Analysis of the Main Technologies for the Utilization of High-Alumina Coal Fly Ash

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Abstract

The resource utilization of high-alumina coal fly ash has long been a focus of research. China's *Guiding Opinions on the Comprehensive Utilization of Bulk Solid Waste During the 14th Five-Year Plan Period* emphasizes that for bulk industrial solid wastes like coal fly ash, the fundamental principle is to combine large-scale and high-value utilization. The extraction and utilization of aluminium resources therefore represents an essential pathway to achieve its high-value application. Among China's technological routes for alumina resource recovery from high-alumina fly ash, the methods that have undergone pilot-scale or industrial production mainly include the one-step acid-leaching method, pre-desilication-soda-lime sintering process, and limestone sintering process. This paper summarizes these three technologies, analysing their technical characteristics, feasibility, advantages, and disadvantages. Meanwhile, based on the same fly ash composition, the consumption and production costs of these processes are calculated through equilibrium analysis and actual production data, followed by a comparative analysis. Additionally, the production costs of these processes are compared with those of the Bayer process using imported and domestic bauxite ores, respectively. The analysis determines the price range of bauxite at which the Bayer process becomes more cost-effective and, conversely, the conditions under which producing alumina from high-alumina fly ash proves economically advantageous.

Keywords: High-alumina coal fly ash, Bauxite, Alumina, Process comparison, Economic analysis.

1. Context and Present Situation

China is the world's largest producer and consumer of aluminium, yet it suffers from relatively scarce bauxite resources, predominantly consisting of low-grade diasporic and high-sulphur bauxite with high production costs [1]. Currently, China relies heavily on bauxite imports, being the world's top importer. In 2023, China imported 140 million tonnes of bauxite, a 12.7 % year-on-year increase; in 2024, imports reached 159 million tonnes, up 12.3 % year-on-year, with external dependence continuing to rise [2]. Excessive reliance on imports increases risks for the aluminium industry and threatens its development. For instance, from 2024 to 2025, due to policy changes in Guinea regarding bauxite mining and exports, imported bauxite prices surged, driving up alumina prices and severely impacting downstream industries such as electrolytic aluminium and aluminium alloys in China.

Fly ash typically refers to the fine particulates and residue generated by coal-fired power plants, as well as resource utilization power plants processing coal gangue and coal slurry. Generally, burning 1 tonne of coal produces 0.20–0.30 tonnes of fly ash [3, 4]. Currently, China's fly ash output accounts for approximately 50 % of the world's total production and continues to rise, with accumulated storage exceeding 3 billion tonnes. As the largest-volume industrial solid waste in China, its disposal has long been a major concern [5, 6]. Consequently, achieving high-valueadded recycling of fly ash to enable a green circular economy has become a prominent research focus in academia.

International research on the comprehensive utilization of fly ash began relatively early. Poland has conducted extensive exploration in fly ash utilization, with the Mineral and Energy Economy Research Institute of the Polish Academy of Sciences developing a sintering technology for mixed fly ash and bauxite residue to extract alumina, achieving an extraction rate of 75–80 %. The United States has carried out multiple technological developments for extracting aluminium, gallium, and rare earth elements from fly ash, though its fly ash utilization focuses more on the construction materials sector (e.g., as concrete admixtures), with relatively fewer studies on valuable metal extraction. Germany places greater emphasis on the application of fly ash in construction materials, ceramics, and other fields, with limited research on metal extraction.

The Siberian Branch of the Russian Academy of Sciences has developed a soda fusion-hydrothermal treatment process for high-alumina coal fly ash, achieving an aluminium recovery rate of over 80 %, though the process flow is relatively lengthy.

