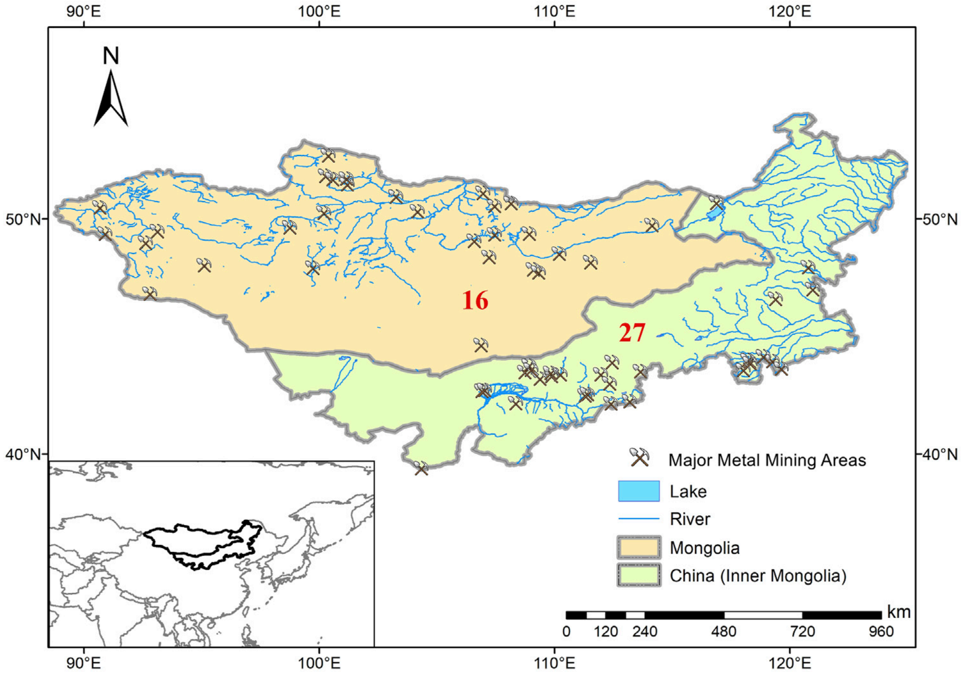

FIGURE 2
The main surface water resources, the locations of metal mining areas, and the number of articles (16 and 27) employed in the present study for two sub-regions of the Mongolian Plateau.

concentrations of As, Cu, Pb, Zn, Hg, and Cd in the overlying water were higher than the international WHO or the Chinese and Mongolian water quality standards, and the content of As in the sediment was 15.89 (95% CI = 5.94–25.84 mg/kg), which was higher than the Mongolian soil environmental quality standard. The meta-analysis was basically consistent with the descriptive statistical results, which reflected the accuracy and reliability of the meta-analysis in the present study.

3.2 Country-specific differences in the effects of metal mining resource development on the heavy metal content of surface water

The subgroup analysis and boxplot of the overlying water showed that the content of heavy metal content in the overlying water of Inner Mongolia Autonomous Region

