A New Calcification Transformation Method for Clean Production of Alumina

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https://doi.org/10.71659/icsoba2025-aa010

Abstract

This paper proposes a novel approach to the clean production of alumina through the source blocking of mineral phase reconstruction, addressing the global challenge of utilizing medium and low-grade bauxite. Based on the characteristics of these bauxite types, we have developed a series of technologies, including "calcification-carbonation", "calcification-biomass," and "calcification-potassium alkali" along with their intersections, to facilitate the clean production of alumina during the dissolution process. This approach enables the efficient recovery of alumina during bauxite leaching while reducing sodium oxide emissions, achieving a Na_2O content of less than 1% in the final transformed slag. This lays a theoretical foundation for the scalable and harmless utilization of red mud. The elimination of red mud varies with different transformation processes in various regions. The calcification-carbonation method not only efficiently recovers alumina but also allows the new red mud to be utilized in cementation or soil applications. The calcification-biomass method achieves a hematite to magnetite transformation rate exceeding 90 %, enabling the recovery of iron oxide in low magnetic field strengths. The calcification-potassium alkali method, as a new dissolution system, exhibits a higher alumina dissolution rate than the Bayer process, and the resulting transformation slag can be repurposed as a mineral compound fertilizer, achieving high-value utilization. Through case studies, we systematically elaborate on the fundamental concepts, principles, and methodologies of the "Calcification Transformation" series, elucidating the evolution of the mineral phase and briefly introducing the engineering processes involved. This work successfully achieves the goal of source blocking and demonstrates significant theoretical and practical implications for advancing scientific and technological progress in the alumina industry.

Keywords: Alumina clean production, Medium and low-grade bauxite, Calcic carbonization, Calcic biomassification, Calcic potash alkali

1. Introduction

Driven by the rapid development of the global economy, alumina has emerged as a crucial raw material, with its consumption continually rising across various sectors, particularly in the production of aluminium products. However, the increasing scarcity of high-quality bauxite presents significant challenges. The effective utilization of low- and medium-grade bauxite, along with the environmental pollution caused by red mud generated during alumina production, has become a critical issue for the sustainable development of the industry.

Currently, over 95 % of global alumina production utilizes the Bayer process, which, while dominant, has significant shortcomings [1]. Firstly, the Bayer method imposes stringent requirements on the aluminium to silicon ratio of bauxite (Al/Si > 7), making it challenging to efficiently and economically process low-grade bauxite resources. This challenge is exacerbated by the increasingly depleted state of global bauxite resources [2]. For instance, in China, bauxite reserves account for only 3 % of the world's total, with most being low-grade ores; high-silica bauxite ores constitute over 90 % [3]. Consequently, resource utilization faces substantial challenges. Secondly, the Bayer production process generates 1.0 to 1.5 tonnes of red mud for every tonne of alumina produced. The global reserves of red mud exceed 4 billion tonnes, with an annual increment of 120 million tonnes [4]. In China, the annual discharge of Bayer's red mud exceeds 100 million tonnes, accounting for more than half of the global emissions [4]. Red mud is characterized by its strong alkalinity and the presence of harmful substances, with a utilization rate of only 7.6 %. The mainstream method of dry storage not only occupies considerable land resources but also poses serious environmental pollution risks [5]. For example, the leaching of heavy metal ions from red mud can contaminate soil and water bodies, while the release of alkaline substances can disrupt ecological balance, threatening the surrounding environment [6, 7].

In light of this, the development of an alumina clean production process that effectively addresses the challenges associated with the utilization of low- and medium-grade bauxite, while simultaneously mitigating red mud pollution at its source, is of paramount importance. This necessity holds significant practical relevance and strategic implications for advancing the green and sustainable development of the alumina industry. Against this backdrop, this paper introduces a novel alumina clean production method based on mineral phase reconstruction, termed the calcification transformation method. This approach emphasizes the mineral phase characteristics of bauxite and red mud, leveraging the principle of mineral phase reconstruction to disrupt the sodium-aluminium-silicon bond present in red mud generated by the traditional Bayer method. By reconstructing the equilibrium solid phase during the dissolution process, the method facilitates the efficient recycling of alumina from middle- and low-grade bauxite while simultaneously reducing sodium oxide emissions. This lays a theoretical foundation for the large-scale, harmless utilization of red mud. The related technologies can be categorized into three sub-methods: the calcification-carbonation method, the calcification biomass method, and the calcification potassium alkali method. This paper will systematically elucidate the principles and methodologies of these calcification transformation methods in treating low-grade bauxite ore and the evolution of the mineral phase. Additionally, it will provide a concise overview of the engineering processes involved, with the aim of offering theoretical support for achieving green, low-carbon, sustainable, and high-quality clean production within the alumina industry.

2. Principles of Calcification Transformation

2.1 Calcification-Carbonization Method

The calcification-carbonation method is a clean production technology for alumina that focuses on the reconstruction of the mineral phase. This method is primarily employed for processing medium- to low-grade bauxite and Bayer red mud. By altering the equilibrium solid phase during the dissolution process of bauxite or red mud, a new structure of alkali- and aluminium-free red mud is produced. This approach facilitates the efficient recovery of alumina while promoting the reduced and harmless utilization of red mud [8, 9].

The primary reactions involved in the two core aspects of the calcification-carbonation method for treating bauxite and red mud – namely, pressurized calcification and pressurized carbonation – are outlined as follows.

