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Value Addition to Odisha's Bauxite Reserves: Developing Sustainable Alumina Production Technologies

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Abstract

Odisha, home to one of the largest bauxite reserves in India, is a critical hub for the country's aluminium industry. The extraction and processing of bauxite into alumina, however, pose significant environmental challenges, necessitating the adoption of sustainable technologies. With growing global emphasis on green practices and stringent environmental regulations, the alumina industry must innovate to balance economic growth with ecological responsibility. This study explores the latest advancements in sustainable alumina production technologies, focusing on their relevance and potential implementation in Odisha's industrial landscape. Key areas of innovation include energy-efficient refining processes, waste management strategies, and the utilization of alternative raw materials to reduce dependency on high-grade bauxite. The study also examines the role of low-carbon technologies such as renewable energy integration, improved Bayer process modifications, and zero-waste solutions like red mud valorisation. These approaches aim to enhance resource efficiency while mitigating adverse environmental impacts. Furthermore, the study highlights industry-driven initiatives and policy frameworks that support sustainable alumina production. Case studies from global best practices are analysed to draw insights into how Odisha's alumina sector can align with international sustainability standards. Collaborative efforts between government bodies, research institutions, and industry stakeholders are also discussed, emphasizing the need for technology adoption and regulatory support to foster responsible mining and refining practices. By addressing both technical advancements and policy measures, this study provides a comprehensive perspective on how Odisha can leverage its bauxite reserves for long-term industrial sustainability. The findings contribute to the discourse on eco-friendly alumina production and serve as a roadmap for developing Bauxite Residue an environmentally resilient and economically viable aluminium sector in the region.

Keywords: Odisha, bauxite reserves, sustainable technologies, green practices, waste management, valorisation

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INTRODUCTION

Odisha stands as a beacon of mineral wealth in India, particularly due to its vast deposits of bauxite, which form the backbone of the aluminium industry. Bauxite, a sedimentary rock with high aluminium content, is the principal ore used for aluminium extraction. In India, nearly 50% of the country's bauxite reserves are located in Odisha, making it a crucial geographical zone for mining and metallurgical activities. The state's strategic advantage is further amplified by its proximity to ports, industrial hubs, and an established network of mining infrastructure. However, the journey from bauxite mining to refined aluminium presents a range of socio-environmental complexities and technological challenges that warrant a rethinking of traditional production paradigms [1, 2]. Historically, alumina extraction has relied heavily on the Bayer process, an energy-intensive method that involves high-temperature digestion and caustic soda usage to separate alumina from bauxite. While effective, this process generates significant quantities of bauxite residue, commonly known as red mud, which poses considerable disposal challenges due to its alkalinity and volume [3].

In Odisha, where large-scale alumina refineries operate near ecologically sensitive regions, the safe disposal and management of red mud have become pressing issues. With increasing environmental consciousness and the global shift toward net-zero industrial practices, the imperative Low-grade Bauxite to develop sustainable alumina production methods has never been stronger. For Odisha, the challenge is not just to mine and refine, but to do so responsibly, ensuring that the economic gains from resource extraction do not come at the cost of environmental degradation [4].

In recent years, technological innovations have emerged as powerful tools to transition the alumina industry toward sustainable growth. These include novel refining techniques that reduce energy consumption, integration of renewable energy sources like biomass and solar power, and circular economy models that seek to transform industrial waste into value-added products. Odisha, with its unique confluence of natural resources, industrial capacity, and scientific talent, is well-positioned to lead this transformation. However, unlocking this potential requires a coordinated effort among industry stakeholders, research institutions, and policymakers. This study delves into the opportunities and challenges of sustainable alumina production in Odisha, highlighting the technologies, case studies, and policy frameworks that can pave the way for a greener and more resilient aluminium sector.

INNOVATIONS IN SUSTAINABLE ALUMINA PRODUCTION

Alumina, or aluminium oxide (Al_2O_3), is a critical intermediate product in the value chain of aluminium production. As demand for aluminium grows globally, driven by its use in infrastructure, transportation, packaging, and renewable energy, so too does the environmental impact of alumina production [5]. Traditionally, the industry has relied heavily on the Bayer process, an energy-intensive method that generates significant volumes of red mud, a hazardous waste. In the face of climate change, ecological degradation, and community resistance to environmentally destructive mining and processing practices, sustainable innovations in alumina production have become imperative.

Odisha, with its vast bauxite reserves, holds a strategic position in India's alumina production landscape. The focus now shifts from mere extraction to responsible utilization, aiming to align the economic potential of these reserves with sustainable development goals. Innovations in process technology, waste management, energy efficiency, and circular economy principles are playing a pivotal role in this transformation [6].

