



XIAOFU CHEN¹, XUEXIAN LI², PAN WU³, XUEFANG ZHA⁴,
YABIN LIU⁵, TAO WEI⁶, WENRUI RAN⁷

The development and utilization of bauxite resources in the Guizhou Province and relevant challenges to the ecology and the environment

Introduction

Guizhou bauxite resources play an important role in national economic development due to their excellent quality and abundant associated elements (gallium (Ga) and lithium (Li)).

✉ Corresponding Author: Pan Wu; e-mail: pwu@gzu.edu.cn

¹ College of Resources and Environmental Engineering, Guizhou University;

Natural Resources Survey and Planning Institute; Guiyang, China; e-mail: idchenxiaofu@163.com

² Key Laboratory of Karst Georesources and Environment, Ministry of Education, Guiyang, China;
e-mail: 512891037@qq.com

³ College of Resources and Environmental Engineering, Guizhou University;
Key Laboratory of Karst Georesources and Environment, Ministry of Education; Guiyang, China;
ORCID iD: 0000-0003-1083-3025; e-mail: pwu@gzu.edu.cn

⁴ Key Laboratory of Karst Georesources and Environment, Ministry of Education, Guiyang, China;
e-mail: 229856969@qq.com

⁵ Natural Resources Survey and Planning Institute, Guiyang, China; e-mail: 278528643@qq.com

⁶ Natural Resources Survey and Planning Institute, Guiyang, China; e-mail: 180018200@qq.com

⁷ Natural Resources Survey and Planning Institute, Guiyang, China; e-mail: 66636662@qq.com



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China is a country with rich bauxite resources. With the acceleration of industrialization, urbanization, agricultural modernization and the continuous development of intelligent vehicles and new energy vehicles, the demand for bauxite resources is increasing (Miao et al. 2011). Bauxite is the main ore raw material for the production of metallic aluminum (Zhang et al. 2018; Zhang et al. 2017) and is widely used in construction, transportation, electric power, machinery manufacturing, and other industries (Shan 2011; Sun et al. 2015; Wang et al. 2001). Its application is extensive, second only to steel (Kochian et al. 2004; Nayak 2002).

Guizhou is one province in China with abundant bauxite resources. The area has mainly developed paleoweathered crust sedimentary bauxite deposits, which are often associated with a variety of key metal elements, such as Ga, Li, rare earth elements (REEs), and scandium (Sc) (Ling et al. 2015; Cui et al. 2014; Jin et al. 2015; Lei et al. 2013; Liu 1999). The bauxite deposits in central Guizhou were discovered in 1941 and were first developed and used in the early 1950s. Central Guizhou was the first region in Guizhou to develop and use bauxite. Although bauxite plays an important role in the development of the national economy, environmental problems caused by the development and use of bauxite resources are gradually emerging, such as mining-induced problems (including the destruction of local soil and vegetation, dust pollution, and groundwater level decrease) and tailings accumulation-induced problems (including land resource occupation and the destruction and pollution of soil and water bodies). Bauxite utilization mainly refers to the process of using bauxite as the raw material to produce primary aluminum, which includes five steps: bauxite mining, alumina smelting, anode manufacturing, primary aluminum electrolysis, and primary aluminum ingot production (Chen et al. 2008). Unfortunately, bauxite mining and processing can affect surface and groundwater systems and can rapidly destroy landforms and vegetation (Clark et al. 2015), causing irreversible damage to the environment.

Therefore, by analyzing the distribution and development, and the utilization of bauxite resources in Guizhou Province, this paper discusses the characteristics of bauxite deposits in Guizhou and the corresponding ecological and environmental risks associated with the development and the use of these resources. Additionally, this paper proposes countermeasures and suggestions for the sustainable exploitation of bauxite resources to promote the green and sustainable development of the bauxite mining industry and lay an important foundation for ensuring a high-quality mining industry in Guizhou Province.

1. Research method

The current study obtained information regarding mine locations which was collected from the National Mineral Exploration and Mining Information Publicity System, Guizhou Province Cloud Platform, government websites, and technical reports. The adjacent analysis and Kernel Density method in ArcGIS10.2 analyzed the bauxite-mine spatial distribution. We then compared the satellite imagery of the bauxite mine with the field investigation (especially the landscape change).

Satellite imagery of bauxite mines and red mud storage yards can be obtained from Google Earth. Information regarding the environmental risk of bauxite mines was obtained from published journal articles, research reports, government documents, standard specifications, and field investigations.

2. Characteristics of bauxite resources in Guizhou

2.1. Reserves and distribution characteristics of bauxite resources in Guizhou

The bauxite deposits in Guizhou are mainly distributed in the Qingzhen-Xiuwen area and the Wuchuan-Zheng'an-Daozhen area in the city of Zunyi, followed by southern