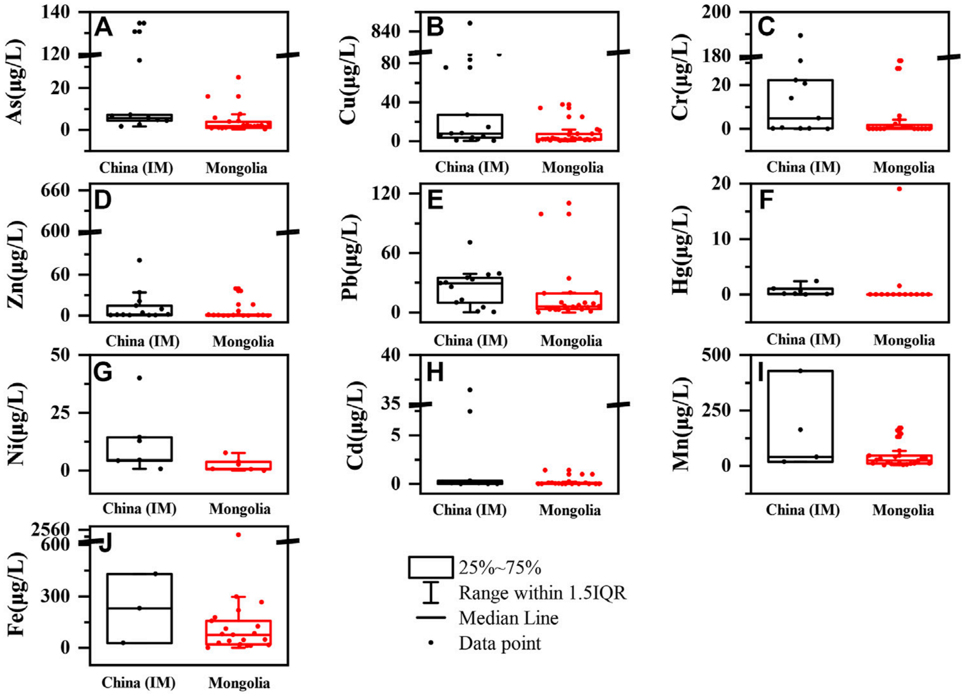

FIGURE 3
Country-specific differences of heavy metal content in overlying surface water. IM, Inner Mongolia: **(A)** As; **(B)** Cu; **(C)** Cr; **(D)** Zn; **(E)** Pb; **(F)** Hg; **(G)** Ni; **(H)** Cd; **(I)** Mn; **(J)** Fe.

was significantly higher than that of Mongolia; the content of As, Cd, Cr, Cu, Hg, and Pb in Inner Mongolia Autonomous Region exceeded the standard to different degrees. The content of As was 3.3 times that given in WHO guidelines, and the contents of Cd, Cr, Cu, Hg, and Pb were 6.6, 1.8, 2.4, 7.8, and 1.7 times Chinese environmental quality standards for surface water, respectively (Figure 3, Supplementary Figure S1). None of the 10 heavy metals analyzed in Mongolian overlying waters were higher than the WHO guideline values and Mongolian water quality standards, but some areas with high concentrations of heavy metals still existed. Batsaikhan et al. (2017) also found in their study that the heavy metal concentrations in the water bodies of north-central Mongolia were not high and mining activities had a low impact on the heavy metal content of river water.

The subgroup analysis and boxplot of the sediments showed that the concentrations of Cd, Cr, Cu, Hg, Ni, Pb, and Zn in the sediment of the water bodies of the Mongolian Plateau were lower than the relevant standards for both China and Mongolia. The concentrations of Fe and Mn did not increase significantly relative to the background value of soil environment quality in Inner Mongolia, and only the concentration of As in Mongolia was higher than the Mongolian soil quality standard (Figure 4, Supplementary Figure S2). Kasimov et al. (2016) found that river sediments around large mining centers in Mongolia, such as Erdenet and Zakamensk, had generally low levels of heavy metals, and the pollutant content in sediments in individual rivers was comparable to the local soil background value.

3.3 Mineral species differences in the effects of metal mining resource development on the heavy metals content of surface water

The subgroup analysis and boxplots of the overlying water showed that gold mining did not significantly affect the concentrations of heavy metals in the overlying water. The mining of copper–molybdenum mines and other polymetallic mines has significantly increased the concentrations of many heavy metals, among which the contents of Cd, Cr, Cu, Fe, Hg, and Pb were 3.6, 1.2, 1.7, 1.8, 6.4, and 1.7 times higher than Class I Chinese surface water environment quality standards, and the content of Zn was also 2.3 times higher than the surface water quality standard for Mongolia. It could be seen that the mining of copper–molybdenum and other polymetallic mines have posed a certain threat to the quality of surface water