Although China started research on fly ash comprehensive utilization later than the aforementioned countries, it has achieved global leadership in the field of extracting alumina from high-alumina fly ash. This is primarily because other countries lack high-alumina coal resources comparable to those in China's Inner Mongolia and Shanxi regions, resulting in generally lower alumina content in the fly ash and insufficient economic feasibility. In recent years, China has established a number of representative demonstration projects for alumina extraction from high-alumina fly ash, providing valuable industrial experience for further technological promotion. For example, Mengxi Group's "0.4 Mtpa alumina project", as China's first industrial-scale production line for alumina extraction from fly ash, has developed a set of industrial production technologies, including material proportioning, calcination, and clinker self-pulverization. Datang International's "0.24 Mtpa high-alumina fly ash to alumina multi-product project" introduced a pre-desilication process, further improving the A/S ratio of high-alumina fly ash and reducing residue volume. Shenhua Zhungeer's "0.3 Mtpa high-alumina fly ash comprehensive utilization project" has completed preliminary design work, with the government also allocating corresponding electrolytic aluminium production quotas in support.

The resource utilization of fly ash is a global challenge. China's *Guiding Opinions on the Comprehensive Utilization of Bulk Solid Waste During the 14th Five-Year Plan Period* emphasizes that for bulk industrial solid wastes like fly ash, the fundamental principle is to combine large-scale utilization with high-value utilization. The extraction and utilization of aluminium resources therefrom represents an essential pathway to achieve its high-value application [7]. After nearly two decades of scientific research, China has developed multiple technological routes for recovering alumina resources from fly ash, including the one-step acid leaching process for alumina production, the pre-desilication--soda-lime sintering process for alumina production, and the limestone sintering process for alumina production [2].

This paper summarizes the above-mentioned technologies, analysing their technical characteristics, feasibility, advantages, and disadvantages. Meanwhile, based on the same fly ash composition, the production costs of these processes are calculated through equilibrium analysis and actual production data, followed by a comparative analysis. Additionally, the production costs of these processes are compared with those of the Bayer process using imported and domestic bauxite ores, respectively. The analysis determines the price range of bauxite at which the Bayer process becomes more cost-effective and, conversely, the conditions under which producing alumina from high-alumina fly ash proves economically advantageous.

2. Characteristics of High-alumina Fly Ash and Raw Materials for Research

The chemical composition of high-alumina fly ash is relatively complex, containing major elements such as aluminium, iron, silica, and calcium, as well as trace elements like gallium and germanium. Notably, high-alumina fly ash has a high content of alumina (Al_2O_3) and silica (SiO_2) [8]. Additionally, high-alumina fly ash features low bulk density, fine grain size, and a large angle of repose [3].

The average Al_2O_3 content in fly ash in China is approximately 27 %, and the higher content can reach more than 45 %. There is no uniform standard for alumina content in high-alumina fly ash in China, and it is generally considered that fly ash with Al_2O_3 content exceeding 38 % is high-alumina fly ash. The raw material studied in this paper is high-alumina fly ash produced by a power plant in Inner Mongolia, China. Its chemical composition is listed in Table 1, and its physical characteristics are listed in Table 2.

Table 1. Chemical composition of high-alumina fly ash.

Composition	Al_2O_3	SiO_2	Fe_2O_3	FeO	TiO_2	K_2O	Na_2O
wt %	48.5	39.11	0.96	0.79	1.62	0.33	0.21
Composition	**CaO**	**MgO**	**P_2O_5**	**Li_2O**	**MISC.**	**LOI**	**Total**
wt %	2.45	0.35	0.23	0.062	1.21	4.237	100.0 %

Table 2. Physical properties of high-alumina fly ash.

Moisture (%)	Bulk density (g/cm^3)	LOI (%)	Angle of repose	Specific surface area (m^2/g)	Grain size Dv10 (μm)	Grain size Dv50 (μm)	Grain size Dv90 (μm)	True density (g/cm^3)
0.14	～0.8	～3.96	～54°	～9.45	5.59	49.69	174.22	～2.35

3. Main Technical Routes for Production of Alumina from High-alumina Coal Fly Ash

For production of alumina from high-alumina fly ash, there are many different technical routes, such as limestone sintering process, soda-lime sintering process, pre-desilication-soda-lime sintering process, one-step acid leaching process, acid-base combination method, sulfuric acid method, ammonium sulphate method, calcium-free sintering process, low-calcium sintering process and fluoride salt method [9–12]. However, most of the technical routes are still in the laboratory research stage, and the technology research and development are still in progress. Currently, the main process routes that have been verified by pilot-scale or industrial tests include one-step acid leaching process, pre-desilication-soda-lime sintering process and limestone sintering process.