Calcification process: During the dissolution phase of the Bayer method, calcium oxide is introduced, facilitating the incorporation of all silicon from bauxite or red mud into the hydrated garnet phase. This results in the formation of a calcified transformation slag devoid of sodium oxide. For instance, considering kaolinite, the calcification reaction can be expressed as in Equation (1):

$$\begin{gathered} x/2(Al_2O_3\cdot 2SiO_2\cdot 2H_2O) + 3CaO + (2-x)NaAlO_2 + (7-3.5x)H_2O = \\ 3CaO\cdot Al_2O_3\cdot xSiO_2\cdot (6-2x)H_2O + (2-x)NaOH \end{gathered} \tag{1}$$

The calcified transformation slag (the main phase is hydrated garnet) is carbonized with CO_2 to obtain a carbonized transformation slag with the main compositions of calcium silicate, calcium carbonate and aluminium hydroxide. The carbonization reaction is as Equation (2):

$$\begin{gathered} 3CaO\cdot Al_2O_3\cdot xSiO_2\cdot (6-2x)H_2O + (3-2x)CO_2 = \\ xCa_2SiO_4 + (3-2x)CaCO_3 + 2Al(OH)_3 + (3-2x)H_2O \end{gathered} \tag{2}$$

Carbonized transformation slag is dissolved in aluminium at low temperature to obtain a new structure of red mud whose main components are calcium silicate and calcium carbonate. The reaction of dissolved aluminium is as Equation (3):

$$Al(OH)_3 + NaOH = NaAl(OH)_4 \tag{3}$$

2.1.1 Mineralogical Evolution

During calcification, in a high-temperature, high-pressure and strongly alkaline environment, kaolinite in bauxite reacts with calcium oxide to form hydrated garnets. As the temperature and reaction time increase, kaolinite is progressively converted into hydrated garnet, accompanied by the formation of small quantities of hydrated calcium aluminate and calcium hydroxide. The silicon saturation factor (x) of hydrated garnet ranges from 0 to 2, which influences its structure and stability. With rising temperature and the addition of calcium oxide, the silicon saturation coefficient of hydrated garnet increases, leading to a decrease in the prism length of the hydrated garnet cell, which exhibits a more linear relationship. Consequently, the crystal structure becomes more stable, as illustrated in Figure 1 below.

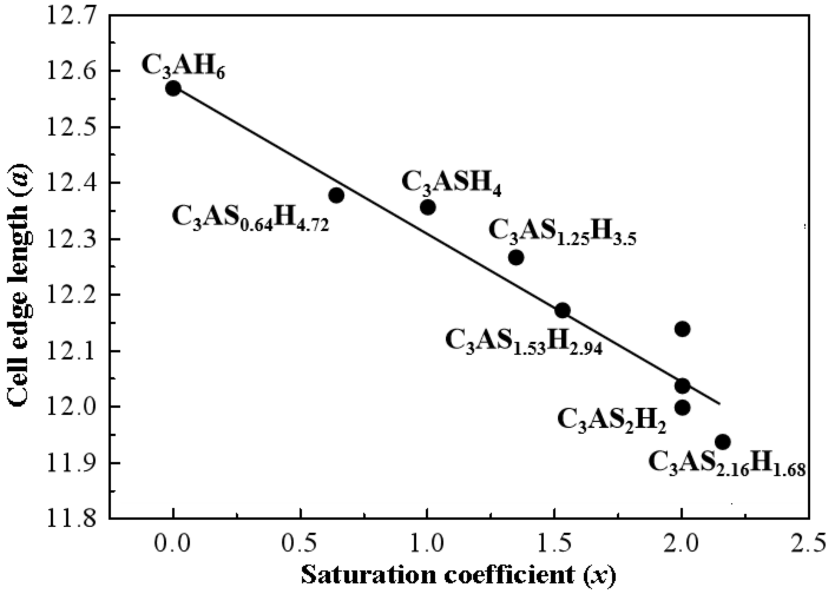

Figure 1. Saturation coefficient of hydrated garnet versus cell prism lengths.

During the process of carbonization, hydrated garnets react with carbon dioxide to produce calcium silicate, calcium carbonate, and aluminium hydroxide. In the early stages of carbonization, carbon dioxide reacts with calcium hydroxide present on the surface of hydrated garnet, resulting in the formation of calcium carbonate. As the carbonization reaction progresses, the hydrated garnet gradually decomposes, leading to a carbonization residue that primarily consists of calcite-type calcium carbonate, aragonite-type calcium carbonate, and a protosilicate phase. The proportions of these phases vary according to changes in carbonization conditions [10].

Subsequently, the carbonized transformed slag can be obtained through the low temperature (60 °C) solubilization of aluminium, leading to the formation of a new structure of red mud. The primary components of this structure are calcium silicate and calcium carbonate, which can be utilized in the preparation of cement that meets the standards for cement [11]. The process flow diagram is illustrated in Figure 2 below.

Figure 2. Process flow for the preparation of cement from the transformation products of bauxite or red mud treated by the calcic carbonation method.

2.1.2 Results from the Calcification-Carbonation Method

The treatment of medium and low-grade monohydrate stibnite ores in various regions of China using the calcification-carbonation method is influenced by the mineral structure. Consequently, some ores exhibit a high aluminium-silicon ratio in the primary treatment slag. As a result, these components undergo a repeated carbonation and aluminium dissolution process during secondary treatment. The outcomes of this process are detailed in Table 1.

As can be seen from Table 1, calcinated carbonization has achieved good experimental results in the laboratory. While efficiently dissolving aluminium, they have also changed the equilibrium structure of red mud, effectively blocking the problem of red mud from the source.

Table 1. The results of calcification-carbonization treatment of different types of bauxite and red mud.