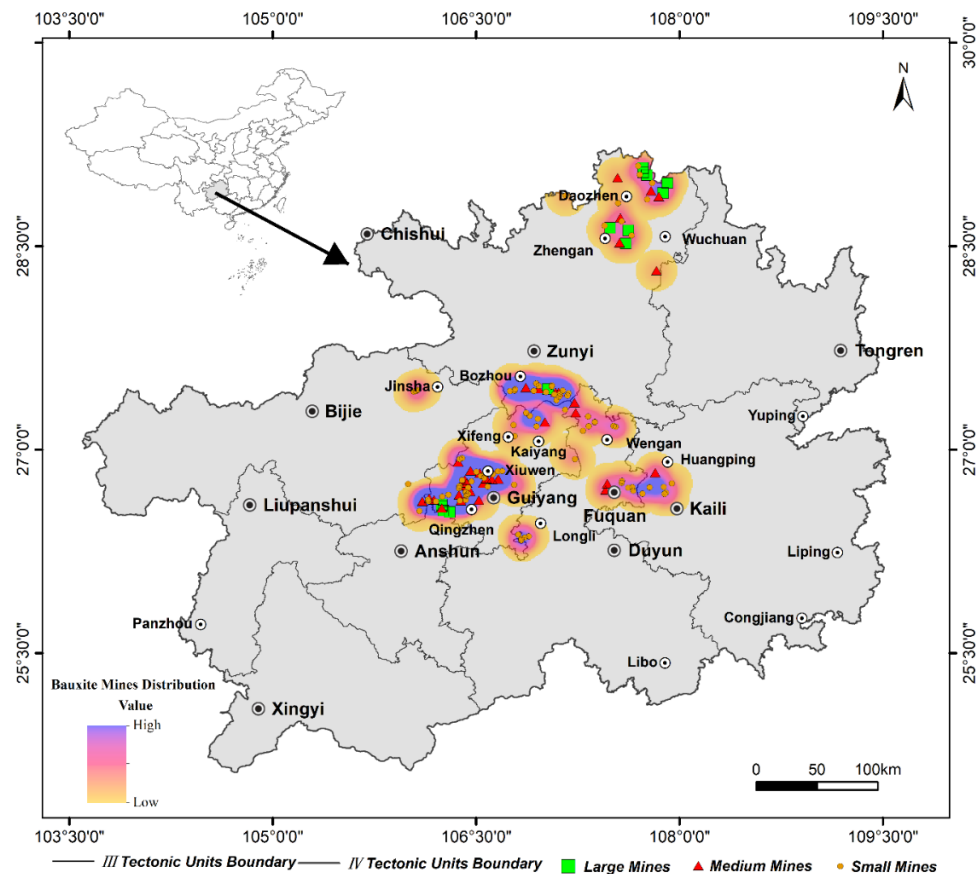


Fig. 1. The distribution of Bauxite resources in Guizhou Province

Rys. 1. Rozmieszczenie zasobów boksytu w prowincji Guizhou

Zunyi-Kaiyang-northern Xifeng, and the Kaili-Huangping area in the Qiandongnan Prefecture (Liu 1999; Liu 1994; Liu et al. 2016) (Figure 1). The mineralization age gradually changes from new to old from north to south. The belt-shaped ore concentration areas are generally EW-trending and NNE-trending and are commonly close to the distribution areas of carbonatite and claystone (Li et al. 2014). In 2020, China's identified reserves of bauxite were 576 million tons. Guizhou's reserves of bauxite were 91 million tons, ranking third and accounting for 15.80% of the total bauxite reserves in China. Guizhou has 136 identified bauxite deposits, and 60% of them are small-scale deposits, accounting for only 15.2% of the total bauxite reserves in Guizhou. Large-scale deposits account for 58.3% of the total bauxite reserves in Guizhou (Figure 2). The bauxite resources in Guiyang and Zunyi together

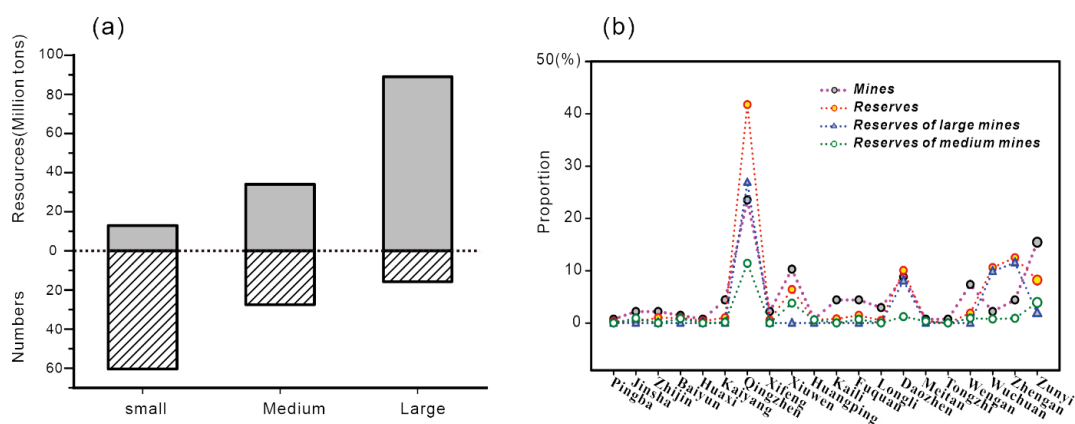


Fig. 2. (a) Bauxite resources and mines scale distribution in Guizhou Province,
(b) Bauxite scale and reserve ratio in each administrative region of Guizhou Province

Rys. 2. (a) Rozmieszczenie skali zasobów boksytu i kopalń w prowincji Guizhou,
(b) Skala i wskaźnik rezerw boksytu w każdym regionie administracyjnym prowincji Guizhou

Table 1. Bauxite resources distribution in Guizhou Province (Million tons)

Tabela 1. Dystrybucja zasobów boksytu w prowincji Guizhou (mln ton)

Area	Reserves	Resource	Resource reserves	The proportion of reserves in China
Guiyang	58.00	549.38	607.38	10.1%
Zunyi	27.27	507.73	534.99	4.7%
Anshun	0.20	1.51	1.71	0.0%
Bijie	2.24	15.25	17.50	0.4%
Qiandongnan	1.14	17.92	19.06	0.2%
Qiannan	2.19	47.21	49.41	0.4%
Total	91.05	1,139.00	1,230.05	15.8%

account for 93.15% of the total in Guizhou Province (51.28% and 41.87%, respectively). The resources in Qingzhen city and Zheng'an County account for 41.75% and 12.5% of the total bauxite resources of the province, respectively (shown in Table. 1 and Figure 2).

2.2. Characteristics of Guizhou bauxite deposits

The karst-type bauxites are the dominant type of deposits in Guizhou province (Ling et al. 2015; Luo et al. 2022; Xiao et al. 2021; Zhou and Liu 2016). The orebody of bauxite in the Qingzhen–Xiuwen region is located in the Lower Carboniferous Jiujialu Formation, which displays unconformable contacts with overlying and underlying lithologies, and the underlying lithologies are the Cambrian dolomite (Ling et al. 2015; Luo et al. 2022). There are three sections of the bauxite horizon that have a typical carbonaceous shale-bauxite-iron rock structure from the upper to the lower section e (Ling et al. 2015; Wang et al. 2018a; Yang et al. 2018). In Huangping-Kaili regions, bauxite was found in the Lower Permian Liangshan formation, overlying the dolomite of the undulatory Devonian Gaopochang formation, and the Ore-bearing rock series has a “coal-bauxite-iron” structure (Wang et al. 2018a; Zhang et al. 2012). And the ore-bearing horizon is the Middle Permian Liangshan formation which shows unconformable contact with underlying lithologies that the middle-lower Silurian Hanjiadian formation shale or Upper Carboniferous Huanglong formation, and display a shale-bauxite-iron rock structure in the Wuchuan-Zheng'an-Daozhen region (Jin et al. 2009; Lei et al. 2013; Zhou and Liu 2016). Furthermore, the diaspore, illite, anatase, chlorite, and kaolinite are the mineral assemblages of the Carboniferous bauxite in Guizhou Province, while diaspore, anatase, illite, chlorite, and kaolinite are found in the Permian bauxite (Ling et al. 2015; Wang et al. 2018a; Jin et al. 2009; Liu et al. 2019). These bauxite have an average grade of 56.5~67.3% (Wang et al. 2018a).

The bauxite ore-bearing rock series in each ore concentration area in Guizhou has a burial depth of 0–1500 m, and the bauxite ores have basically the same mineral composition; however, the proportion of each component varies between mining areas. The mineral composition of bauxite deposits in the Guizhou Province is dominated by diaspore, with small amounts of gibbsite, boehmite and other minerals, as well as clay-, iron- (Fe), titanium- (Ti), and carbonate-based minerals (Jin et al. 2015; Liu 1994; Xiang 2014). A variety of valuable elements are associated with bauxite, including Ga, Sc, nickel (Ni), Li, and REEs, which have certain potential utilization values. The types of associated valuable elements vary between bauxite deposits formed in different ore belts and different mineralization ages, with contents also differing within the same mining area (Liu 1994; Xiang 2014). For instance, bauxite deposits in the Xiuwen area have high contents of zirconium (Zr), strontium (Sr), and barium (Ba) but low contents of Ga, chromium (Cr), Li, niobium (Nb), and tantalum (Ta). Bauxite deposits in the Xifeng area have high contents of Ga, Nb, and Ta but low contents of Sr and Ba. Bauxite deposits in the Zunyi area have a low content of Zr and contents of other elements in between those of bauxite in the Xiuwen and Xifeng areas. Moreover, bauxite

deposits in the Daozhen area have a high content of Li and thus high potential economic value. Among the low-iron and low-sulfur bauxite deposits in various ore belts, ΣREEs are highest in the Xiuwen ore belt and lowest in the Zheng'an ore belt. Early Carboniferous bauxite is characterized by high contents of Cr, Li, and Nb and high ratios of $\Sigma\text{Sm-Ho}/\Sigma\text{REE}$, $\Sigma\text{Er-Y}/\Sigma\text{REE}$, and samarium (Sm)/neodymium (Nd). These differences are mainly related to the formation environment, mineralization source, weathering, and sedimentary differentiation of the aluminum-bearing rock series (Jin et al. 2015; Liu et al. 2019).