3.1 One-step Acid Leaching Process

The technical route is to use the principle that silica in high-alumina fly ash is insoluble in hydrochloric acid liquor, while alumina is soluble in hydrochloric acid liquor to realize the separation of alumina and silica, which was jointly developed by Shenhua Group and Jilin University. This technology not only extracts alumina, but also produces useful (or economically beneficial) by-products such as silicon fertilizer, gallium and iron oxide red. From 2011 to 2017, the process underwent seven pilot-scale test runs and ultimately achieved design capacity and quality standards. The acid-processed alumina produced was tested in industrial electrolytic cells by Yunnan Aluminium Co., Ltd., with favourable test results.

The process steps include slurry preparation, digestion, dilution, separation, oxidation, impurity removal, evaporation crystallization, roasting and other a few other steps. The process schematic is shown in Figure 1.

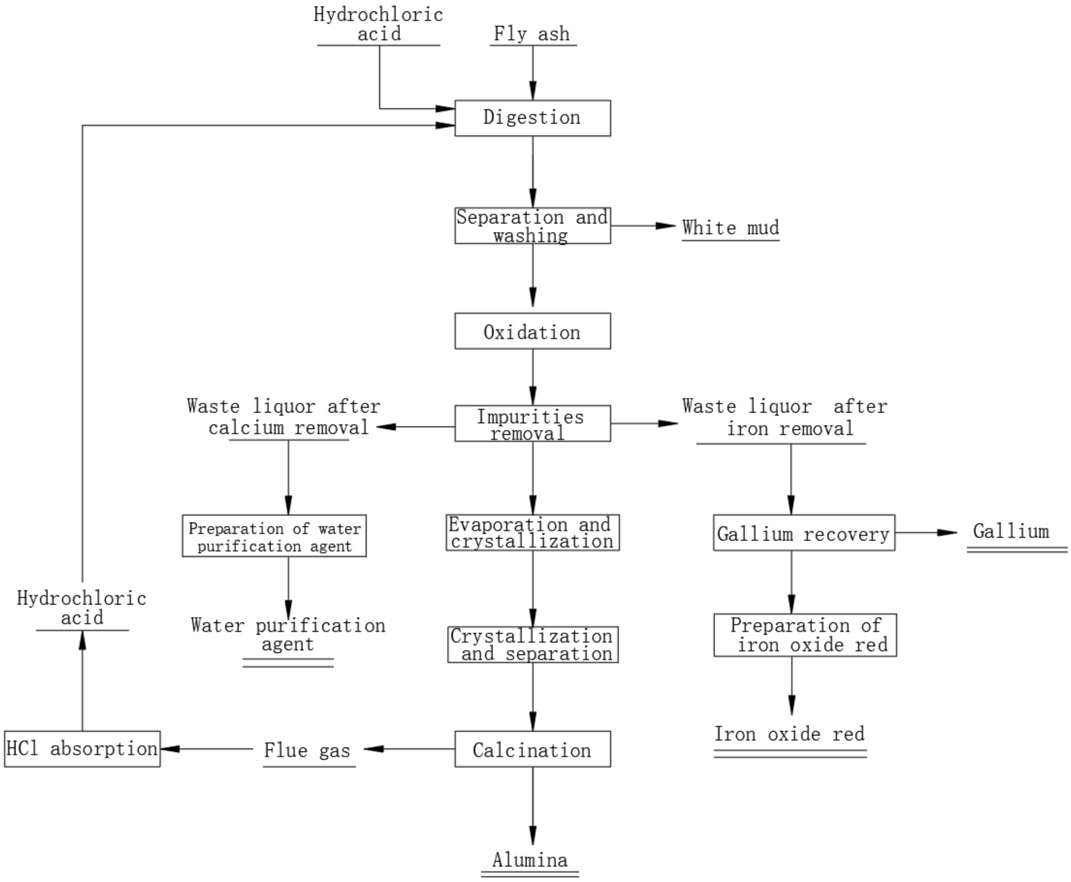

Figure 1. Schematic of the one-step acid leaching process for alumina production.