Substance	Slag bonding			
	Al_2O_3%	SiO_2%	Na_2O%	Al/Si
1# Henan bauxite	54.41	16.55	—	3.29
1# calcified slag	22.0	10.94	0.42	2.01
1# Primary carbonized aluminium slag	11.09	11.02	—	1.01
1# Secondary carbonized aluminium slag	4.41	10.02	0.16	0.44
2# Henan bauxite	58.11	19.02	-	3.06
2# calcified slag	23.70	13.31	0.73	1.78
2# Primary carbonized aluminium slag	16.03	12.84	0.59	1.25
2# Secondary carbonized aluminium slag	8.89	12.01	0.57	0.74
3# Henan bauxite	55.66	15.05	-	3.7
3# calcified slag	21.95	13.52	0.84	1.62
3# Primary carbonized aluminium slag	14.66	12.63	0.65	1.16
3# Secondary carbonized aluminium slag	12.47	11.84	0.46	
4# Shanxi bauxite	61.6	13.53	-	4.55
4# calcified slag	20.71	14.42	0.95	1.44
4# Primary carbonized aluminium slag	13.92	14.43	-	0.96
4# Secondary carbonized aluminium slag	11.81	13.89	-	0.85
5# Yunnan bauxite	56.12	7.32	-	7.67
5# calcified slag	17.30	10.30		1.72
5# Primary carbonized aluminium slag	11.11	11.66	1.54	0.41

2.1.3 Engineering Process

To investigate the feasibility of industrial production of low-grade bauxite treatment through the calcification and carbonization method, we aimed to further examine the changing dynamics of reaction conditions at each stage within a semi-industrial scale device. This study also sought to identify the industrial production equipment required for core processes such as calcification and carbonization. We conducted a semi-industrial experiment with a capacity of 120 kt/y, utilizing low-grade bauxite containing kaolinite, illite, and chlorite sourced from Shanxi and Henan regions, building upon prior laboratory research. This experiment serves as an experimental basis and reference for the future industrial application of the process. Under the experimental conditions of 265 °C, a calcium-silicon ratio of 2.75:1, a liquid-solid ratio of 5:1, and an alkali concentration of sodium aluminate solution ranging from 265 to 270 g/L of Na_2O, a portion of the dissolved slurry was filtered and washed every hour after the commencement of the experiment. The changes in the composition of each component in the solid phase were analysed, as illustrated in Figure 3 and Table 2.

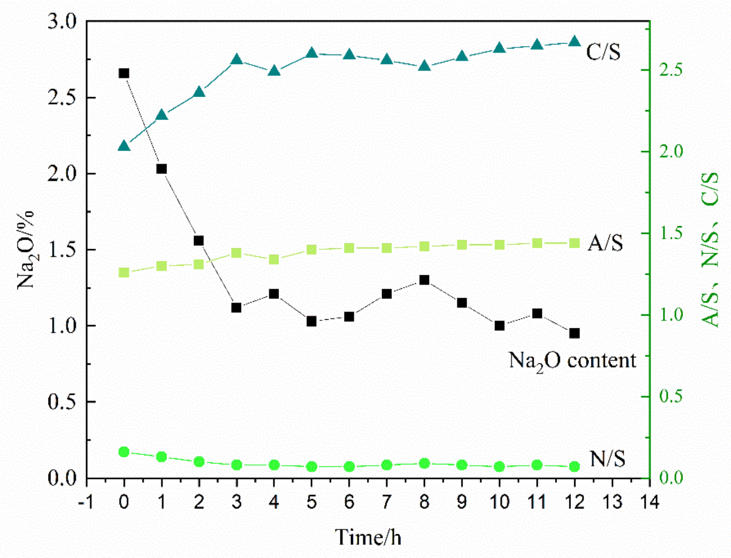

Figure 3. Content of each component in solid phase products dissolved from bauxite.

Table 2. Effects of calcification ratio on Na_2O and A/S (mass fraction /%).

#	Al_2O_3	SiO_2	Fe_2O_3	TiO_2	K_2O	Na_2O	CaO	MgO	Al/Si	Na/Si	Ca/Si
1	22.36	20.48	7.94	4.25	1.31	5.76	21.38	0.97	1.09	0.28	1.04
2	21.65	18.42	6.78	3.7	0.76	4.42	27.13	1.13	1.18	0.24	1.47
3	21.21	17.02	6.66	3.43	0.56	3.44	30.16	1.18	1.25	0.20	1.77
4	20.81	16.36	6.2	3.19	0.46	2.51	32.7	1.34	1.27	0.15	2.00
5	20.44	15.78	5.57	2.86	0.28	2.03	35.04	1.06	1.30	0.13	2.22
6	20.91	14.75	4.36	2.58	0.19	1.3	37.16	1.17	1.42	0.09	2.52
7	20.71	14.42	4.47	2.56	0.13	0.95	38.46	1.14	1.44	0.07	2.67

