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FOCUSED REVIEW

Comprehensive Application Technology of Bauxite Residue Treatment in the Ecological Environment: A Review

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Abstract
The emission of bauxite residue continues to grow with the increase of alumina production capacity, along with the large amounts of bauxite residue currently stored in stockpiles. The exposed problems of high yield, strong alkalinity, low comprehensive utilization rate, and threats to the ecological environment are becoming increasingly prominent. With the strict requirements of environmental protection, improving the comprehensive utilization rate of bauxite residue and bulk consumption of bauxite residue has become an urgent issue to be solved. A large number of researchers have conducted in-depth investigations into the application of bauxite residue over a wide range, and this paper summarizes its application in the environment in recent years, providing guidance for the high value and harmless application of bauxite residue, which can help reduce environmental pollution and human life and health hazards caused by bauxite residue.

Keywords Bauxite residue · Harmlessness · Comprehensive utilization · Environmental remediation

Introduction

Bauxite residue is the industrial solid waste discharged from the production of alumina by bauxite, which contains a certain amount of ferric oxide in a reddish-brown color, so it is also called “red mud”, and is a typical non-ferrous metallurgical solid waste (Wang et al. 2018; Xue et al. 2022). The varieties of bauxite residue depend on the grade of the bauxite and alumina production process. It can be classified as Bayer method bauxite residue (red mud), sintering method bauxite residue (red mud), and Bayer-sintering combination method bauxite residue (red mud) (Ke et al. 2021; Sutar et al. 2014). Currently, the Bayer process is responsible for more than 90% of the world’s alumina production, so Bayer bauxite residue accounts for more than 90% of all bauxite residue emissions (Lu et al. 2019; Zhang et al. 2020a). The Bayer process of alumina production involves bauxite reacting with NaOH solution under high temperature and pressure to obtain sodium aluminate solution, then adding $Al(OH)_3$ crystals to precipitate $Al(OH)_3$ solid and calcining to produce alumina products. The remaining alkali liquor is reused to treat the next batch of bauxite. The tailing obtained in this process is bauxite residue, which is extremely alkaline and therefore a strong alkaline solid waste (Liu et al. 2009; Mishra and Gostu 2017; Narayan et al. 2021). Bayer method has the incomparable advantages of the sintering method and combined method, low energy consumption, simple process and low cost, so it is widely used.

Due to different grades of bauxite, approximately 2–3 tons of bauxite will be consumed to generate 1–2.5 tons for every 1 ton of alumina produced, and the bauxite residue emission progressively increases with the reduction in the bauxite grade (Agrawal and Dhawan 2021; Jones et al. 2012). The annual emissions of bauxite residue in the world range from 100 million tons to 150 million tons (Habibi et al. 2021). In 2020, global alumina production was 136 million tons,

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bauxite residue emissions were approximately 176.8 million tons (USGS, 2021), the amount in China exceeded 100 million, and the accumulated stockpile reached 600 million tons. Affected by the distribution of bauxite mining areas, bauxite residue in China is mainly distributed in Henan, Shanxi, Shandong, Guizhou, and Guangxi, with a secondary distribution in Inner Mongolia, Hebei, Chongqing, and Yunnan, as shown in Fig. 1. At present, the global comprehensive utilization rate of is less than 15%, and less than 5% in China (Wang et al. 2018). A large amount of bauxite residue is in the state of stockpiling, including wet treatment and pumping to storage tanks or open storage using semidry or dry technology (Lyu et al. 2021).

Massive amounts of bauxite residue are being disposed of and stored, which is becoming a severe environmental issue. Experts at home and abroad have focused their attention on the comprehensive utilization technology of bauxite residue to effectively decrease the threat of bauxite residue accumulation to the environment, and have achieved certain results. This study presents local and international studies on the use of bauxite residue in environmental protection, with the goal of assisting in the reduction and safe application of bauxite residue.

Fig. 1 Distribution of bauxite residue in China

Properties of Bauxite Residue

Characteristics of Bauxite Residue

Depending on the alumina production process, the chemical composition and mineral phase structure of bauxite, the composition of bauxite residue is also different. Table 1 shows the composition comparison of different types of bauxite residue (Nan et al. 2009). According to the different iron contents, bauxite residue can be divided into high iron (Fe_2O_3: 30−60%) and low iron (Fe_2O_3: 10−30%).