3.2 Pre-desilication Soda-limestone Sintering Process

The pre-desilication soda-lime sintering process is cooperative project between Datang International and Tsinghua University. Based on the conventional lime sintering process, this method extracts alumina from fly ash by leveraging the fact that SiO_2 in fly ash primarily exists in amorphous form and as mullite, with the amorphous SiO_2 having higher reactivity and thus being more easily dissolved in NaOH solution to enter the liquid phase [13]. This process employs a pre-desilication step before the sintering process, where the amorphous SiO_2 in fly ash is dissolved in soda liquor to achieve preliminary separation of alumina and silica, thereby increasing the A/S ratio and reducing the amount of calcium silicate residue [14, 15]. The main product is smelter grade alumina, with activated calcium silicate as a by-product, while calcium silicate residue is also generated. However, due to economic and environmental concerns, the process has been discontinued. The key steps include pre-desilication, clinker sintering, clinker digestion, primary desilication, deep desilication, precipitation and classification, carbonation precipitation, and calcination. A schematic diagram of the process flow is shown in Figure 2.

3.3 Limestone Sintering Process

This process was jointly developed by Mengxi Group and Central South University based on the traditional limestone sintering process. It first produces high-alumina silica hydrate with an A/S ratio ≥ 60, which is then processed into smelter-grade alumina meeting China's national standard (GB/T 24487-2022) and the domestic alumina industry standard (YS/T 803-2023) through a low-temperature Bayer process. The by-product, calcium silicate residue, is utilized for cement production. In 2006, this process route received approval from China's National Development and Reform Commission for a 0.4 Mtpa alumina project and was granted special national treasury fund support [16]. The schematic diagram of this technology is shown in Figure 3, with key processes including clinker sintering, self-pulverization, clinker digestion, separation, carbonation precipitation, and calcination.