From the data presented in Figure 3 and Table 2, it is evident that as the calcification dissolution reaction progresses, the calcium-silicon ratio of the dissolution slag gradually increases, while the Na_2O content in the slag steadily decreases. When the calcium-silicon ratio reaches 2.67:1, the mass fraction of Na_2O in the calcification dissolution slag is reduced to only 0.95 %. This observation indicates that the addition of calcium oxide effectively lowers the alkali content in the dissolution slag, thereby reducing alkali consumption in the alumina production process. Furthermore, an increase in the addition of calcium oxide during the calcification process significantly enhances the A/S ratio of the dissolved slag. This is attributed to the formation of hydrated garnet and hydrated calcium aluminate during the calcification process, which combine with a portion of the aluminium in solution, resulting in a slight increase in the A/S ratio of the calcified slag. After the bauxite is dissolved through calcification, the calcium-silicon ratio of the dissolved slag approaches a predetermined value of approximately 2.75 when it is transferred from the dissolution system to the calcification slurry tank for storage, in preparation for the subsequent aluminium carbonization process. An examination of the carbonization time and reaction pressure indicated that the semi-industrial experiments demonstrated superior control over temperature and mixing of reaction materials compared to laboratory conditions, thereby achieving better carbonization results at a pressure of 0.9 MPa and a reaction time of 60 minutes. Additionally, increasing the amount of carbonization can further reduce the A/S ratio in the final red mud; however, the enhancement effect becomes negligible when the carbonization is increased to three times the original amount. Consequently, it was determined that only the second carbonization is necessary, with the related results presented in Table 3.

Table 3. Results of multiple carbonization (aluminium dissolution experiment).

Number of Carbonized Dissolved Aluminium	**Results**			
	Al_2O_3(%)	**SiO_2(%)**	**A/S**	**Dissolution rate (%)**
1	13.92	14.43	0.96	78.9
2	11.81	13.89	0.85	81.32
3	10.58	12.89	0.82	81.98

As illustrated in Table 3, following the second carbonization treatment, the aluminium-silicon ratio (A/S) in the final red mud can be reduced to 0.85, achieving a comprehensive recovery rate of alumina of 81.32 %. Concurrently, the sodium oxide (Na_2O) content in the calcified dissolved slag is limited to only 0.95 %. This reduction not only minimizes the alkali consumption in alumina production but also mitigates the environmental impact of red mud, allowing it to be utilized as a raw material for other construction materials, such as cement. In contrast, using traditional Bayer dissolution processes on bauxite of the same grade yields a theoretical maximum alumina dissolution rate of 77.1 %, with a Na_2O mass fraction in the slag of approximately 10.0 % (when the red mud has an aluminium-to-silicon ratio of 1 and a sodium-to-silicon ratio of 0.608). Typically, the actual alumina dissolution rate in Bayer process plants is around 70 %, indicating that the calcification-carbonization method presents significant advantages in processing low-grade bauxite. The feasibility and stability of the calcification-carbonization method have been validated through semi-industrial tests, leading to further optimization of process parameters and equipment design. This provides a solid technical foundation and valuable experience for industrial production. Currently, we are actively advancing the industrial demonstration project for this technology and constructing a larger scale production unit. By integrating this method with the traditional Bayer process, we aim to achieve clean alumina production and large-scale, environmentally friendly utilization of red mud, thereby offering technical support for the sustainable development of the alumina industry.

2.2 Calcification-Biomass Method

The calcification-biomass process is proposed for high iron bauxite, i.e. adding biomass in the calcification transformation process to synergistically strengthen the dissolution process. The transformation of hematite to magnetite is realized at the same time with high efficient dissolution, and the transformation product can be obtained by magnetic separation to obtain concentrated iron ore powder, which can be used as raw material for pelletizing, and the non-magnetic tailings from magnetic separation can be directly used as raw material for cement or soil treatment, thus realizing the valuable resources and rational use.

2.2.1 Mineralogical Evolution

Biomass degradation can be divided into three stages[12], at lower temperatures (< 200 °C) starch and cellulose are first hydrolysed to generate reducing monosaccharides such as glucose/fructose, as the temperature increases (200-400 °C), glucose/fructose is further hydrolysed, depolymerized and degraded to generate small molecules of furfural, organic acids, and phenolic compounds, and finally gasification to generate gases such as H_2, CH_4 and CO (> 400 °C). The structure of biomass degradation products is shown in Figure 4. The carbon-carbon triple bond (-C≡C-), cumulative double bond (-C=C=C-), free aldehyde group (-CHO), hydroxyl (-OH) carbonyl (-C=O) in the structural unit of the degradation products are all strongly reducing groups, and phenolics are also a highly reducing organic reductant. This is the principle behind the reducing effect of starch and lignocellulosic biomass under alkaline hydrothermal conditions.