Bauxite residue has fine particles with an average particle size of less than 10 μm, and 90% of the particles are less than 75 μm (Rao and Reddy 2017). Bauxite residue has a large specific surface area, which is generally 64.09–186.9 m^2/g depending on the degree of bauxite being crushed during the production process, and has similar characteristics to porous materials with a pore ratio of 2.5–3 (Nan et al. 2010). In addition, bauxite residue has a high water content (700–1000 kg/m^3), accounting for 79–93% of the total weight, and it has strong compressibility with a plastic index of 17–30. The chemical composition and specific physicochemical properties of bauxite residue determine its broad application potential in many fields.

Hazards of Bauxite Residue

In the past, some coastal alumina producers have taken advantage of their location to discharge bauxite residue into the ocean (Burke et al. 2012). In recent years, with the increase in global environmental awareness, the direct discharge of bauxite residue into the sea has been explicitly restricted. In China, a large amount of bauxite residue is stored in the open air, and most dams are constructed from bauxite residue. Its effective treatment has become a worldwide environmental protection problem, and its main hazards are as follows:

(1) The bauxite residue storage not only occupies a large amount of land to construct the storage yard but also has serious safety risks. Notably, in extreme weather, such as a rainstorm, the leakage of the bauxite residue storage yard will have a devastating impact on downstream farmland.

(2) Bauxite residue contains a large amount of strongly alkaline chemicals, which leads to strong corrosion of biomass, metals, and silica materials (Kannan et al. 2021), and it seeps into underground or surface water, raising the pH

Table 1 Chemical composition of different types of bauxite residue (wt%)

Production methods	Al_2O_3	SiO_2	Fe_2O_3	Na_2O	CaO	TiO_2
Bayer process	10–30	5–30	10–60	2–10	0–22	4–20
Sintering process	5–10	15–25	7–10	2–2.5	40–50	1–3
Combination process	5–8	15–20	6–8	2.5–3	35–47	6–8

value of water and critically polluting water sources (Liang and Chen 2014).

(3) Dehydrated and weathered bauxite residue can easily cause dust pollution. The flying bauxite residue dust not only causes air pollution but also seriously affects the visibility of the storage site.

In recent years, there have been many incidents of bauxite residue yard breaches in alumina production enterprises all over the world. On October 4, 2010, the bauxite residue dam burst at the Ajkai alumina refinery in southwestern Hungary, resulting in the release of 1.0×10^6 cm^3 of bauxite residue, causing heavy casualties and sparking panic in many European countries (Burke et al. 2012); On August 8, 2016, a bauxite residue landslide occurred at the dam of an aluminum company's bauxite residue reservoir in Henan Province, China, resulting in the burying of a huge number of houses, livestock, grain and other properties in a village downstream, affecting more than 300 people (Novais et al. 2018). Obviously, the disposal of bauxite residue has a direct impact on the aluminum industry's long-term sustainable development.

Utilization of Bauxite Residue

Currently, the technologies for the integrated application of bauxite residue include the following:

(1) Production of building materials (Babisk et al. 2020; Molineux et al. 2016; Somlai et al. 2008). However, this method is not suitable for the treatment of Bayer process bauxite residue, because of the high alkali content of Bayer bauxite residue, the cost of its dealkalization is expensive, and the small transportation radius;

(2) The production of decorative tiles, door filler materials, etc. (Xu et al. 2019). The main drawback of this method is that the amount of use is relatively small, which cannot be achieved for the large-scale elimination of Bayer bauxite residue.

(3) Extraction of valuable metal elements (Li et al. 2016; Wang et al. 2021; Zhu et al. 2019). The main technologies include two types: one is to recover valuable components such as aluminum, iron, and scandium by acid leaching, which has technical problems such as high operation costs, large equipment investment, and secondary pollution caused by acidic slag. The other is to recover the iron, but this kind of technology is only applicable to the treatment of bauxite residue discharged from alumina production areas using high-iron bauxite.