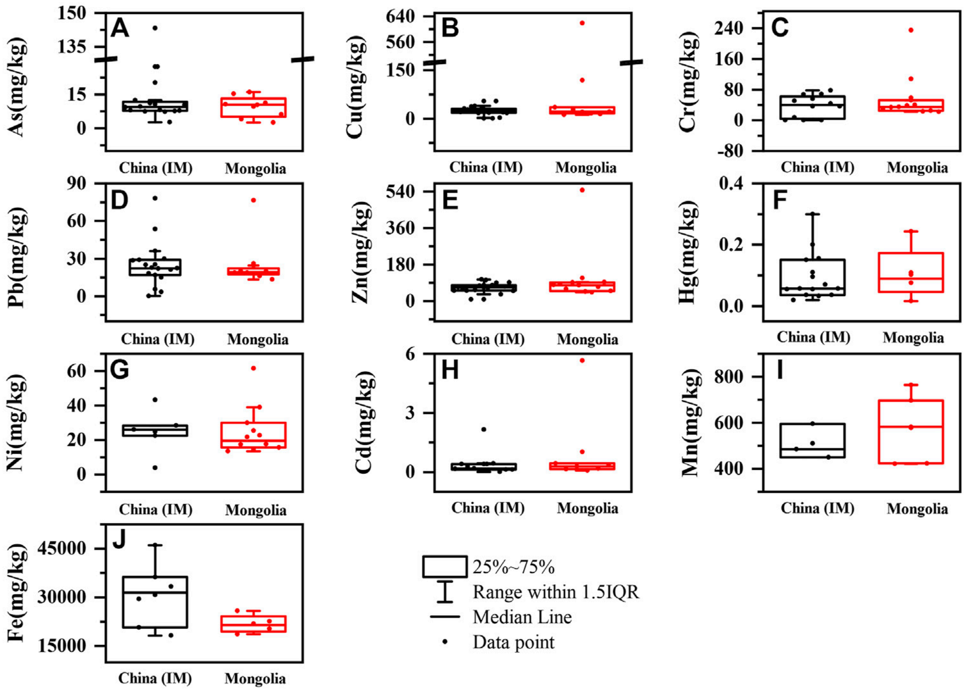

FIGURE 4
Country-specific differences of heavy metal content in sediments of surface water. IM, Inner Mongolia: **(A)** As; **(B)** Cu; **(C)** Cr; **(D)** Pb; **(E)** Zn; **(F)** Hg; **(G)** Ni; **(H)** Cd; **(I)** Mn; **(J)** Fe.

(Figure 5, Supplementary Figure S3). Lead and zinc mining significantly increased the content of As, Cr, Pb, and Zn in the overlying water, and all of the abovementioned heavy metals exceeded the standards to different degrees. Among them, As had the highest pollution level, with a concentration of 134.26 μg/L or 13.4 times higher than the WHO guideline and Mongolian surface water quality standard, and cannot even reach Class V water quality requirements of China. Liu. (2017) found that Pb and Zn were the main health risk factors in surface water of a lead–zinc mining area, while As was the element causing the highest carcinogenic risk, accounting for 86.4% of the total carcinogenic risk index of heavy metal pollutants in China.

The subgroup analysis and boxplots of the sediments showed that the concentrations of Cd, Cr, Cu, Fe, Hg, Mn, Ni, Pb, and Zn in the surface water sediments of the Mongolian Plateau were lower than the relevant standards of both China and Mongolia. However, the content of As in the sediments affected by three minerals, namely gold–silver, copper–molybdenum, and other polymetallic mines as well as lead–zinc mines, was 76.61, 11.37, and 6.41 mg/kg, respectively, which were higher than the Mongolian soil quality standards, and were 12.2, 11.4, and 1.1 times higher than the background value of soil environment in Inner Mongolia, respectively (Figure 6, Supplementary Figure S4).

4 Discussion

4.1 Cause analysis of heavy metal pollution in surface water of Mongolian Plateau

In general, numerous sources of heavy metal pollution exist in the surface waters of the Mongolian Plateau. The sources of heavy metals in rivers and lakes can mainly be divided into natural and anthropogenic sources; the differences in natural sources cause the variations observed in the environmental background values of heavy metals in different regions, while among the various anthropogenic sources industrial, agricultural, and transportation sources result in a high proportion of environmental heavy metal pollution (Vareda et al., 2019).