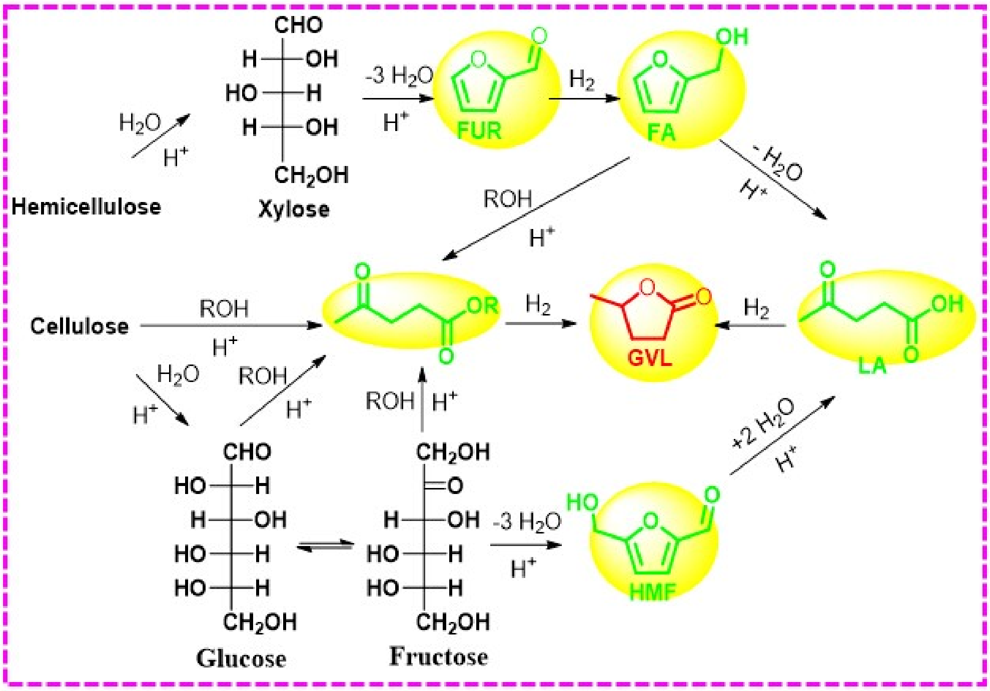

Figure 4. Structure of biomass hydrolysis products.

The iron phase in high iron bauxite exists in the form of iron trioxide (Fe_2O_3), and when it is added to a concentrated alkaline solution and heated, Fe_2O_3 reacts with OH^- to generate free $Fe(OH)_4^-$, as shown in Equation (4).

$$Fe_2O_3 + 2OH^- + 3H_2O = Fe(OH)_4^- \quad (4)$$

Hydrolysis of biomass produces reducing groups capable of reducing $Fe(OH)_4^-$ to form Fe_3O_4, as shown in Equation (5).

$$Fe(OH)_4^- + R\text{（Reducing group)}= Fe_3O_4 + OH^- \quad (5)$$

Thus, under alkaline hydrothermal conditions, biomass is able to transform the iron-rich phase by hydrolysing to form reducing groups to obtain a magnetite phase with a high degree of monolithic dissociation (Figure 5).

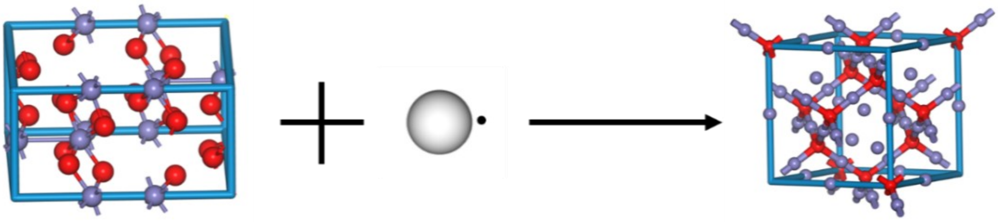

Figure 5. Iron oxide cell reacts with R (reducing group) to form iron tetroxide cell.

2.2.2 Results from Calcification - Biomass Method

The primary chemical compositions of the bauxite trihydrate imported from Australia were processed using the 'calcification-biomass transformation' method, as illustrated in Table 4. The physical composition of the ore is depicted in Figure 6, revealing that the predominant physical components of the mineral are alumina trihydrate and hematite. This mineral exhibit high iron and aluminium content, along with a relatively elevated aluminium-silicon ratio.

Table 4. Main chemical composition of raw ore (%)

Element	Al_2O_3	SiO_2	CaO	Fe_2O_3	TiO_2	Na_2O	A/S
Content	58.2	5.49	0.149	28.4	2.51	0.0325	10.60

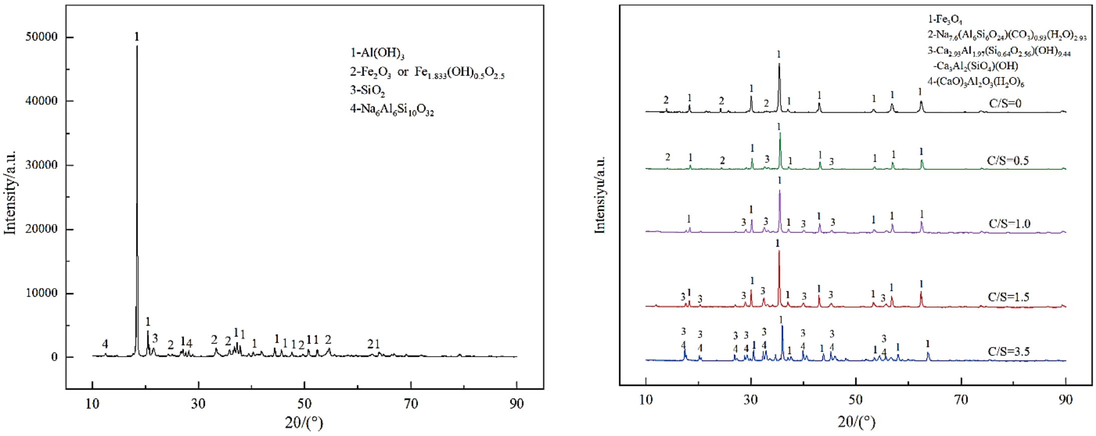

Figure 6. XRD patterns of transformed red mud from raw ore (left) and at different Ca/Si ratios (right).