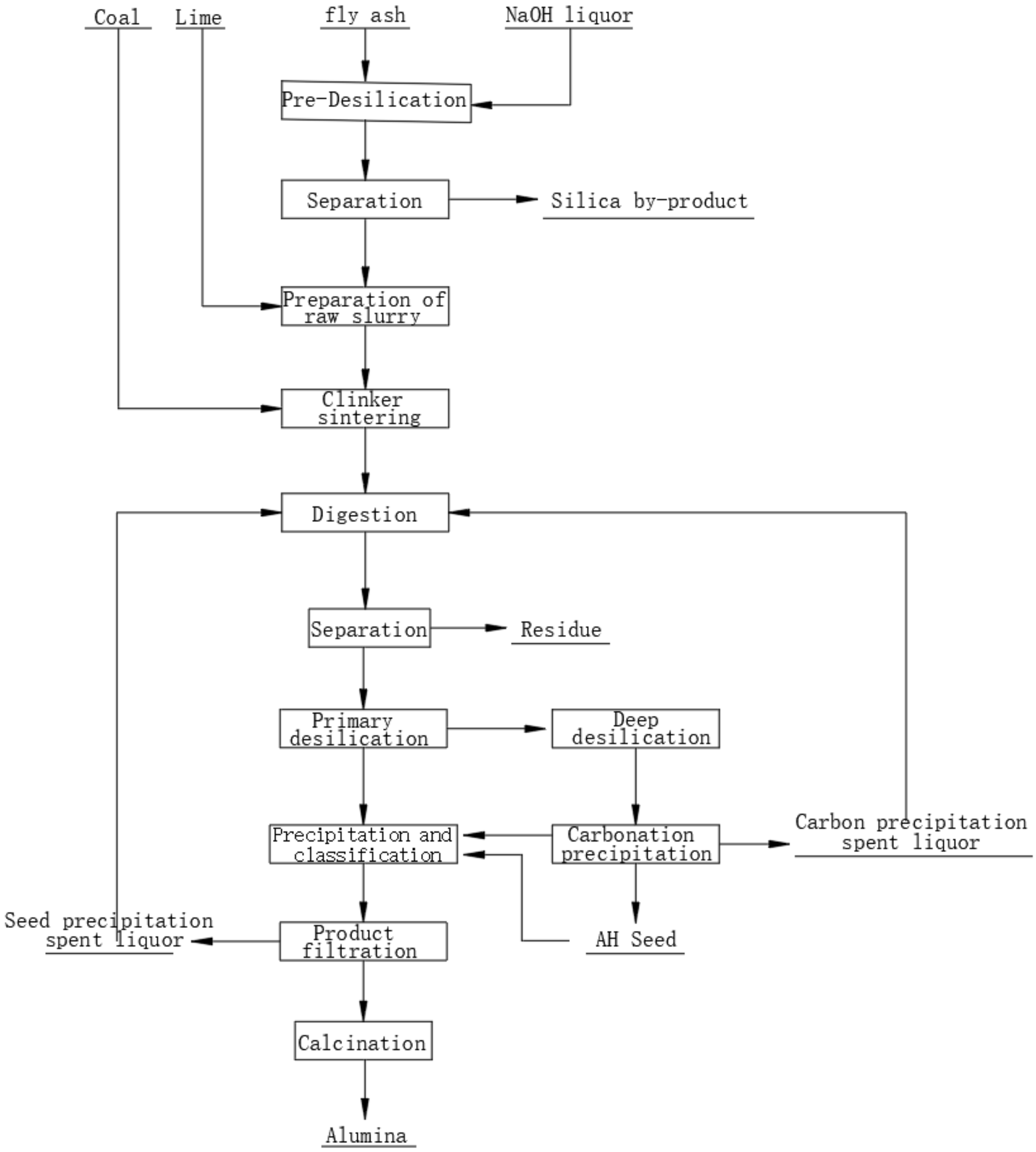

Figure 2. Process flow diagram of pre-desilication-soda-lime sintering process.

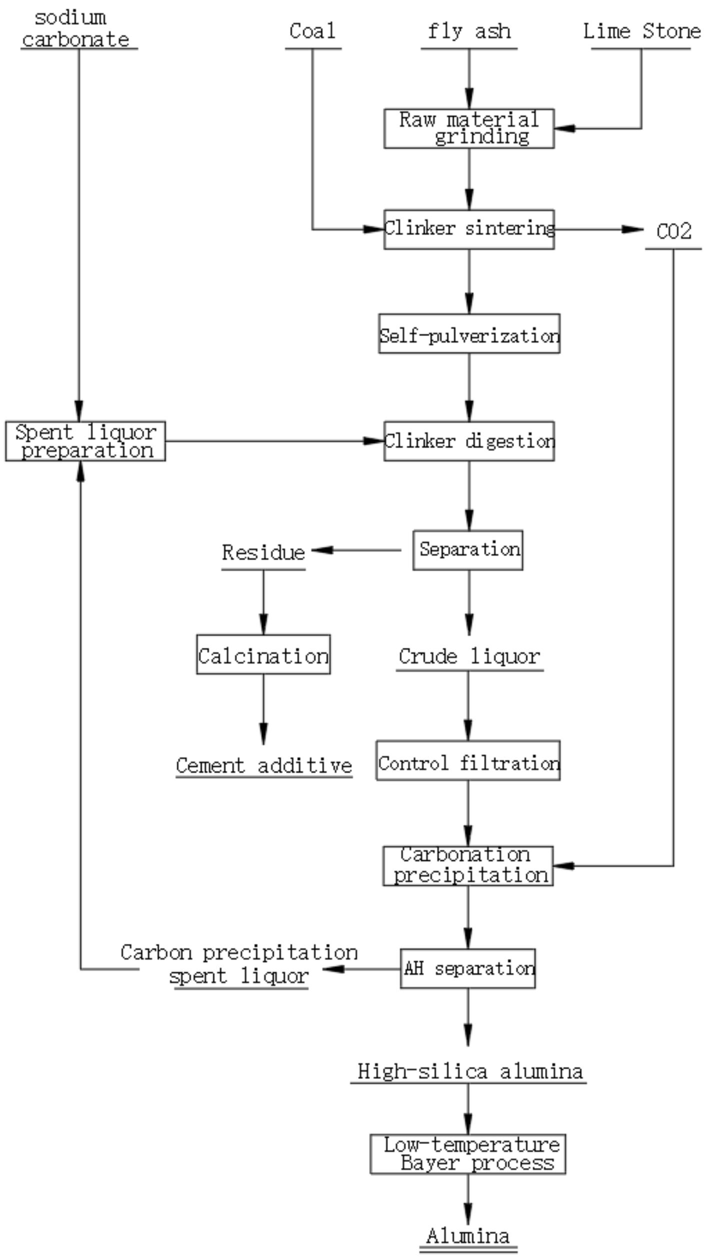

Figure 3. Process flow diagram of limestone sintering process.