Modified Bayer Process

The Bayer process, developed over a century ago, remains the dominant method for extracting alumina from bauxite (Figure 1). However, modern variations aim to improve energy efficiency and reduce waste. Innovations include:

- *High-pressure digestion optimization:* Researchers have optimized temperature and pressure profiles to reduce caustic soda consumption and improve alumina yield.
- *Use of additives:* Certain mineral additives can improve desilication and increase the recovery rate, reducing the formation of red mud.

Alternative Extraction Techniques

To supplement and eventually replace the Bayer process, several alternative methods are under development:

- *Acid leaching:* Using mineral acids like HCl or H_2SO_4 to leach alumina from low-grade ores or red mud itself. This method produces less waste and can recover rare earth elements.

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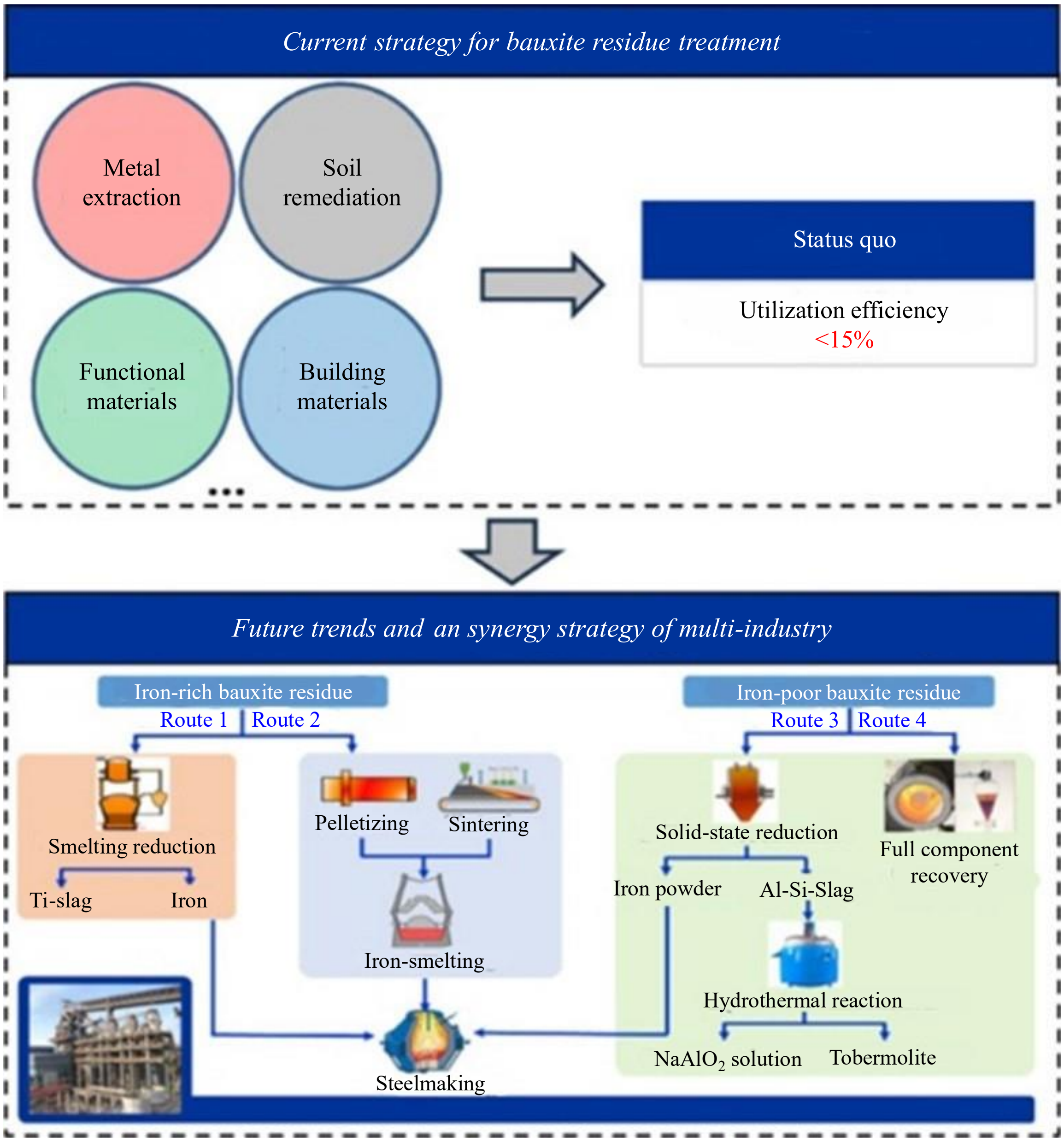

Figure 1. Process diagram for bauxite residue reduction.