In recent years, the economy of the Mongolian Plateau region has been growing rapidly, and the demand for water resources has been increasing in urban and rural areas. Take Ulaanbaatar, the capital of Mongolia, as an example; its “mother river”, the Tuul River, is the “water for life” for the people of Ulaanbaatar; however, the construction of many business-related and residential buildings along the Tuul River have caused the amount of available surface water to decrease, while the quality of water is deteriorating and the amount of pollution in the water has seriously increased

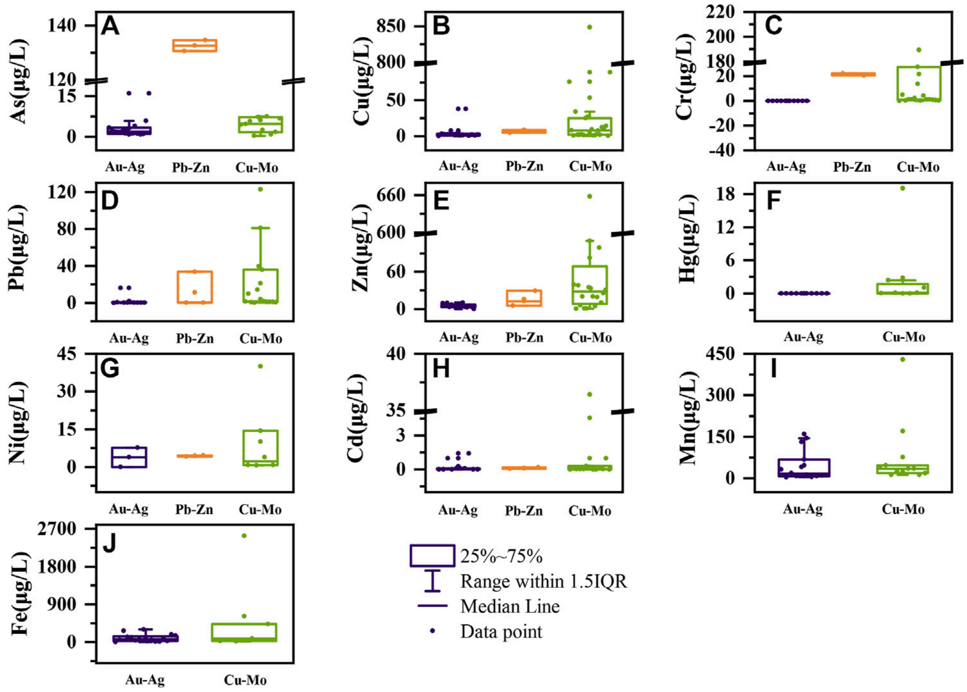

FIGURE 5
Mineral difference of heavy metal content in overlying surface water. Au–Ag, gold–silver mines; Pb–Zn, lead–zinc mines; Cu–Mo, copper–molybdenum mines and other polymetallic mines: **(A)** As; **(B)** Cu; **(C)** Cr; **(D)** Pb; **(E)** Zn; **(F)** Hg; **(G)** Ni; **(H)** Cd; **(I)** Mn; **(J)** Fe.

(Batsaikhan et al., 2018). At the same time, the agricultural and animal husbandry industry still occupies an important position in the economy of the Mongolian Plateau due to its solid development foundation and long history (Miao et al., 2021). In modern agricultural production, the irrational application of fertilizers and pesticides containing heavy metals and the generation of agricultural wastes can lead to heavy metal pollution in the environment (Alengebawy et al., 2021). The livestock and poultry industry is also an important aspect that cannot be ignored because heavy metal elements such as Zn, Cu, and As are widely used as feed additives to promote disease resistance or stimulate growth (Hejna et al., 2018). In addition, wastewater from anthropogenic sources such as non-ferrous metal mining, smelting, and other industrial production processes is one of the most important sources of heavy metal pollution. The Mongolian Plateau is rich in metal deposits and has excellent production potential; mining has gradually developed into a pillar industry in the region since the 1990s, but the resulting surface water pollution problem has become increasingly prominent. Studies have shown that the water quality of rivers in northern Mongolia deteriorated due to frequent mining activities and a tendency has been observed to further increase the concentration of toxic heavy metals in the downstream areas of open-pit mines (Myangan et al., 2017).