4. Comprehensive Comparative Analysis of Three Process Routes

For the production of alumina products from high-alumina fly ash, a comprehensive benchmarking analysis is conducted on the three aforementioned process technologies, mainly from the aspects of technical characteristics, technical feasibility, process advantages and disadvantages, and economy.

4.1 Analysis of Technical Characteristics, Feasibility, Advantages, and Disadvantages

The technical characteristics, feasibility, and advantages and disadvantages analysis of the three alumina production routes from high-alumina fly ash are presented in Table 3.

Table 3. Analysis of technical characteristics, feasibility, advantages and disadvantages of the three process technologies.

	Pre-desilication soda-limestone sintering process	Limestone sintering	One-step acid leaching process
Technical characteristics	Pre-desilication to increase the A/S ratio of fly ash and reduce residue volume	Utilization of low-cost limestone as raw material to reduce production costs	Efficient separation of alumina and silica to minimize residue generation
Pilot-scale and industrialization status	A 0.2 Mtpa alumina production line was put into operation in 2010 but is currently shut down	A 1000 tonne pilot-scale test was completed in 2004, and a 0.2 Mtpa production line has been constructed	A 4000 t/a acid-leaching pilot-scale production line for alumina extraction from fly ash was commissioned in 2011, but is now shut down
Technical feasibility	The process and equipment have production application examples, and the technology has been identified - technically feasible	The process and equipment have production application examples, and the technology has been identified - technically feasible	After seven stable pilot-scale test runs, the technology has been identified - technically feasible
Advantages	Simple process, high maturity of equipment, low cost, and high alumina recovery rate	Simple process, high maturity of equipment, low cost, and strong process adaptability	Simple process, high alumina recovery rate, minimal residue generation, low energy consumption, enabling multi-metal recovery, strong process adaptability, and high product purity
Disadvantages	High raw material consumption and large residue volume (approximately 3 t/t Al_2O_3), significant environmental pressure, high energy consumption, and poor process adaptability	High raw material consumption and the largest residue volume (approximately 8 t/t Al_2O_3), significant environmental pressure, high energy consumption, and low alumina recovery rate	Strong acid corrosion, with challenges in equipment selection, high costs for equipment, valves, and pipelines, high impurity removal costs, short equipment lifespan, difficult production operations, high maintenance costs, high investment, and poor product adaptability

4.2 Comparative Analysis of Consumption and Production Costs

Using the same high-alumina coal fly ash (Table 1) and based on equilibrium calculations combined with actual production data, the main consumption and production costs (excluding tax) of the three technical routes were determined. The results are presented in Table 4.

Table 4. Comparative analysis of consumption and production costs of three processes.

Number	Consumption /production	Unit /t A_2O_3	Unit price (excluding tax)	Pre-desilication soda-limestone sintering process	Limestone sintering	One-step acid leaching process
1	Fly ash	t	100 RMB/t	2.65	2.74	2.42
2	Lime	t	350 RMB/t	—	—	0.005
3	Lime Stone	t	50 RMB /t	3.65	6.65	—
4	Soda consumption	t	RMB 2800/t	0.15	0.09	0.015
5	Coal consumption	t	450 RMB/t	1.00	1.05	—
6	Flocculant	kg	15 RMB/kg	0.20	0.20	0.60
7	Natural gas	Nm^3	2.57 RMB/Nm^3	81.00	81.00	367.00
8	Live steam	t	92 RMB/t	6.20	4.1.00	7.00
9	Power electricity	kWh	0.4 RMB/kWh	930.00	950.00	840.00
10	Fresh water	t	5.5 RMB/t	4.23	2.88	—
11	Resin	L	40 RMB/L	—	—	4.20
12	Hydrochloric acid	t	190 RMB/t	—	—	0.83
13	Externally discharged residue	t	45 RMB/t	3.10	8.00	1.25
Prod. costs (RMB/t Al_2O_3)				2 633.84	2 675.87	2 605.24