3. Environmental problems during the development and utilization of bauxite deposits in Guizhou

3.1. Environmental issues in the mining process

With the development of the economy and society and the acceleration of industrialization and intelligent industries, the demand for mineral resources in various industries has also increased. However, the contradiction between the development and utilization of mineral resources and environmental health has become increasingly prominent, and bauxite mining is no exception (Clark et al. 2015). Bauxite mining in China is mostly based on open-pit mining (Feng et al. 2016; Peng et al. 2007). This mining method has a large impact on the environment, and in particular, it irreversibly affects the surface landscape. In recent years, the negative impact of bauxite mining on the environment has been continuously reported worldwide. For example, bauxite mining in western, southern, and eastern India has caused the destruction of landforms, dust pollution, loss of vegetation, reduction of forest area, loss of biodiversity, decline in groundwater level, water pollution, creation of wasteland, adverse social impacts, etc. (Lad and Samant 2015; Rao et al. 2016; Sijinkumar et al. 2014). Malaysia has also reported the negative impact of bauxite mining activities on the environment, social psychology, and occupational health (Hussain et al. 2016; Lee et al. 2017).

3.1.1. Destruction of the landscape during the mining process

There are eighty-three mines with bauxite mining rights in Guizhou Province, including three large-scale mines, ten medium-sized mines, and sixty-seven small-scale mines. The soil cover must be removed by heavy machinery before open-pit mining, which directly impacts the natural environment, resulting in soil erosion, vegetation destruction, large scale landscape changes, and slow crop growth.

Google Earth satellite images of the mining area of a bauxite mine in Xiuwen County, Guizhou Province, from 2009 and 2018 were compared. The results show that bauxite mining has significantly increased the destruction of landforms in the past nine years (Figure 3a–b). The mining activities of the bauxite mine only caused limited damage to the

surface environment in 2009 (Figure 3a). However, in 2018, the surface environment in this region was damaged on a large scale, with land degradation and a sharp decline in vegetation (Figure 3b). The area of occupied or destructed land resources in 2018 was three- to five-fold that in 2009. The actual survey also confirmed the adverse impact of mining activities on the environment.

The waste rocks discharged from the stope, mine industrial land, mine road construction, and mining process directly destroy or occupy the land (Figure 3c–d). In addition, mine dumps are likely to cause mine geological disasters, such as landslides and debris flow. Bauxite mining has destroyed the natural resources and landscape in the Qingzhen-Xiuwen area, causing geological disasters. The occupied and destroyed land resources due to bauxite mining included mining sites, tailings depositories, dumps and smelters, and areas damaged by mining-induced geological disasters, totaling approximately 20.08 km².

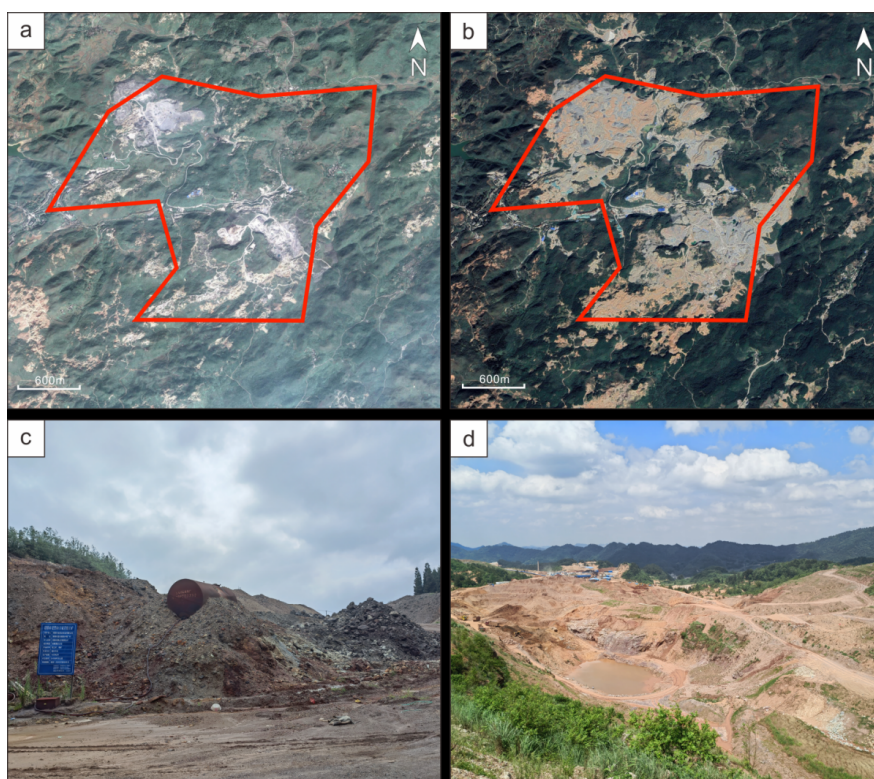


Fig. 3. Mine environment status of Guizhou Bauxite in southern of China.

The Satellite image were taken from Google Earth

- a – Satellite image of A bauxite mine in Xiuwen County, Guizhou province in 2009;
- b – satellite image of bauxite Mine in Xiuwen County, Guizhou province in 2018;
- c – Destruction and occupation of land caused by bauxite waste storage in Liwo area, Qingzhen County;
- d – Open-pit mining resulted in mountain gullies in Maige area of Qingzhen County

Rys. 3. Stan środowiska kopalni boksytu z Guizhou na południu Chin.

Zdjęcie satelitarne zostało pobrane z Google Earth

In terms of dust and aerosol emissions, the global extent of the affected area and the toxic elements present, mining operations are one of the most notable anthropogenic activities (Csavina et al. 2012; Entwistle et al. 2019). Mining activities with heavy machinery, wind transported mineral dust from mines and tailings as well as debris from uncovered trucks are the main sources of the road dust pollution in mining areas; similar risks have been reported in other regions in previous studies (Lad and Samant 2012; Tian et al. 2019). A great deal of dust from the mine and along the transport road is attached to the leaves of plants, inhibiting photosynthesis and triggering a decrease in plant growth, which ultimately results in the death of plants (Lad and Samant 2012). Previous research suggested that the road dust was extreme pollution with the inclusion of Ce, As, Cd, and Mo in mining areas and more than 50% of road dust pollution originates from mines. the inhalation of potentially toxic elements in road dust led to health risks for both adults and children (Tian et al. 2019). To prevent dust pollution, government authorities require enterprises to implement dust removal and dust suppression measures on roads and mining areas, but the effect is unsatisfactory, especially in sunny weather, when dust pollution is more severe.