The primary technical conditions employed in this study included a dissolution temperature of 280 °C, a mass ratio of corn starch to bauxite Fe_2O_3 of 1:4, a Na_2O concentration of 260 g/L, the molecular ratio of mother liquor (a_k) value of 3.5, and a liquid-to-solid (L/S) ratio of 5:1. The slag samples obtained under varying calcium-to-silica (Ca/Si) conditions are illustrated in Figure 7. The original ore, characterized by a reddish hue, underwent treatment through the "Calcification-Biomass Transformation" process, resulting in gray-brown hematite mud, which indicates a transformation of the hematite phase. Following this transformation process, further X-ray diffraction (XRD) analysis of the slag samples, as depicted in Figure 6 on the right, revealed that the original hematite phase primarily transitioned into the magnetite phase, which is advantageous for subsequent iron extraction via magnetic separation. Additionally, a portion of the iron phase was converted into ferrihydrated garnet, thereby enhancing the dissolution process of Al_2O_3. In the absence of lime, the aluminium-containing silica phase predominantly exists as a sodium aluminosilicate phase. However, as the calcium-to-silica ratio increases, the sodium aluminosilicate phase gradually diminishes and is replaced by the hydrated garnet phase, effectively blocking the source of sodium and alkali. The results of the XRD analysis of red mud indicated that the predominant iron phase in the red mud produced under various calcium-to-silica ratios was the magnetite phase, with the reduction of the iron phase showing minimal dependence on the calcium-to-silica ratio.

Globally, high-iron bauxite resources are extremely abundant. However, traditional treatment methods not only lead to significant environmental pollution but also hinder the recycling of strategic mineral resources such as iron [13]. This paper proposes the use of novel technology that involves the coupled calcification-biomass transformation treatment of high-iron bauxite, focusing on altering the structural composition of the solid phase (red mud) during the bauxite dissolution process. This approach aims to achieve source-blocking cleaner production of alumina from high-iron bauxite and to facilitate the effective utilization of valuable resources.

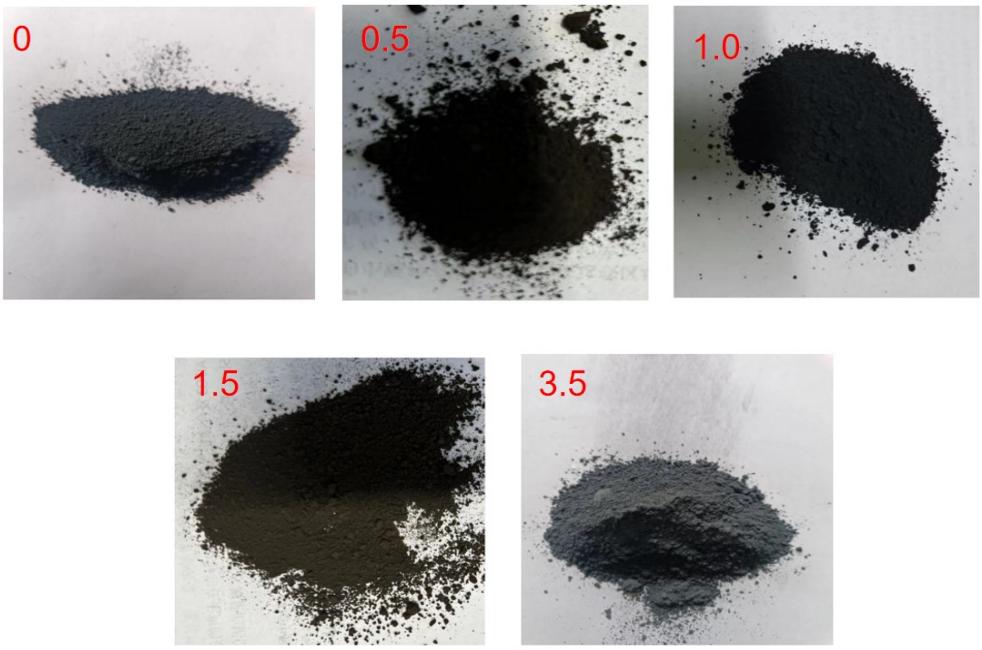

Figure 7. Red mud samples under different Ca/Si ratios.

2.3 Calcification - Potassium Alkali Method

For low-grade bauxite, the traditional Bayer method has low resource utilization rate, poor economic benefits, and produces strong alkaline by-product red mud, which has high sodium-alkali content and complex structure, making it difficult to be comprehensively utilized on a large scale. Therefore, for the low-grade bauxite ore, the proposed calcification-potassium alkali method adopts potassium alkali instead of sodium alkali required for the production of alumina by the traditional Bayer method, and lime is added in the process of dissolution, which can realize the sodium-free production of alumina, change the solid-phase equilibrium structure of red mud, and ultimately, the red mud produced does not contain harmful sodium, and obtain a new type of structural red mud with calcium aluminosilicates and potassium aluminosilicates, which can be used as the raw material source of silica and potassium minerals used in fertilizer or soil treatment.

2.3.1 Mineralogical Evolution

This method begins with the reconstruction of the mineral phase. By employing the principle of mineral phase reconstruction without altering the original equipment, KOH is utilized instead of NaOH to produce alumina. This substitution significantly enhances the dissolution rate of medium- and low-grade bauxite, transforming the product from hydrated sodium aluminosilicate (Na_2O-Al_2O_3-$1.7SiO_2$-nH_2O) to potassium aluminosilicate (K_2O-Al_2O_3-SiO_2). This transformation allows for the synergistic preparation of silica-potassium-calcium composite fertilizers, which can be applied in agricultural and other fields [14]. This process not only improves economic efficiency compared to the traditional Bayer method but also facilitates the clean production of slag-free alumina, eliminating the need for red mud dumps. Consequently, it holds excellent application prospects for the efficient utilization of low- and medium-grade bauxite and for green engineering initiatives [15].