(4) Environmental treatment and ecological restoration, such as water purification, flue gas purification, soil improvement, bauxite residue reclamation, and preparation of environmental restoration materials, as shown in Fig. 2. (Wang and Liu 2021; Zhang et al. 2021; Zhang et al. 2020b).

Fig. 2 Research progress in the environmental application of bauxite residue

Research Status of Application in Ecological Environmental

Application in Wastewater Treatment

Bauxite residue is utilized as an adsorbent for water treatment because of its large specific surface area and porosity, as well as its strong adsorption capacity, which allows it to filter and remove pollutants from wastewater. Currently, the main applications are the preparation of wastewater clarifiers for the removal of toxic heavy metals or quasi-metallic ions such as Cu (II), Cr (V), As (V), Cd (II) (Danış 2005; Nadaroglu et al. 2010), inorganic anions such as PO_4^{3-}, F^-, NO_3^- and organic pollutants from wastewater (Çengeloğlu et al. 2002). Lu et al. (2021) investigated the use of bauxite residue to treat wastewater discharged from a non-ferrous smelter, and the results showed that bauxite residue could remove nearly 100% of As from the wastewater at room temperature, with a maximum arsenic removal capacity of 101.5 mg/g at a ratio of bauxite residue to wastewater of 40 g/L. Gao et al. (2021) studied the use of bauxite residue and corn straw pyrolysis to prepare functional biochar composites to treat acid dye wastewater, the results showed that the material prepared at 600 °C contained CaO for acid neutralization, Fe^0 for magnetic material collection, and biomass carbon for adsorption, and had good wastewater treatment capacity. Shi et al. (2020) explored the preparation of bauxite residue/g-C_3N_4 composites by one-step thermal polymerization of bauxite residue and melamine to treat the organic matter in wastewater and found that the optimal 0.8% bauxite residue/g-C_3N_4 composite had good antibiotic (TC, OTC, and CTC) and dye (MB and MG) removal ability in the synergistic action of adsorption and photocatalysis.

Application in Soil Remediation

Bauxite residue can be used to restore contaminated soil, upgrade acidic soil and soil lacking in nutrients because of its special physicochemical properties (Brennan et al. 2019; Xue et al. 2021). Zhang et al. (2021) studied the rapid transformation of bauxite residue into a soil matrix by co-hydrothermal carbonization with biomass waste, and the results showed that the elimination of bauxite residue alkalinity could be achieved by this technique, the soil properties of tailings were improved, and ryegrass grew well in this soil substrate. Li et al. (2018) investigated the use of bauxite residue, diatomaceous earth, and lime (5:3:2) as passivation agents to remediate acidic Cd-contaminated rice fields, and the results showed that the application of bauxite residue -based passivation agents reduced the cadmium concentration and increased the pH value in acidic soils and improved rice yields. Ujaczki et al. (2016) evaluated the potential use of red mud-soil mixture (RMSM) as a surface additive for landfills and showed that the incorporation of RMSM at 20% w/w into the subsoil could be used as a surface layer for landfill covering systems. Wang et al. (2021; 2019) studied the extraction of alumina and sodium oxide from bauxite residue by the calcification-carbonization method, and the tail residue was remediated for soil reclamation. The main process of this technology is illustrated in Fig. 3. The basic principle is to complete the calcification transformation of bauxite residue by adding CaO and obtaining the calcification residue with hydrogarnet as the main phase. Following that, the calcified residue was carbonized by passing CO_2 through it, yielding the carbonized residue containing $CaCO_3$, xCaO·ySiO$_2$, and $Al(OH)_3$. Last, the low-concentration alkaline solution is used to dissolve the carbonized residue under low-temperature conditions to obtain tailings with lower Na_2O and Al_2O_3 contents, where the Na_2O content does not exceed 1%, which meets the general soil indicators.