The soil in some sections of the Qingzhen-Xiuwen area was also polluted due to mining activities, mainly by F^- and As^{2+} pollution, with varying degrees of SO_4^{2-} , Cl^- , HCO_3^- , Al^{3+} , and Fe pollution. In Guangxi Province, the mercury (Hg), cadmium (Cd), Cr, lead (Pb), arsenic (As), and aluminum (Al) contents of the reclaimed soil in the goaf area of bauxite mines exceeded the soil background values in Guangxi, and the Cd pollution was the most severe, followed by As pollution (Cui et al. 2021). In addition, in acidic or waterlogged soils, manganese (Mn) is easily released from the soil, causing the manganese poisoning of crops (Denise et al. 2016). Bauxite mining causes lengthy exposure and oxidization of rocks (ore) with sulfur-containing iron ore. Atmospheric precipitation leaches waste soil and rocks to form an acidic environment in which Mn in soil and rock is further oxidized and then flows into the low-lying areas of the mining area, causing Mn pollution.

3.1.2. The impact of mining activities on the water environment

The pits formed by open-pit mining activities may cut through several aquifers and aquicludes. In addition, mining activities cause the strata to break, leading to the development of rock fissures, which may break the regional groundwater balance and change the natural flow field, recharge, runoff and the discharge of groundwater (Yang et al. 2008), causing wastewater containing toxic and harmful elements to enter the groundwater system or causing groundwater leakage and the decline of the groundwater level. In this study, we investigated ten bauxite mining areas in the Qingzhen-Xiuwen area and found that springs or streams and small rivers passed by almost all areas within 10 km of the surveyed mining area (shown in Table 2). Many harmful pollutants in the open-pit mining area are washed and transported by rainwater, and some even flow into nearby rivers, polluting the soil and water bodies along the surface run off with heavy metals or other harmful elements.

Table 2. Reservoir and river in the 10 km radius border from the bauxite mine

Tabela 2. Zbiornik i rzeka w promieniu 10 km granicy od kopalni boksytu

Name of the mining site	Name of the reservoir and river within 10 km radius border	The nearest distance to an adjacent reservoir and river
Yanlong-Lindai	Anliu River (W); Yinyan Reservoir (E)	The shortest distance to the Anliu River is 4 km, and it is close to the Yingyan Reservoir
Changchonghe	Baihuahu Reservoir (Se)	Within 5 km distance
The first Bauxite	Xiuwen River (N); Wangguan Reservoir (W); Gelaozhai Reservoir(E)	The distance to the Xiuwen River is 3 km, and the Wangguan Reservoir and Gelaozhai Reservoir are within 2 km
213 Bauxite	Qingshui River (W); Qingshuihe Reservoir(W)	Adjacent to Qingshuihe Reservoir, and the distance to the Qingshui River is 3 km
Xianrenyan Bauxite	Wujiang River (S); Longyan Reservoir (NE)	Within a distance of 3 km
Wachangping Bauxite	Changxi (SE) and Furong River (NW)	The distance to Furong River and Changxi River is 10 km and 5 km, respectively.
Maochang Bauxite	Sancha River (W); Yinzidu Reservoir (W)	The distance to the Sancha River and the Yinzidu Reservoir is less than 4 km.
Dazhuyuan Bauxite	Changxi (NE) and Furong River (NW); Sanhuixi Reservoir	Within 2 km
Hualu Bauxite	Maotiao River (SE)	Within 300 m

The groundwater and surface water in some sections of the Qingzhen-Xiuwen area may be polluted by bauxite mining activities, affecting the areas near the calcining and smelting sites (Yin et al. 2010). Analysis of the groundwater quality shows that the pH range of the groundwater near the bauxite mining area in the Qingzhen-Xiuwen area was 6.65–8.00, with an average of 7.24, and the coefficient of variation was small. The surface water had similar characteristics and was overall neutral or weakly alkaline, but the surface water was strongly alkaline at a few abnormal points, with a pH of 14 (shown in Table 3). The concentrations of Cl^- , SO_4^{2-} , and HCO_3^- in groundwater followed the order of $\text{HCO}_3^- > \text{SO}_4^{2-} > \text{Cl}^-$, and the concentrations of Cl^- , SO_4^{2-} , and HCO_3^- in surface water followed the order of $\text{SO}_4^{2-} > \text{HCO}_3^- > \text{Cl}^-$. The sum of the HCO_3^- and SO_4^{2-} contents accounted for more than 90% of the total amount of anions, so HCO_3^- and SO_4^{2-} were the main anions in groundwater and surface water in this area. In addition, the coefficient of variation of the SO_4^{2-} content was relatively large, which may be related to the distribution pattern of bauxite mines. The ternary diagram of Cl^- , SO_4^{2-} , and HCO_3^- shows that the distribution of anions was relatively concentrated (Figure 3a), indicating that the chemical types of anions in the groundwater and surface water were relatively consistent, with HCO_3^- and $\text{HCO}_3^- \cdot \text{SO}_4^{2-}$ as the main types. The scatter plot of HCO_3^- and $\text{SO}_4^{2-} + \text{Cl}^-$ shows that most of the water points are

Table 3. Statistical characteristic values of water pollution components in Qingzhen-Xiuwen area (mg/L)

Tabela 3. Statystyczne wartości charakterystyczne składników zanieczyszczenia wody na obszarze Qingzhen-Xiuwen (mg/L)

Content		Al^{3+}	Si	As^{2+}	Cl^-	SO_4^{2-}	HCO_3^-	F^-	pH
Groundwater (39)	Minimum	0.110	0.920	0.001	0.500	6.870	55.190	0.050	6.650
	Maximum	0.590	5.970	0.004	19.140	817.800	437.550	0.300	8.000
	Average	0.253	2.517	0.001	3.230	64.670	199.857	0.136	7.237
	Standard	0.124	1.110	0.001	3.633	127.956	94.945	0.079	0.352
	Variation	0.488	0.441	0.569	1.125	1.979	0.475	0.586	0.049
Surface water (49)	Minimum	0.120	0.120	0.001	0.240	13.490	9.850	0.050	2.180
	Maximum	292.200	65.160	0.075	16.120	3,857.000	1,009.120	5.000	14.000
	Average	10.752	4.567	0.003	3.861	212.086	157.354	0.469	7.399
	Standard	46.745	10.858	0.011	3.248	586.115	140.823	0.936	1.492
	Variation	4.347	2.377	3.507	0.841	2.764	0.895	1.997	0.202

* The data in this table is obtained from the statistical analysis of the original data, which is cited from Yin et al. 2010.