Notes:
1. All unit prices are based on the 2024 average prices (excluding tax) in Inner Mongolia, China.
2. The calculation only compares production costs and does not include by-products, labour wages, employee benefits, manufacturing or other expenses, thus not representing the complete costs.
3. Material prices vary by region and period, so costs may differ accordingly.

According to the above consumption and production cost analysis, among the three processes, the limestone sintering process has the highest production cost due to its highest raw material consumption, lengthy process flow, and high-power consumption, in addition to its large volume of residue discharge. The pre-desilication soda-limestone sintering process ranks second, with its primary cost drivers being high soda consumption, substantial steam and power consumption, as well as high coal consumption, and with relatively large residue discharge. The high production costs and significant residue volumes are the main factors limiting the further industrial application of the two technologies. The one-step acid leaching process has the lowest production cost, with its primary expenses from steam consumption, natural gas consumption, and power consumption. This is attributed to the high steam demand for evaporation crystallization in the process, substantial natural gas consumption for the calcination of crystalline aluminium chloride, and significant electricity consumption due to the lengthy process flow. Overall, the production costs of the three processes do not differ significantly, all remaining within 80 RMB/t Al_2O_3 (11.2 USD/ t Al_2O_3 approx.).

5. Comparative Analysis of Production Costs Between the Bayer Process and High-Alumina Fly Ash Alumina Extraction

The above three process technologies for producing alumina from high-alumina fly ash were compared with the Bayer process using Chinese diaspore (Al_2O_3 content 55 %, A/S = 5.5) and imported gibbsite (Al_2O_3 content 43.5 %, A/S = 18), respectively. The comparison primarily focused on a production cost analysis (excluding tax) under different bauxite prices, with the results shown in Figure 4.

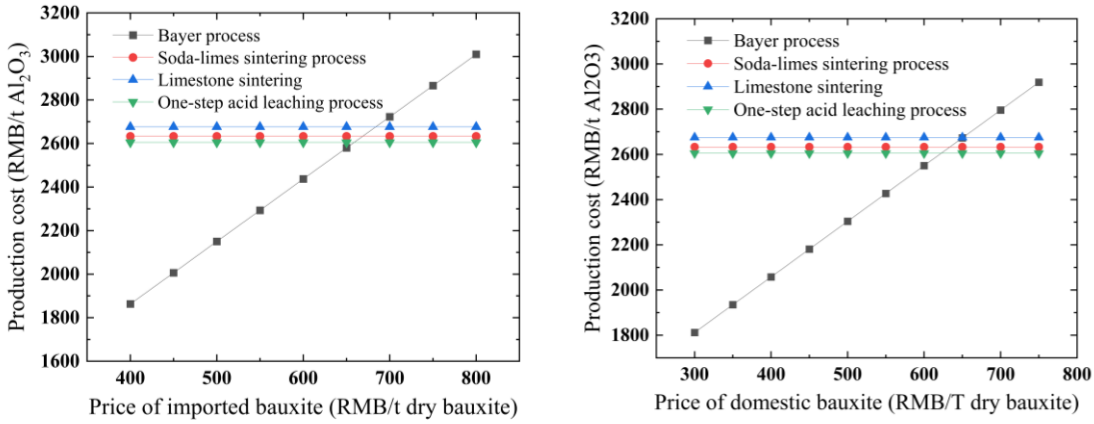

Figure 4. Comparative cost analysis of three processes versus the Bayer process for alumina production. Left: Imported bauxite, Right: Domestic bauxite.