$$AlOOH + KOH + H_2O = KAl(OH)_4 \tag{6}$$

$$Al_2O_3 \cdot 2SiO_2 \cdot 2H_2O + 2KOH = K_2O \cdot Al_2O_3 \cdot 2SiO_2 + 3H_2O \quad (7)$$

$$Al_2O_3 \cdot 2SiO_2 \cdot 2H_2O + 3Ca(OH)_2 + KAlO_2 = 3CaO \cdot Al_2O_3 \cdot SiO_2 \cdot 4H_2O + KAlSiO_4 + H_2O \quad (8)$$

2.3.2 Results from Calcification-Potassium Alkali Method

The process of transforming bauxite ore using the calcification-potassium alkali method involves raw material sourced from an alumina plant in Shanxi, China. The primary chemical composition of the bauxite ore is detailed in Table 5. Additionally, the physical phase composition of the ore is illustrated in Figure 8. The analysis reveals that the predominant physical phase of the mineral is monohydrate alumina, while the silica-containing mineral phase is identified as kaolinite. This ore exhibits notable characteristics of high aluminium content and high silicon content.

Table 5. Main chemical composition of bauxite.

Element	Al_2O_3	SiO_2	Fe_2O_3	TiO_2	K_2O	MgO	CaO
Content	45.26	16.54	12.14	2.47	2.41	0.21	1.37

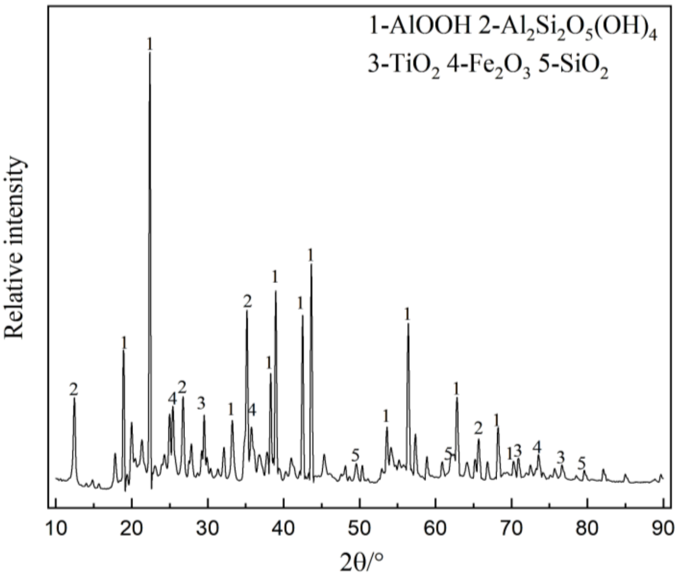

Figure 8. XRD pattern of bauxite raw materials.

Alumina monohydrate ore served as the raw material for the calcification transformation, conducted at a reaction temperature of 280 °C, with a K_2O concentration of 260 g/L, a calcium to silica ratio of 0.2:1 (Ca/Si), a stirring speed of 300 r/min, and hydrothermal leaching for 1 hour. The resulting transformation slag was analysed for its oxide chemical composition using X-ray fluorescence (XRF), as presented in Table 6. The calcification potassium-alkali method yielded favourable results in the laboratory, with mass fractions of K_2O and SiO_2 in the transformation slag recorded at 8.67 % and 21.2 %, respectively. Notably, the aluminium to silica ratio of the transformation slag reached an innovative value of 0.93, which is lower than the theoretical aluminium to silicon ratio of red mud produced by the traditional Bayer method.

Table 6. Main chemical components of calcified potassium alkali transition slag.

Element	Al_2O_3	SiO_2	Fe_2O_3	TiO_2	K_2O	CaO	MgO
Content	19.76	21.2	20.21	3.13	8.67	8.6	1.43

The economic benefit analysis presented in Table 7 indicates that, when solely accounting for the costs associated with ore, red mud, and alkali consumption, the production of Al_2O_3 from bauxite using the calcification-potassium alkali method demonstrates an economic efficiency improvement of approximately 1000 CNY compared to the traditional Bayer method utilizing sodium alkali. Furthermore, this method enhances the utilization rate of red mud, addressing the global challenge of high soda ash red mud consumption. It facilitates the recovery of tens of thousands of square meters of land from existing red mud landfill sites, thereby reducing environmental pollution while simultaneously improving arable land quality. This approach embodies an efficient and environmentally friendly production method for alumina from China's typical low-grade bauxite ore.

Table 7. Comparison table of economic analysis of bauxite treated with sodium alkali and potassium alkali.

Category	Sodium alkali	Potassium alkali
Solid-phase equilibrium composition	$Na_2O·Al_2O_3·1.7SiO_2$	$K_2O·Al_2O_3·2SiO_2$
The aluminium-silicon ratio of red mud（Al/Si）	1	0.85
The alkali-silicon ratio of red mud（Na/Si、K/Si）	0.608	0.783
Theoretical dissolution rate	66.7 %	71.7 %
The ore consumption for producing 1 tonne of Al_2O_3	2.347 t	2.183 t
The amount of red mud produced in the production of 1 tonne of Al_2O_3	1.86 t	1.73 t
Specific treatment cost	-25 CNY/t	1300 CNY/t
Red mud treatment cost	-46.5 CNY	2249 CNY
Alkali consumption for producing 1 tonne of Al_2O_3	0.120 t	0.173 t
Economic comparison (Ore consumption + Alkali consumption + red mud value)	-1099.32 CNY	210.1CNY