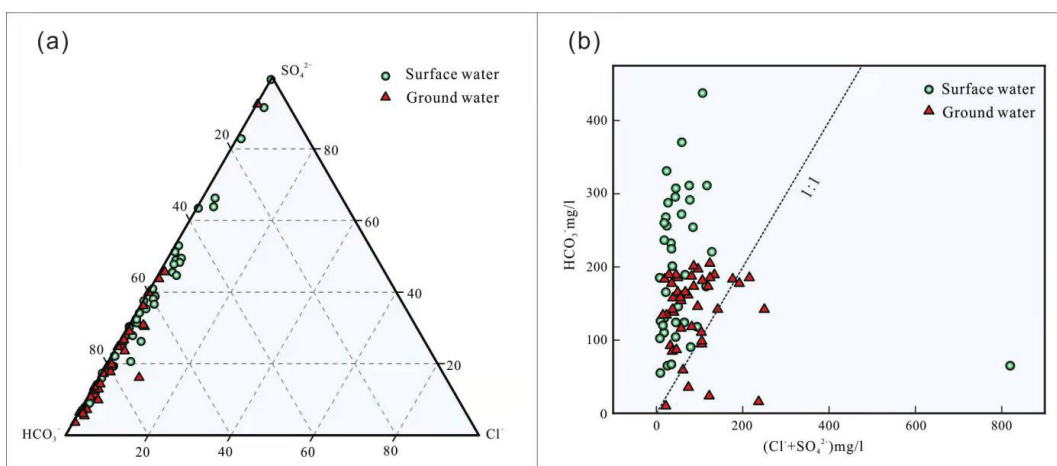


Fig. 4. Relationship diagram of water environment ions in Qingzhen-Xiuwen area. The data in this figure are obtained by the statistical analysis of the original data, which is cited from Yin et al. 2010. (a) Ternary diagram of HCO_3^- , Cl^- and SO_4^{2-} in water environment; (b) Illustration of the correlation between HCO_3^- and $(\text{Cl}^- + \text{SO}_4^{2-})$ in water environment

Rys. 4. Schemat zależności jonów środowiska wodnego w obszarze Qingzhen-Xiuwen

located above the 1:1 contour line, indicating that the main effect of the formation of water chemistry in this area is the dissolution of carbonates, and points below the 1:1 contour line may be related to the oxidation of sulfur-bearing minerals in high-sulfur bauxite (Figure 4b).

In addition, the highest concentrations of Al, As, and fluoride (F) in the surface water were 292.2 mg/l, 65.16 mg/l, and 5 mg/l, respectively. Among them, As and F exceed the limits of the Class V surface water quality criteria (0.1 mg/l and 1.5 mg/l, respectively); the Al concentration was three orders of magnitude higher than the Al limit of 0.5 mg/l in the Class V groundwater quality criteria. Although the concentrations of Al, As, and F in the groundwater changed slightly, they still exceeded the respective limits in some samples according to the groundwater quality classification, possibly because of bauxite mining activities.

3.1.3. Impact of waste rock and slag on the environment

In the process of bauxite mining, the removed gangues and waste rocks are transported to slag dumps around the mines, occupying and destroying many land resources. More seriously, most slag dumps do not have an underlying impervious membrane (Figure 3c). Hence, after long-term leaching by atmospheric precipitation, harmful elements, such as Cd, Cr, Sc, S, and Fe, in the waste rock and slag are infiltrated by the leaching water and pollute the soil and groundwater. Because almost no slag dumps are equipped with dust prevention facilities, the generated dust can easily pollute the atmospheric environment. The surrounding land is always covered by dust from the slag dumps, which not only wastes land resources but also pollutes the soil.

As a result of various forms of destruction of land, instance mining and occupation, giant patches of cropland and forest were cracked and reduced, and the impervious surface was dramatically increased. The landscape pattern of land use/cover was changing towards fragmentation, the results are similar to previous research (Qian et al. 2017; Xu et al. 2021; Zhang et al. 2020a). The land has lost 2 million hectares due to mining in China, and it is still growing at a rate of 25,000 hectares per year (Wang 2005). The coefficient of pollutant discharge ($10.235\text{m}^3/\text{t}$) which was issued by the Ministry of Ecology and Environment (MEEPRC 2021), Ministry of Finance and State Administration of Taxation, was calculated for the solid waste of bauxite mining; results indicate that 4.6 million tons of bauxite are produced in Guizhou province per year (DNRP 2020), whereas about 47 million cubic meters of solid waste are generated. This will lead to increased environmental risks and land cover pressure in mining areas, especially in karst areas with a fragile environment in Guizhou Province.

Moreover, the main pollution indicators of the 72 samples of waste slag and waste residue leachate at the Qingzhen-Xiuwen smelting site showed that the pH of the leachates varied from 5.23 to 10.35, with an average of 7.72 (shown in Table 4), indicating that the leachates were weakly acidic to alkaline. The contents of Al, Fe (Fe^{2+} , Fe^{3+}), and F^- in the leachate reached 25.47 mg/l, 4.20 mg/l, and 20.00 mg/l, respectively, indicating that leachates

Table 4. Statistical characteristic values of leaching solution of bauxite slag and waste residue in Qingzhen-Xiuwen area (mg/L)

Tabela 4. Statystyczne wartości charakterystyczne roztworu ługującego żużel boksytowy i pozostałości odpadów na obszarze Qingzhen-Xiuwen (mg/L)

Content	Al	Fe	As	F-	pH
Minimum	0.010	0.007	0.001	0.100	5.230
Maximum	25.470	4.200	0.412	20.000	10.350
Average	1.709	0.273	0.040	1.526	7.724
Standard	4.070	0.846	0.075	2.575	1.146
Variation	2.382	3.103	1.848	1.687	0.148

* The data in this table is obtained from the statistical analysis of the original data, which is cited from [Yin et al. 2010](#).

formed by atmospheric precipitation leaching smelting waste slags and waste residues piled up at the smelting site were very likely to pollute the geological environment, such as the soil environment and the groundwater environment at the dumpsite and in the surrounding area.

3.2. Environmental problems in the use of bauxite

The impacts of bauxite use on the environment are mainly the smelting process and the comprehensive use of resources, including the impacts of emissions, red mud, and the comprehensive utilization on the environment. Red mud has the greatest impact on the environment.

3.2.1. The impact of gas emissions on the environment

Alumina and electrolytic aluminum production processes involve exhaust-gas emissions. Specifically, the main exhaust gas in the alumina production process is the flue gas generated during aluminum hydroxide calcination and the exhaust steam generated in each storage tank during the production process of the dissolution devices ([Xing 2020](#)), mainly including solid and gaseous fluoride, as well as other pollutants, such as CO, CO₂, and SO₂. ([Wu et al. 2010](#)) noted that CO₂ and perfluorocarbons (PFC, CF₄, and C₂F₆) are the main greenhouse gases emitted by the primary aluminum industry and that 1.7–2.8 tons of greenhouse gases are emitted for the production of every 1 ton of primary aluminum ingots in China. Greenhouse gas emissions are highest in the primary aluminum electrolysis step of the primary aluminum industrial process, accounting for 82.7% of total emissions ([Wu et al. 2010](#)).

On the basis of this estimate, the 1.3558 million ton output of electrolytic aluminum in Guizhou in 2020 corresponded to approximately 2.3–3.8 million tons of greenhouse-gas emissions.