4.2 Country-specific differences in the analysis of heavy metal pollution in surface water of the Mongolian Plateau

The present study showed that the surface water of Mongolian Plateau was generally polluted to a certain extent by metal mining activities. The elements As, Cd, Pb, and Hg were more sensitive in responding to environmental conditions, which was consistent with the findings of related studies to a certain extent (Meybeck, 2013). However, significant differences in heavy metal concentrations also were observed for different sub-regions.

The surface waters of Inner Mongolia Autonomous Region had a relatively high content of heavy metal pollutants when compared with Mongolia, while the content of As, Cd, Hg, and Pb in the overlying waters was higher than the national or international standard values. The main reasons are as follows. 1) The environment of Inner Mongolia is fragile, and the ecologically fragile areas ranked above the moderate level of these pollutants accounted for 62.5% of the entire land area, among which the severely and extremely severely fragile areas accounted for 36.7%; this causes the region to be relatively vulnerable to the negative impacts of metal mining (People's Government of Inner Mongolia Autonomous Region of China, 2017). 2) The natural background concentrations of heavy metals in

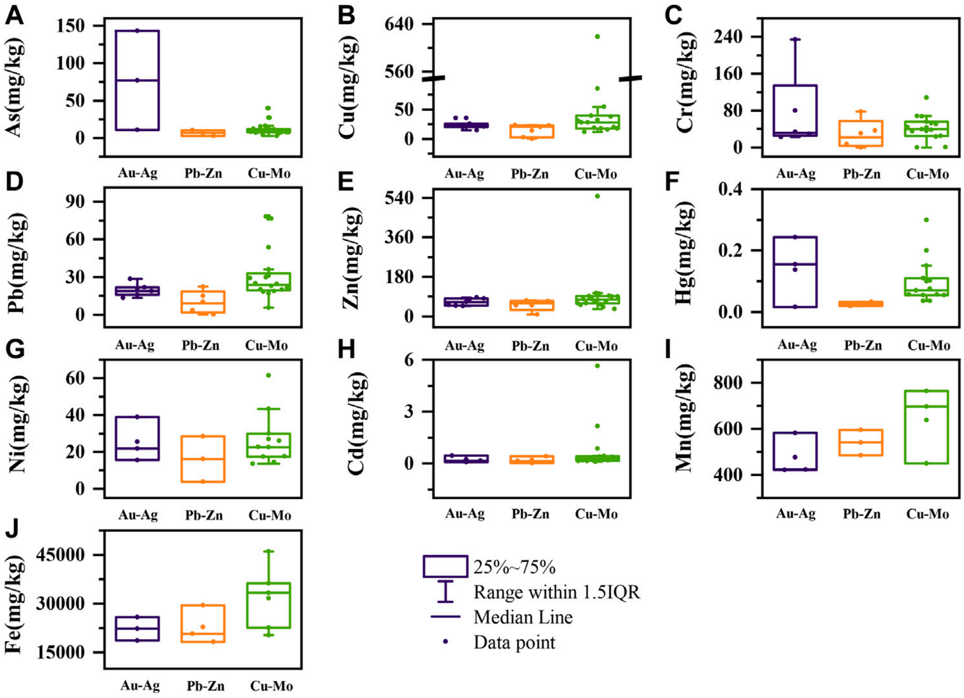

FIGURE 6
Mineral difference of heavy metal content in sediments of surface water. Au–Ag, gold–silver mines; Pb–Zn, lead–zinc mines; Cu–Mo, copper–molybdenum mines, and other polymetallic mines: **(A)** As; **(B)** Cu; **(C)** Cr; **(D)** Pb; **(E)** Zn; **(F)** Hg; **(G)** Ni; **(H)** Cd; **(I)** Mn; **(J)** Fe.