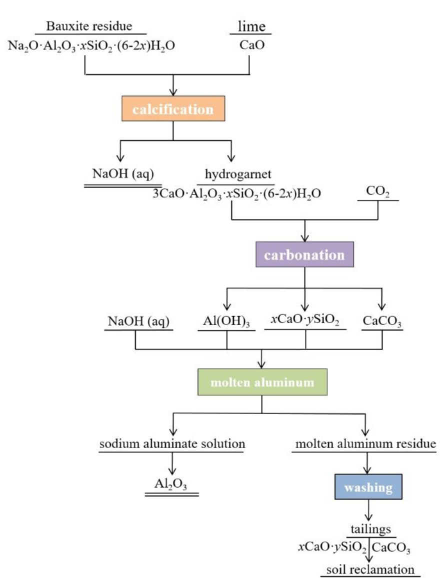

Fig. 3 Process diagram of bauxite residue treatment by calcification-carbonization-tailings soil reclamation technology

Application in Flue Gas Purification

Bauxite residue is rich in alkaline substances and has good absorbability, which makes it widely used in flue gas purification treatment of SO_x, H_2S, NO_x, CO_x, and so on (Sahu et al. 2011). Yang et al. (2018) researched the removal of elemental mercury from flue gas using various potassium halides modified bauxite residue, and the findings revealed that KI modified bauxite residue had the best Hg^0 removal efficiency. Nie et al. (2019) researched the use of bauxite residue for flue gas desulfurization, and the results showed that bauxite residue has good desulfurization ability and that desulfurized tailings can be used as a chemical activator, in which C-grade fly ash was added to produce a high-quality product. Yadav et al. (2010) studied the sequestration of CO_2 gas by bauxite residue, and the results showed that bauxite residue with a 4.57% weight%, 1.8 g/cm^3 relative density, and an average size of 30 μm could capture CO_2 more effectively, reaching 5.3 g CO_2/100 g bauxite residue, which makes an important contribution to carbon emission reduction.

Conclusions

Bauxite residue as bulk solid waste from the aluminum industry poses a great threat to the ecological environment as well as human life safety. This paper describes the applications of bauxite residue for wastewater treatment technology, soil remediation technology, and flue gas purification technology, which have made some research progress in terms of adsorption mechanisms and optimization techniques. The current status of the integrated utilization of bauxite residue treatment in the environment is reviewed, which provides a research basis for the large-scale disposal of bauxite residue in industry. In general, putting these technologies into actual industrial production deserves further development and research to contribute to the reduction of bauxite residue.

In conclusion, the treatment of bauxite residue and the improvement of its comprehensive utilization rate are urgent problems to be resolved. This research indicates that it is feasible to produce mineral compound fertilizer with bauxite residue according to its chemical composition and special physicochemical properties. Bauxite residue can be used on a large scale in this way, which has the advantages of low cost and easy industrial production. On the one hand, it can improve the utilization rate of bauxite residue and decrease the threat to ecological environmental safety. On the other hand, it can alleviate the deficiency of soil trace elements, provide nutrition for crop growth and reduce the pressure on the fertilizer industry.

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Declarations

Declaration of Competing Interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

Agrawal S, Dhawan N (2021) Evaluation of red mud as a polymetallic source-A review. Miner Eng 171:107084

Babisk MP, Amaral LF, Ribeiro LdS, Vieira CMF, Prado USd, Gadioli MCB, Oliveira MS, Luz FSd, Monteiro SN, Garcia Filho FdC (2020) Evaluation and application of sintered red mud and its incorporated clay ceramics as materials for building construction. J Mater Res Technol 9(2):2186–2195

Brennan RB, Murnane JG, Sharpley AN, Herron S, Brye KR, Simmons T (2019) Soil phosphorus dynamics following land application of unsaturated and partially saturated red mud and water treatment residuals. J Environ Manage 248:109296

Burke IT, Mayes WM, Peacock CL, Brown AP, Jarvis AP, Gruiz K (2012) Speciation of arsenic, chromium, and vanadium in red mud samples from the Ajka spill site, Hungary. Environ Sci Technol 46(6):3085

Çengeloğlu Y, Kır E, Ersöz M (2002) Removal of fluoride from aqueous solution by using red mud. Sep Purif Technol 28(1):81–86

Danış U (2005) Chromate removal from water using red mud and crossflow microfiltration. Desalination 181(1):135–143