According to the analysis in Figure 4 (left), when the price of imported bauxite is 683 RMB/t (dry bauxite), the production costs of the Bayer process and the limestone sintering process are approximately equal. When the bauxite price falls below 683 RMB/t (dry bauxite), the Bayer process has lower production costs; conversely, the fly ash-limestone sintering process becomes more cost-effective. When the imported bauxite price is 670 RMB/t (dry bauxite), the production costs of the Bayer process and the soda-limestone sintering process are nearly identical. If the bauxite price is lower than this price, the Bayer process is more economical; otherwise, the fly ash-soda-limestone sintering process offers lower costs. Similarly, at an imported bauxite price of 660 RMB/t (dry bauxite), the production costs of the Bayer process and the one-step acid leaching process are comparable. Below this price level, the Bayer process is more cost-efficient; otherwise, the fly ash one-step acid leaching process offers lower costs.

According to the analysis in Figure 4 (right), when the price of domestic bauxite is 650 RMB/t (dry bauxite), the production costs of the Bayer process and the limestone sintering process are approximately equal. When the bauxite price falls below 650 RMB/t (dry bauxite), the Bayer process has lower production costs; conversely, the fly ash-limestone sintering process becomes more cost-effective. When the domestic bauxite price is 633 RMB/t (dry bauxite), the production costs of the Bayer process and the soda-limestone sintering process are nearly identical. If the bauxite price is lower than this price, the Bayer process is more economical; otherwise, the fly ash-soda-limestone sintering process offers lower costs. Similarly, at a domestic bauxite price of 622 RMB/t (dry bauxite), the production costs of the Bayer process and the one-step acid leaching process are comparable. When the bauxite price falls below 622 RMB/t (dry bauxite), the Bayer process has lower production costs; otherwise, the fly ash one-step acid leaching process offers lower costs.

Additionally, as can be seen from Figure 4, when other costs and prices remain unchanged, the relationship between the import price of bauxite and production cost is Y=2.865X+716.75, while the relationship between the price of domestic diaspore and production cost is Y=2.46X+1074. This indicates that the production cost of alumina by the Bayer process is significantly influenced by bauxite prices.

Based on the above analysis, when bauxite prices are high, the use of high-alumina fly ash to produce alumina has certain advantages in terms of production costs. However, attention should be paid to its high construction investment, carbon emissions caused by high energy consumption, new and greater environmental problems caused by a large amount of residue, and market problems caused by a large amount of by-products.

6. Conclusion

The following conclusions have been derived from this study.

(1) All three processes and equipment for producing alumina from high-alumina fly ash have undergone pilot-scale or industrial verification, with their technologies being certified, and are technically feasible with low risks. Under identical boundary conditions, the limestone sintering process has the highest production cost, followed by the pre-desilication soda-lime sintering process, while the one-step acid leaching process has the lowest production cost.

(2) The main issues and challenges of the pre-desilication- soda-lime-sintering process and the limestone sintering process lie in the large volume of calcium silicate residue, significant environmental pressure, and high energy consumption, which are the primary factors restricting their further industrialization. The key problems and challenges of the one-step acid leaching process include the highly corrosive acidic environment, high capex, elevated impurity removal expenses, short equipment lifespan, high maintenance costs, and operational difficulties. These also constitute major obstacles to the industrialization of this process.

(3) Currently, the balance point in production costs between the Bayer process using bauxite and alumina production from high-alumina fly ash primarily lies in the bauxite cost, which is approximately 620–670 RMB/t (dry bauxite, approx. 87–94 USD/t). When the bauxite price falls below this price range, the Bayer process holds an economic advantage; conversely, alumina production from high-alumina fly ash becomes more cost-effective. Additionally, attention must be paid to the high capital investment and energy consumption (leading to carbon emissions) in the high-alumina fly ash, the large volume of residue posing greater environmental challenges, and the marketability issues arising from the substantial by-products.

(4) For the pre-desilication soda-lime sintering process and the limestone sintering process, further optimization is required to address existing challenges. Pretreating high-alumina fly ash to reduce its silica content and increase the A/S ratio represents a key research focus and trend, as well as an effective pathway toward industrialization. Regarding the one-step acid leaching process, process optimization, simplification of impurity removal steps, and exploration of more cost-effective acid-resistant materials are essential measures to accelerate its industrial application.

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