Mongolian rivers are low, and the concentrations of dissolved heavy metals in the middle and upper reaches are usually below detection limits (such as cadmium and lead) under conditions of no significant anthropogenic disturbance. This has led to low levels of heavy metals in overall surface water (Hofmann et al., 2010). 3) Inner Mongolia is rich in lead and zinc mineral resources, and the reserves of these two minerals rank first among the administrative regions of China. Meanwhile, Cd and As are often found together with zinc ore as well as lead and zinc ore, and so on. When mining, selecting, and smelting these ores, Cd and As will be discharged into the surrounding environment through waste gas, water, and other residues, resulting in the pollution of the surrounding environment by Cd and As [National Research Council (US), 1977; Thornton, 1986]. 4) Although Mongolia is rich in mineral resources, it has few professional teams that have been trained in geological exploration and mines tend to lack modern technology and equipment. As a result, geological exploration has been carried out only recently and the mineral resources have not been documented and developed on a large scale; the accumulation of heavy metal pollutants in the surrounding environment is low (Hugjilt, 2017).

4.3 Analysis of mineral species differences of heavy metal pollution in surface water of the Mongolian Plateau

The present study showed that significant differences exist in the effects of different types of metal mining on heavy metals in surface water of the Mongolian Plateau.

The mining of copper–molybdenum and other polymetallic mines caused the surface water to contain excessive levels of many heavy metals, which may have occurred because the copper extraction process in copper–molybdenum mines required large amounts of acid, and wastewater from mines was oxidized by interaction with water, air, and microorganisms to form acidic wastewater, which carried large amounts of heavy metal ions into surface water, causing water pollution and environmental risks (Oraby and Eksteen, 2014). Specifically, copper–molybdenum mining tended to release higher amounts of Cd and Pb (Ghazaryan et al., 2016) and thus the concentrations of Cu, Cd, and Pb in surface waters under copper–molybdenum mines and other polymetallic mines investigated in the present study significantly exceeded relevant international and national standards. As common heavy metal elements in the industry, levels of Fe, Cr, and Zn exceeded the standard, which was also related to the parent rock, natural weathering, and soil erosion

(Liu et al., 2019). Moreover, in areas with large polymetallic coeval deposits, the copper–molybdenum and other polymetallic mines had more associated elements, so the types and contents of heavy metals exceeding the standard in surface water increased accordingly. The concentrations of As and Cr in the overlying water affected by lead–zinc mines were too high as were those of Pb and Zn. At the same time, the content of As in the sediments of the three mineral species analyzed in the present study also exceeded the standard to varying degrees, mainly because As occurs in non-ferrous metal deposits and is an important element associated with metal ores. According to statistics, the associated arsenic ores accounted for more than 80% of the total reserves of arsenic ores in China (Zhang et al., 2017). Previous studies have proposed that the primary geochemical environment was the material basis for the distribution of heavy metal elemental content in water bodies in mining areas (Li et al., 2007). Lithological/geological Origin is closely related to metallic accumulation in water bodies (Yuksel et al., 2021; Yuksel et al., 2022). Because the Mongolian Plateau has been influenced by multiple phases of large-scale tectonic movements, intrusive rocks such as skarn were well developed; skarn is closely related to lead–zinc deposits. Studies showed that the distribution of lead–zinc deposits was basically consistent with that of skarn (Cai et al., 2021). The types and characteristics of pollutants in the surrounding environment created by lead–zinc mines were quite different depending on the topography, climate, as well as soil physical and chemical properties of the contaminated area (Feng et al., 2020). In addition to the primary geochemical background, the distribution of heavy metal elements in the water bodies of mining areas was also affected by a supergene geochemical role; with the processes of rock weathering, soil leaching, and surface runoff, heavy metal elements released by ore weathering were continuously leached into the water bodies, resulting in excessive heavy metal content in the water bodies (Li et al., 2007).