Gao Y, Zhang J, Chen C, Du Y, Teng G, Wu Z (2021) Functional biochar fabricated from waste red mud and corn straw in China for acidic dye wastewater treatment. J Clean Prod 320:128887

Habibi H, Piruzian D, Shakibania S, Pourkarimi Z, Mokmeli M (2021) The effect of carbothermal reduction on the physical and chemical separation of the red mud components. Miner Eng 173:107216

Jones BEH, Haynes RJ, Phillips IR (2012) Addition of an organic amendment and/or residue mud to bauxite residue sand in order to improve its properties as a growth medium. J Environ Manage 95(1):29–38

Kannan P, Banat F, Hasan SW, Abu Haija M (2021) Neutralization of Bayer bauxite residue (red mud) by various brines: A review of chemistry and engineering processes. Hydrometallurgy 206:105758

Ke W, Zhang X, Zhu F, Wu H, Zhang Y, Shi Y, Hartley W, Xue S (2021) Appropriate human intervention stimulates the development of microbial communities and soil formation at a long-term weathered bauxite residue disposal area. J Hazard Mater 405:124689

Li H, Liu Y, Zhou Y, Zhang J, Mao Q, Yang Y, Huang H, Liu Z, Peng Q, Luo L (2018) Effects of red mud based passivator on the transformation of Cd fraction in acidic Cd-polluted paddy soil and Cd absorption in rice. Sci Total Environ 640–641:736–745

Li R, Zhang T, Liu Y, Lv G, Xie L (2016) Calcification–carbonation method for red mud processing. J Hazard Mater 316(Oct5):94–101

Liang Y, Chen J (2014) Hazards and utilization of red mud. Popular Sci Technol 16(07):33–34

Liu W, Yang JK, Xiao B (2009) Review on treatment and utilization of bauxite residues in China. Int J Miner Process 93(3):220–231

Lu G, Zhang T, Guo F, Zhang X, Wang Y, Zhang W, Wang L, Zhang Z (2019) Clean and efficient utilization of low-grade high–iron sedimentary bauxite via calcification–carbonation method. Hydrometallurgy 187:195–202

Lu Z, Qi X, Zhu X, Li X, Li K, Wang H (2021) Highly effective remediation of high-arsenic wastewater using red mud through formation of AlAsO4@silicate precipitate. Environ Pollut 287:117484

Lyu F, Hu Y, Wang L, Sun W (2021) Dealkalization processes of bauxite residue: A comprehensive review. J Hazard Mater 403:123671

Mishra B, Gostu S (2017) Materials sustainability for environment: Red-mud treatment. Front Chem Sci Eng 11(003):483–496

Molineux CJ, Newport DJ, Ayati B, Wang C, Connop SP, Green JE (2016) Bauxite residue (red mud) as a pulverised fuel ash substitute in the manufacture of lightweight aggregate. J Clean Prod 112(JAN20PT1):401–408

Nadaroglu H, Kalkan E, Demir N (2010) Removal of copper from aqueous solution using red mud. Desalination 251(1):90–95

Nan XL, Zhang TA, Liu Y, Dou ZH (2010) Analysis of Comprehensive Utilization of Red Mud in China. Chin J Process Eng 10:264–270

Nan XL, Zhang TA, Liu Y, Dou ZH, Zhao QY, Jiang XL (2009) Main categories of red mud and its environmental impacts. Chin J Process Eng 9:459–464

Narayan A, Mac-Quhae C, Rosales J, Mora A (2021) Does Alumina-Refining Waste Increase the Nutrient Level in Tropical Mesotrophic Floodplain Lakes? Bull Environ Contam Toxicol 107:506–513

Nie Q, Hu W, Huang B, Shu X, He Q (2019) Synergistic utilization of red mud for flue-gas desulfurization and fly ash-based geopolymer preparation. J Hazard Mater 369:503–511

Novais RM, Carvalheiras J, Seabra MP, Pullar RC, Labrincha JA (2018) Innovative application for bauxite residue: Red mud-based inorganic polymer spheres as pH regulators. J Hazard Mater 358:69–81

Rao BH, Reddy NG (2017) Zeta Potential and Particle Size Characteristics of Red Mud Waste. Geoenvironmental Practices and Sustainability