3.2.2. The impact of red mud on the environment

Red mud is a strongly alkaline solid waste discharged from the industrial production of alumina. This waste has a high salt content and is difficult use as a resource. The main components of red mud include Fe_2O_3 , Al_2O_3 , SiO_2 , CaO , Na_2O , and TiO_2 (Gräfe et al. 2011; Hind et al. 1999; Kong et al. 2017). It also contains small amounts of As, Cr, Cd, Hg, Pb, and vanadium (V), as well as Sr, thorium (Th), and uranium (U) (Liu and Li 2015). The high alkalinity and salinity of red mud have the greatest impact on water quality. After the dam failure of the Ajka red mud depository in western Hungary, the As, copper (Cu), Cr, Ni, and V concentrations in the Marcal Basin with an area of 3076 km² increased significantly, and high alkalinity was observed in water samples collected within 2 km of the source area (Mayes et al. 2011; Nagy et al. 2013). The high pH, high Na^+ levels, soluble V, and high concentration of Al in red mud have inhibitory and toxic effects on the growth and genetics of organisms, resulting in an ion-concentration imbalance in organisms, the growth inhibition of organisms, and a reduction in biological diversity (Mišík et al. 2014; Ruyters et al. 2011; Winkler 2014). In addition, the dust generated by bauxite mining and utilization pollutes the air, threatening the physical and mental health of residents (Gelencsér et al. 2011; Hussain et al. 2016; Lee et al. 2017). In the southwestern karst region, because of the restriction of special geographical and geomorphic conditions, most of the typical bauxite tailing (red mud) depositories in Guizhou are located in relatively closed karst depressions (Figure 4a–d), while the karst valleys are often areas with relatively strong karst development. This situation not only leads to the occupation and damage of many land resources but also has a high risk for karst leakage pollution problems because if the anti-seepage measures are not handled properly, the As, Cr, high Na^+ , soluble V, and high Al concentrations in the high-pH red mud will enter the water-bearing systems through the karst channels and fractures (Ding et al. 1998a; Ding et al. 1992; Ding et al. 1998b). Due to a sudden accident in the Zhatang red mud depository in Guiyang, Guizhou Province, during the period of use, several leakages of wastewater occurred from the depository to the west of the depository area, which polluted the karst groundwater in the west (Ding et al. 1992).

The assessment of red mud and its impact on the environment have attracted widespread attention. (Dauvin 2010) reported the environmental impact of red mud discharged into the Cassidaigne Canyon in the Mediterranean Sea from alumina plants in the Marseilles area (Barasse and Gardanne) of France. The mixture of red mud rich in Fe, Ti, V, and Cr with sediments due to mechanical transport resulted in a decreased diversity of the foraminifera community (Fontanier et al. 2012), and the increased concentrations of Fe, Ti, Cr, V, and As in the marine area caused potential harm to deep-sea animals and the food chain. Because of the inflow of red mud, the deep-sea environment became turbid and hypoxic, and the benthic

community died of hypoxia or burial by muddy sediments (Bouchoucha et al. 2019; Dauvin 2010; Fontanier et al. 2012). Bauxite mining in the Bakhuis region of western Suriname in South America may also harm the diversity and abundance of small- and medium-sized mammals (Lim 2009). In the Cassidaigne Canyon area, although there was no definitive evidence that the contamination of fish species (especially by Al and a small amount of Ti and V) was caused by the red mud discharged from alumina refineries, fish near the alumina refineries contained relatively high levels of trace elements (Bouchoucha et al. 2019).

Press filtration and dry storage after dewatering are often used for red mud disposal (Xue et al. 2016). However, as the stock of red mud piles continues to increase, the risk of dam failure in the red mud depository is increased.

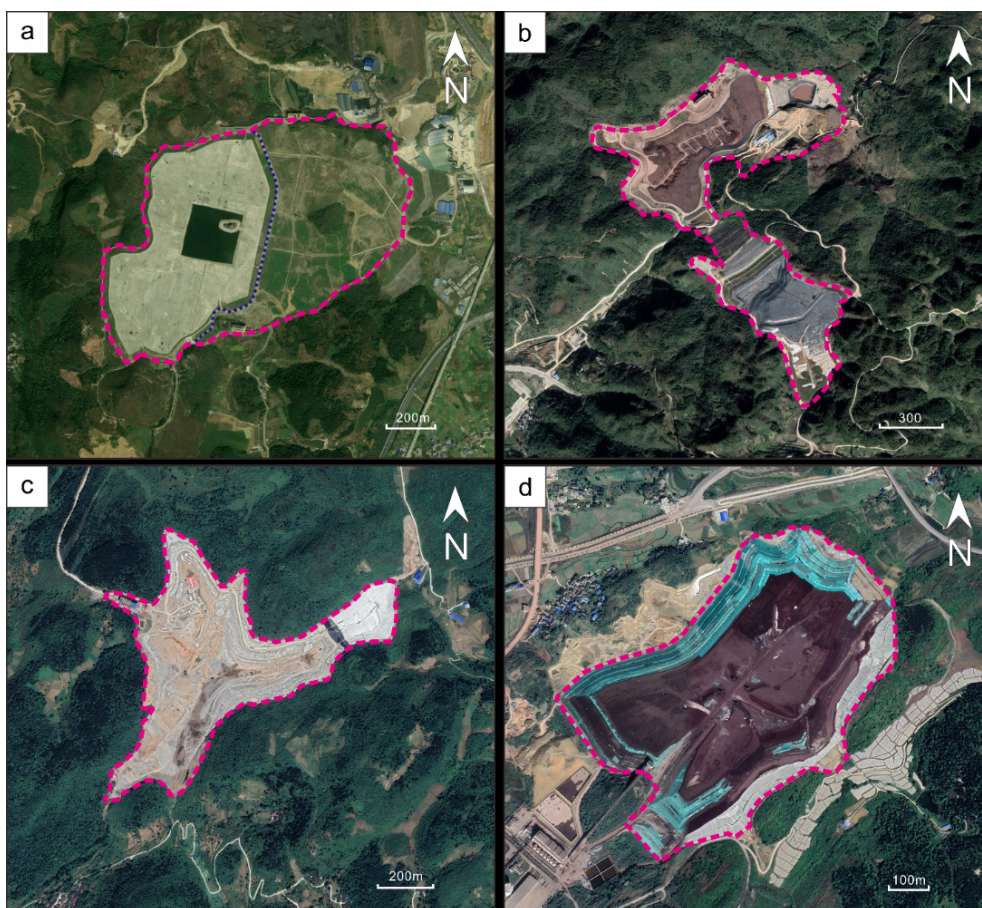


Fig. 5. The satellite image of the Current status of main red mud storage yards in Guizhou Province.