This study also investigates the effect of applying red mud transformed sludge-silica-potassium mineral fertilizer on the growth of Chinese cabbage through potting experiments, as illustrated in Figure 8. Specifically, Figure 8(a) and (d) depict the growth state of Brassica napus seedlings after 15 days of sowing in natural soil, while (b) shows their growth after 25 days, (c) after 65 days, (e) after 10 days of applying red mud transformed slag, (f) 50 days after applying red mud transformed slag, and (g) represents the growth state of the pelletized red mud transformed slag-silica-potassium mineral fertilizer. Additionally, (h) provides a comparison of cabbage plants after uniform sampling, and (i) and (j) present the front views of (c) and (f), respectively. From Figure 8, it is evident that the application of red mud transformation sludge positively influences the growth of Chinese cabbage. As shown in (b) and (c), cabbage grown in natural soil without the application of red mud transformation sludge exhibits slow growth, characterized by wilting, a small mature leaf area, and yellowing of the leaf surfaces. In contrast, comparing Figures (b), (e) and (c), (f) indicates that after the application of transformation sludge, cabbage development improves significantly, with a larger and more vigorous mature leaf area.

A comparison of plant heights from two pots containing uniform samples reveals that the average height of Chinese cabbages after the application of transformation residue reaches 20 cm, which is significantly greater than that of cabbages harvested from natural soil. Furthermore, it is observed that the number of leaves per plant in natural soil is lower, whereas the application of transformation slag results in an increased leaf count per plant. The robust growth and development of cabbages following the application of red mud transformation sludge is closely linked to the abundance of silicon, potassium, calcium, and other essential elements. The application of red mud in the slag not only neutralizes the acidity of natural soil but also enhances the effective nutrient content, thereby increasing the availability of silicon, potassium, calcium, and other nutrients for cabbage absorption. Silicon and potassium are particularly beneficial for promoting plant photosynthesis, facilitating improved nutrient uptake, resulting in sturdier stalks and increased yields. Therefore, the transformation slag of red mud supplies essential nutrients for the growth and development of Chinese cabbage, effectively promoting its growth and increasing yield. This indicates that the preparation of silica-potassium mineral fertilizer via hydrothermal leaching of red mud with KOH holds significant agricultural application value.

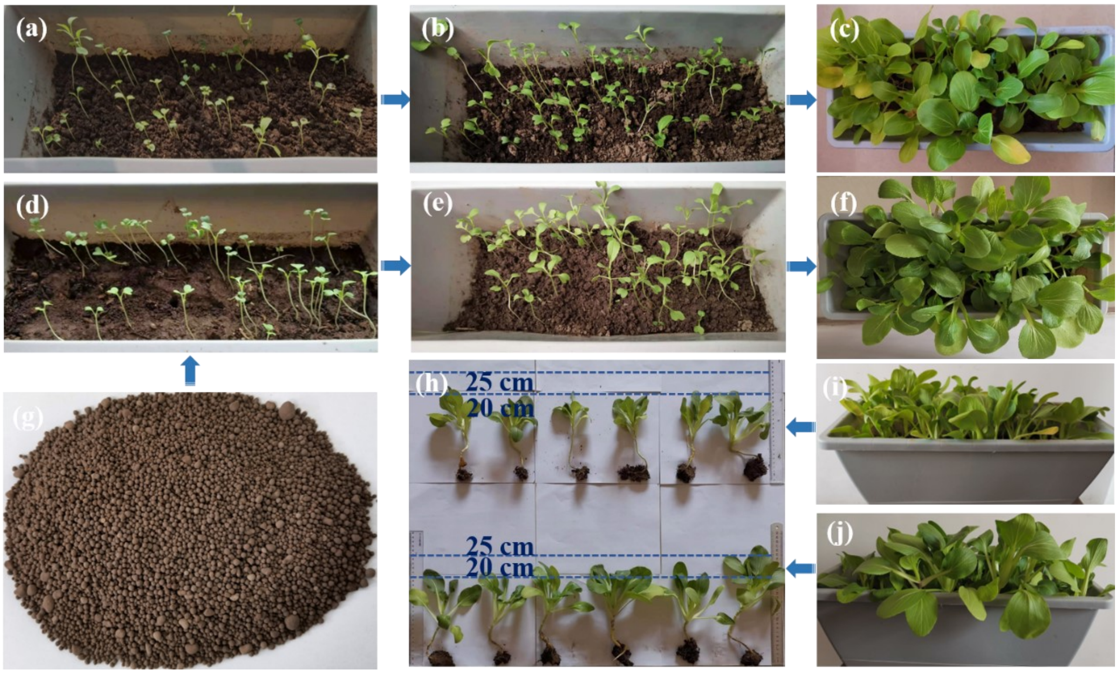

Figure 8. Growth status of Chinese cabbage at different periods.

3. Conclusion

The calcification transformation method based on mineral phase reconstruction proposed in this paper provides an innovative solution for the efficient utilization of medium- and low-grade bauxite and the large-scale harmless utilization of red mud. Through the core technologies of calcification-carbonation, calcification-biomass and calcification-potassium alkali, the efficient recovery of alumina from the bauxite leaching process and the reduction of sodium oxide emission are realized, and the Na_2O content in the transformation slag is less than 1 %, so that the pollution caused by the red mud is blocked from the source. Calcification - carbonation method can be used for cementation or soil treatment of a “new” red mud; Calcification - biomass method makes the transformation rate of hematite to magnetite reach more than 90 % and realizes the high efficiency recovery of iron oxide; Calcification - potassium alkali method, utilizes the transformed slag as mineral composite fertilizer to realize the high-value utilization. These technologies have achieved good results in laboratory and semi-industrial tests, providing strong technical support for the clean production and sustainable development of the alumina industry, and the research results are of great theoretical and practical significance in promoting the scientific and technological progress of alumina industry.

4. References

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