4.4 Assessment for publication bias

Funnel plots as well as Egger's and Begg's statistical tests were used to detect the publication bias and the effectiveness of other biases on the results of meta-analysis (Sterne and Harbord, 2004). Usually, effect size point estimates for studies with small sample sizes were scattered at the bottom of each funnel plot; with an increase in sample size, the effect size point estimates for studies gradually tended to be dense within a narrower range (Kossmeier et al., 2019). Funnel plot results of the present study are shown in Supplementary Figures S4, S5; the results of Egger's regression analysis are shown in Tables 3, 4. Funnel plot and Egger's regression analysis showed that the results of Cu, Cr, Zn, Hg, Ni, Cd, Mn, and Fe in overlying surface water were affected by publication bias ($p < 0.05$). The results of Cr, Zn, Hg, Ni, and Cd in surface water sediments were affected by publication bias ($p < 0.05$), and Egger's test could not be performed on Mn because the number of related studies was less than 10.

The main limitation of the present study was that the studies analyzed here included in the meta-analysis for studies that were sampled in different periods, so the heterogeneity in sampling time and space greatly affected the results of the meta-analysis. In addition, the different distances of water bodies from mining areas and the different impacts of agricultural production or other human activities on surface water in these studies might cause publication bias.

5 Conclusion

1) The sequence of content of heavy metals in the overlying water of the Mongolian Plateau was Fe > Mn > As > Zn > Cu > Pb > Cr > Ni > Cd > Hg, and the sequence of content of heavy metals in the sediment was Fe > Mn > Zn > Cr > Pb > Ni > Cu > As > Cd > Hg. In addition, As, Cr, Zn, Hg, Cd and Pb in overlying water exceeded relevant international and national standards to varying degrees. among which the contents of As and Pb were 1.4 and 1.3 times higher than the WHO guideline, and the contents of Cr, Pb, Hg, Cd were 1.5, 1.3, 25.4, 2.6 times Chinese environmental quality standards for surface water, and the contents of As, Pb, Zn, Hg were 1.4, 1.3, 4.7, 12.7 times Mongolian water quality standards, respectively. The content of As in sediments was 2.6 times the background value of soil environmental quality in Inner Mongolia.
2) The content of heavy metal pollutants in overlying water of the surface water in Inner Mongolia Autonomous Region was significantly higher than that in Mongolia. The contents of As, Cd, Cr, Cu, Hg, and Pb were higher than the relevant standards, among which the content of heavy metal pollutants in overlying water of the surface water in Inner Mongolia Autonomous Region was significantly higher than that in Mongolia. The contents of As, Cd, Cr, Cu, Hg, and Pb were higher than the relevant standards, and the content of As in sediments was 2.6 times the background value for soil environmental quality in Inner Mongolia.
3) The mining of copper–molybdenum and other polymetallic mines significantly increased the contents of Cd, Cr, Cu, Fe, Hg, Pb, and Zn in the overlying water, and the mining of lead–zinc mines significantly increased the contents of As, Cr, Pb, and Zn in the overlying water. However, the mining of gold–silver, lead–zinc, copper–molybdenum, and other polymetallic mines all significantly affected the concentration of As in the sediments, and the content of As in the sediments affected by three minerals, namely gold–silver, copper–molybdenum, and other polymetallic mines as well as lead–zinc mines, was 76.61, 11.37, and 6.41 mg/kg, respectively, which were higher than the Mongolian soil quality standards.
4) Compared with previous studies on heavy metals in the surface water of a single and a few mining areas, the

present study could provide more effective decision support for the prevention and control of surface water pollution and environmental quality protection in metal mining areas on the Mongolian Plateau.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding authors.

Author contributions

LM conceptualized and designed the study, collected and organized the data, and drafted the initial manuscript. HL collected and organized the data, reviewed the included articles, and conducted the analyses. YL, RZ, ZX and WQ collected and organized the data and reviewed the included articles. XK, XC and LW conceptualized and designed the study and critically reviewed and revised the manuscript. JJ and LW conceptualized and designed the study, coordinated and supervised data collection, and critically reviewed and revised the manuscript. All authors read and approved the final manuscript.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenvs.2022.1048500/full#supplementary-material

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