The Satellite image were taken from Google Earth

- a – Guiyang Caoguan Red Mud storage (March 2020); b – Qiya Red Mud Tailings Pond in Kaili (November 2020);
c – Red mud storage yard in Wuchuan-Zhengan-Daozhen (May 2019); d – Zunyi Shangji Red Mud Yard

Rys. 5. Zdjęcie satelitarne aktualnego stanu głównych składowisk czerwonego szlamu w prowincji Guizhou.
Zdjęcie satelitarne zostało pobrane z Google Earth

Taking Guizhou Province as an example, in 2020 alone, approximately 1.3 million tons of primary aluminum was produced. Based on an average production of 1.0–1.8 tons of red mud per ton of alumina produced, approximately 4.2–7.3 million tons of red mud was produced in Guizhou in 2020. According to the survey (Figure 5), the Caoguan red-mud depository in Guiyang, Guizhou Province, covers an area of 76 hm² and stores 2300×10⁴ m³ of red mud, and the maximum dam height is 79 m (Figure 5a). The Qiya red mud depository in Kaili, Guizhou Province, has an area of 100 hm², a designed storage capacity of 2655 m³, and a designed service life of 7.3 years (Figure 5b). The Wuchuan–Zheng’an–Daozhen red-mud depository in Guizhou has an area of 38 hm² (Figure 5c), a designed storage capacity of 821×10⁴ m³, and a designed service life of 9.73 years. The Dongneng red-mud depository in Zunyi, Guizhou Province, has an area of approximately 117 hm², a designed storage capacity of 2507×10⁴ m³, and a designed service life of 7 years. On the basis of this estimate, each red-mud depository occupies and destroys approximately 4–16 hm² of land per year. If corresponding measures are not taken to accelerate the use of red mud as a resource, more land will be needed to store more slag and red mud, which poses a challenge to the management policies of the land-management department and seriously threatens ecology and the environment.

3.2.3. Environmental problems of the comprehensive use of red mud

Most commonly, the comprehensive use of red mud is for building materials (Pontikes and Angelopoulos 2013). Red mud is rich in iron and aluminum compounds, β -dicalcium silicate, and amorphous aluminosilicate, which give it certain hydraulic and chemical solidification properties (Chen and Chen 2006; Liao et al. 2019; Liu et al. 2019). The addition of red mud in the production of concrete building materials is conducive to increasing the mechanical properties of the resulting materials (Hu et al. 2018; Panwar and Chauhan 2018; Tang et al. 2018; Toniolo et al. 2018). Moreover, the addition of red mud in the ceramic process can optimize the performance of ceramics (Zong et al. 2018; Wei et al. 2019). Red mud contains a large amount of Fe, Al, Ti, and Na and relatively high concentrations of Sc, Th, and U, so the main metals and rare metals in red mud can be recovered. For example, iron can be extracted from red mud through high-gradient wet magnetic separation, smelting technology, and direct reduction technology (Borra et al. 2016; Marabini et al. 1998; Zhu et al. 2012; Guan 2000; Huang et al. 2009; Li et al. 2014), and 567 kg of 72% Fe₂O₃ and 57 kg of pure zinc can be recovered from 1 ton of red mud (containing 51.30% Fe₂O₃ and 13.29% ZnO) (Marabini et al. 1998). Calcification-carbonization and sintering methods are used to recover alumina from red mud (Wang et al. 2018b; Zhou et al. 2008). The recovery of Ti from red mud has also been extensively reported (Agatzini-Leonardou et al. 2008; Kasliwal and Sai 1999; Sun 2008; Zhang 2003; Zhu et al. 2015). In addition, the recovery of Sc, Sr, lanthanide, REEs, and radioactive elements from red mud has been reported (Ochsenkühn-Petropulu et al. 1996; Qu and Lian 2013; Sinha et al. 2014; Smirnov and Molchanova 1997; Wang et al. 2013; Xu et al. 2018). Red mud can be used as a soil remediation agent because

of its strong alkalinity, high concentrations of Fe, Al, Ti, and Ca oxides, small particle size, and large specific surface area (Klauber et al. 2011; Chen and Chen 2006; Xue et al. 2017). Because red mud can inhibit the mobility of As, Garau et al. achieved soil remediation by using this mud to fix As in contaminated subacidic soil (Garau et al. 2010).

The chemical composition of the red mud produced by different bauxite ores and different processes is different, and the route of utilization should also be different. The alkali bound in red mud has a certain dissolution equilibrium, and the complete removal of soluble alkaline substances is difficult. Therefore, the use of red mud as building materials is prone to cause secondary pollution, resulting in groundwater pollution (Yang and Xiao 2008). Additionally, its radioactivity risk is uncertain, so its radioactivity level must be detected during the preparation of building materials (Xue et al. 2017). The recovery of valuable metals in red mud also leads to the problem of secondary pollution. For example, the use of H_2SO_4 to leach lanthanum (La), Ti, and Sc in red mud generates much waste acid and waste residue (Agatzini-Leonardou et al. 2008; Sinha et al. 2014; Wang et al. 2013). More environmentally harmful materials are used as additives to recover REEs from red mud, which may cause secondary pollution and produce other toxic and harmful byproducts (Xue et al. 2017). A study has shown that *Acidianus manzaensis*-mediated iron-sulfur redox reactions drive the solution characteristics, main element morphological transformations, and phase changes during the high-efficiency release of Al and REEs in red mud. The study found that the two-stage (aerobic-anaerobic) bioleaching method is an economical and feasible way to efficiently recover aluminum and REEs from red mud (Zhang et al. 2020b). The toxic effects of a high pH, high Na^+ content, soluble V, and high concentration of Al in red mud inhibit the growth and genetics of organisms, which must be considered when using red mud as a soil remediation agent or in the preparation of other environmentally friendly functional materials.

Currently, the Guizhou Aluminum Industry Solid Waste Recycling Demonstration Project (which has not been put into operation) is planned to process 20,000 tons of aluminum ash, 10,000 tons of carbon dust in aluminum electrolysis, 10,000 tons of waste-tank lining in aluminum electrolysis, and 10,000 tons of waste cathodes in aluminum electrolysis per year to produce high-alumina materials, slag-modifier agents for steel refining, sodium aluminate, recycled cryolite, raw materials of cement, artificial graphite, high-purity electrolytes, and other products.

4. Management countermeasures and measures to reduce environmental impact

It is particularly important to formulate practical environmental governance and control systems or policies targeting the series of environmental problems caused by bauxite mining and use. The current environmental management policies mainly aim to prevent or reduce the damage or impact of mining activities on the environment and balance economic devel-

opment and the sustainable management of natural resources, rather than environmental governance (Hens and Boon 1999; Li et al. 2020; Tuokuu et al. 2018). Imperfect environmental governance and control systems have led to a lack of effective execution in actual environmental management or supervision, and the environmental management of mines is faced with problems such as difficulties in multi-departmental management and coordination and the existence of ambiguous management rights and responsibilities. Therefore, the need for changing the concept and improving the management system is very urgent.

The change of a development concept is a gradual process. Green mining has been recognized as one of the effective strategies; it is a modern type of mining model to reduce the impact associated with the extraction and processing of mineral resources on the environment (Badamfirooz et al. 2022; Ghose 2009; Heemskerk and Kooye 2003; Shi 2012). It comprehensively considers the environment, resource recovery, environmentally friendly mining techniques, employees, results of the company, and the emphasis is on reducing land degradation and mine reclamation (Huang et al. 2021; Pekka 2017; Ro et al. 2020). Currently, a few countries have implemented green mining initiatives, such as Canada, Finland, Iran and China, and the evaluation index of green mining is different in different countries. The Canadian government aims to reduce the amount of waste generated during mining as much as possible, restore the landscape, and maintain a healthy ecosystem by implementing green mining policies and new green mining techniques, namely, the green mining policies include mining area restoration, mine environmental evaluation systems, reducing pollutant emissions, innovation and continuous improvement in waste management, ecosystem risk management, and mine closures (Huang et al. 2021; Ro et al. 2020). To achieve sustainable development in mining, the Green Mining Plan of Finland was implemented in 2011 (Nurmi and Wiklund 2012). The content of the Green Mining Plan includes five themes: promoting materials and energy efficiency; ensuring the availability of mineral resources for the future needs; minimizing adverse environmental and social impacts; improving work and organizational practices, ensuring sustainable land use following mine closures (Huang et al. 2021; Pekka 2017).