Sahu RC, Patel R, Ray BC (2011) Removal of hydrogen sulfide using red mud at ambient conditions. Fuel Process Technol 92(8):1587–1592

Shi W, Ren H, Huang X, Li M, Tang Y, Guo F (2020) Low cost red mud modified graphitic carbon nitride for the removal of organic pollutants in wastewater by the synergistic effect of adsorption and photocatalysis. Sep Purif Technol 237:116477

Somlai J, Jobbágy V, Kovács J, Tarján S, Kovács T (2008) Radiological aspects of the usability of red mud as building material additive. J Hazard Mater 150(3):541–545

Sutar H, Mishra SC, Sahoo SK, Prasadchakraverty A, Maharana HS (2014) Progress of Red Mud Utilization: An Overview. Am Chem Sci J 4(3):255–279

Ujaczki É, Feigl V, Molnár M, Vaszita E, Uzinger N, Erdélyi A, Gruiz K (2016) The potential application of red mud and soil mixture as additive to the surface layer of a landfill cover system. J Environ Sci 44:189–196

USGS (2021) Mineral Commodity Summaries: Bauxite and alumina. U.S. Geological Survey. https://pubs.usgs.gov/periodicals/mcs2021/mcs2021-bauxite-alumina.pdf

Wang M, Liu X (2021) Applications of red mud as an environmental remediation material: A review. J Hazard Mater 408:124420

Wang Y, Zhang TA, Lv GZ, Liu Y, Zhang W, Zhao Q (2021) Overview of process control of novel calcification–carbonation process for bauxite residue treatment. Hydrometallurgy 199:105536

Wang YX, Zhang TA, Lv G, Zhang W (2019) Assessment of Bauxite Residue for Reclamation Purposes After Calcification–Carbonization Treatment.JOM: the journal of the Minerals, Metals Materials Society71(9)

Wang YX, Zhang TA, Lyu GZ, Guo FF, Zhang WG, Zhang YH (2018) Recovery of alkali and alumina from bauxite residue (red mud) and complete reuse of the treated residue. J Clean Prod 188:456–465

Xu X, Song J, Li Y, Wu J, Liu X, Zhang C (2019) The microstructure and properties of ceramic tiles from solid wastes of Bayer red muds. Constr Build Mater 212:266–274

Xue S, Huang N, Fan J, Liu Z, Ye Y, He Y, Hartley W, Zhu F (2021) Evaluation of aggregate formation, stability and pore characteristics of bauxite residue following polymer materials addition. Sci Total Environ 765:142750

Xue S, Liu Z, Fan J, Xue R, Guo Y, Chen W, Hartley W, Zhu F (2022) Insights into variations on dissolved organic matter of bauxite residue during soil-formation processes following 2-year column simulation. Environ Pollut 292:118326

Yadav VS, Prasad M, Khan J, Amritphale SS, Singh M, Raju CB (2010) Sequestration of carbon dioxide (CO_2) using red mud. J Hazard Mater 176(1):1044–1050

Yang W, Hussain A, Zhang J, Liu Y (2018) Removal of elemental mercury from flue gas using red mud impregnated by KBr and KI reagent. Chem Eng J 341:483–494

Zhang TA, Wang K, Liu Y, Lyu G, Chen X (2020a) A Review of Comprehensive Utilization of High-Iron Red Mud of China. In: Springer International Publishing, Cham, pp 65–71

Zhang X, Huang R, Cao Y, Wang C (2021) Rapid conversion of red mud into soil matrix by co-hydrothermal carbonization with biomass wastes. J Environ Chem Eng 9(5):106039

Zhang Y, Shen Z, Zhang B, Sun J, Zhang L, Zhang T, Xu H, Bei N, Tian J, Wang Q, Cao J (2020b) Emission reduction effect on PM2.5, SO_2 and NOx by using red mud as additive in clean coal briquetting. Atmos Environ 223:117203

Zhu X, Niu Z, Li W, Zhao H, Tang Q (2019) A novel process for recovery of aluminum, iron, vanadium, scandium, titanium and silicon from red mud. J Environ Chem Eng 8(2):103528