Since 2017, the construction of ecological civilization in China has risen to an unprecedented level. The development of green mining and the construction of green mines, as important aspects and effective means for the construction of ecological civilization in the mining industry, have effectively maintained the balance between mining development and utilization and the environment have become an important direction for the future development of China's mining industry. In 2018, China formed a green mine standard system and subsequently issued the corresponding green mine evaluation indicators. From 2018 to 2019, Guizhou Province successively introduced provincial green exploration standards, green demonstration area requirements, and a green mine acceptance inspection evaluation system. The evaluation index of green mines includes six aspects: mining area environment; resource development mode; comprehensive utilization of resources; energy conservation and emission reduction; scientific and technological innovation and intelligent mine; enterprise management and corporate image (MNRPRC 2020; MNRPRC 2018). The score of

each index should not be less than 75% of the index score, and the score of total evaluation exceeding 80% of the total score is considered qualified (MNRPRC 2020). In 2020, there were twenty-nine provincial-level green mines of nonferrous metals in Guizhou Province, including seventeen bauxite mines. These bauxite mines were mainly distributed in the Qingzhen, Xiuwen, and Zunyi areas.

Some foreign scholars have proposed that voluntary agreement may be an effective tool for environmental governance in the mining industry (Li et al. 2020). This approach is similar to the establishment of the mine geological environment restoration fund system in China. The mining concessionaire implements environmental management according to the principle of meeting actual needs. However, some environmental sociologists believe that the only concern of investors is how to adjust the industrial structure to achieve more benefits, rather than environmental issues (Akabzaa and Darimani 2001; Li et al. 2020). Therefore, voluntary agreements used in foreign countries and China's environmental management system have proposed high requirements on the integrity of the construction of mining enterprises and challenged the supervision of government management agencies.

To achieve the sustainable use of bauxite resources and the development of green mining, these factors of the green mine should be comprehensively considered to reduce the impact of bauxite development and utilization on the environment. At the same time, effective regulations and policies are also important. For example, government departments must adopt policies to control, support, and guide the development and use of bauxite resources; the key technologies and applications for the industrialization and use of red mud must be researched and developed; and “determining production based on slag” forces enterprises to accelerate the use of slag and red mud as a resource.

Conclusion

The demand for bauxite in Guizhou is expected to continue to grow in the short to medium term, which will lead to an increase in the scale of bauxite mining in different areas of Guizhou, including the Wuchuan–Zheng'an–Daozhen area in northern Guizhou. Because of the many types and high concentrations of associated elements in bauxite and the high alkalinity, heavy metal components, and radioactive elements in red mud, the development and utilization of bauxite resources are associated with higher environmental risk. The government must strengthen macroscopic policy control, establish an enterprise credit responsibility system, and control the technical strength and statutory obligations of bauxite mining enterprises to reduce the adverse impact of the development and use of bauxite resources on the environment. In addition, the impact of bauxite mining on regional biodiversity, soil, air, surface water, and groundwater need to be evaluated. The research and development of the environmental restoration and management of bauxite mines and the technology for the use of red mud as a resource should be strengthened, especially with regard to research on large-scale, inexpensive, environmentally friendly application technology. These measures

are expected to promote the green and sustainable development of bauxite mining activities and meet future environmental requirements.

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DEVELOPMENT AND UTILIZATION OF BAUXITE RESOURCES IN GUIZHOU PROVINCE AND RELEVANT CHALLENGES TO THE ECOLOGY AND ENVIRONMENT

Key words

Guizhou, bauxite, development and utilization, ecological environment, countermeasures

Abstract

The environmental problems caused by the development and utilization of mineral resources have become important factors affecting ecological security. Guizhou is a Chinese province with relatively developed paleoweathered sedimentary bauxite deposits, abundant resource reserves, and a long history of mining. And, the demand for bauxite in Guizhou is expected to continue to grow. However, long-term or unreasonable resource development has produced a series of prominent environmental problems, such as the occupation and destruction of land resources and heavy metal pollution in soil and water bodies. Based on the existing research results in China and abroad, this paper analyzes the current situation, distribution characteristics, and development and utilization of bauxite resources in Guizhou to explain the corresponding environmental impacts. The results show that because of the many types and high concentrations of associated elements in bauxite and the high alkalinity, heavy metal components, and radioactive elements in red mud, the development and utilization of bauxite resources are associated with higher environmental risk. And more impact of bauxite mining on regional biodiversity, soil, air, surface water, and groundwater need to be evaluated. This paper also proposes coping strategies or countermeasures of environmental governance and control to achieve the green, sustainable and high-quality development of bauxite-related industries for meeting future environmental requirements.

ROZWÓJ I WYKORZYSTANIE ZASOBÓW BOKSYTU W PROWINCJI GUIZHOU ORAZ ISTOTNE WYZWANIA DLA EKOLOGII I ŚRODOWISKA

Słowa kluczowe

Guizhou, boksyt, rozwój i wykorzystanie, środowisko ekologiczne, środki zaradcze

Streszczenie

Problemy środowiskowe spowodowane zagospodarowaniem i wykorzystaniem surowców mineralnych stały się ważnymi czynnikami wpływającymi na bezpieczeństwo ekologiczne. Guizhou to chińska prowincja ze względnie rozwiniętymi osadowymi złożami boksytu, bogatymi rezerwami surowców i długą historią wydobywania. Oczekuje się, że popyt na boksyt w Guizhou będzie nadal rósł. Jednak długoterminowy lub nieracjonalny rozwój wykorzystania zasobów spowodował szereg znaczących problemów środowiskowych, takich jak: zajmowanie i niszczenie zasobów ziemi oraz zanieczyszczenie metalami ciężkimi gleby i zbiorników wodnych. W oparciu o istniejące wyniki badań w Chinach i za granicą, w artykule dokonano analizy obecnej sytuacji, charakterystyki dystrybucji oraz rozwoju i wykorzystania zasobów boksytu w Guizhou, w celu wyjaśnienia odpowiedniego wpływu na środowisko. Wyniki pokazują, że ze względu na wiele rodzajów i wysoką koncentrację towarzyszących pierwiastków w boksycie oraz wysoką alkaliczność, składniki metali ciężkich i pierwiastki radioaktywne w czerwonym szlamie, rozwój i wykorzystanie zasobów boksytu wiąże się z wyższym ryzykiem dla środowiska. Ponadto należy ocenić większy wpływ wydobywania boksytu na regionalną bioróżnorodność, glebę, powietrze, wody powierzchniowe i gruntowe. Niniejsza praca proponuje również strategię radzenia sobie lub środki zaradcze zarządzania i kontroli środowiska w celu osiągnięcia ekologicznego, zrównoważonego i wysokiej jakości rozwoju przemysłu związanego z boksytem dla spełnienia przyszłych wymagań środowiskowych.