- *Molten salt electrolysis:* Although still in pilot stages, this technique directly produces aluminium from bauxite without intermediate alumina refining, reducing energy consumption.
- *Bioleaching:* Using microbes to break down bauxite or red mud to release alumina, this eco-friendly technique is promising for low-grade ore deposits.

Red Mud Management and Valorisation

The generation of red mud remains a critical environmental concern in the Bayer process. Recent advancements have focused on minimizing the volume of residue through process optimization. In 2023, Vedanta Aluminium, in collaboration with IIT Kharagpur, developed a proprietary technique that reduces bauxite residue generation by nearly 30%. This process enhances alumina yield and significantly reduces the total organic content in the waste stream. Laboratory validation has demonstrated promising results, and pilot-scale implementation is underway. These improvements not only mitigate waste management issues but also lower production costs by increasing raw material efficiency [5].

Red mud is the most significant environmental liability in alumina production. Each ton of alumina produces 1.5–2 t of red mud. Following are the innovations focused on red mud utilization.

Red Mud Utilization

- *Construction materials:* Research is demonstrating the viability of using red mud in bricks, tiles, and cement, turning waste into a valuable input.
- *Metal recovery:* Technologies like plasma smelting or acid leaching can recover rare earth elements (REEs), iron, titanium, and scandium from red mud.
- *Soil remediation and road building:* Pilot projects have shown that treated red mud can be used as a soil amendment or in road construction, provided leachability is controlled.

Dry Stacking Technology

Instead of conventional red mud ponds, which pose a risk of catastrophic failure and groundwater contamination, dry stacking involves dewatering red mud to minimize its environmental footprint. Though more expensive upfront, it offers long-term sustainability benefits [6].

Energy Efficiency and Decarbonization

As part of the broader decarbonization strategy, Odisha's alumina producers are increasingly integrating renewable energy into their operations. One such initiative involves the use of biomass briquettes derived from local agricultural waste. In 2024, Vedanta Aluminium began using these briquettes at its Lanjigarh refinery, displacing significant quantities of fossil fuel and reducing annual CO_2 emissions by over 10,000 t. This not only supports climate goals but also stimulates rural economies by providing an alternate revenue stream to farmers [7].

Solar and wind energy are also being considered for long-term integration, particularly for powering ancillary operations such as water treatment, lighting, and administrative facilities. The use of hybrid energy systems combining solar and biomass has the potential to meet a substantial portion of a refinery's base load.

Energy accounts for nearly 30% of the production cost in alumina refining. Sustainability requires innovations that reduce fossil fuel dependence and carbon emissions. Energy consumption during alumina and aluminium production accounts for a substantial portion of the industry's carbon footprint. To address this, Vedanta Aluminium introduced a patented pot-lining technology designed to enhance energy efficiency in aluminium smelting. The innovation reduces energy use by 200 to 250 kWh/t of aluminium and extends the operational lifespan of smelting pots. These gains contribute to lower greenhouse gas emissions and operational costs [8].

Use of Renewable Energy

- *Solar thermal energy:* High-temperature solar energy can be used for calcination and digestion stages in the Bayer process.
- *Biomass and green hydrogen:* Replacing fossil fuels with biomass or hydrogen in high-temperature processes is gaining traction.

Heat Recovery Systems

Advanced heat exchangers and regenerative systems are now used to capture and reuse heat from digestion and precipitation stages, reducing overall energy demand by up to 15%.

Digitalization and AI for Energy Management

Digital twins, AI-based process simulations, and predictive maintenance tools optimize energy use and reduce downtime. These digital interventions help refineries respond dynamically to fluctuating energy prices and availability.

Water Efficiency and Zero Liquid Discharge (ZLD)

Water is another critical input in alumina refining. Sustainable practices now emphasize:

- *Closed-loop water systems:* Recycling and reusing process water significantly reduce freshwater intake.
- *ZLD technologies:* Systems that recover water and crystallize dissolved solids ensure no discharge of effluents into the environment.
- *Rainwater harvesting:* Particularly in monsoon-rich regions like Odisha, collecting and using rainwater for process needs is both sustainable and cost-effective.

Sustainable Mining of Bauxite

Before alumina can be refined, bauxite must be mined, often from ecologically sensitive areas. Innovations in this upstream segment include:

- *Precision mining:* Use of drones, GIS, and remote sensing to reduce overburden removal and optimize ore extraction.
- *Biological reclamation:* Reforestation and ecological restoration of mined lands using native plant species.
- *Community-integrated mining:* Social innovations include benefit-sharing models, skill development for local youth, and establishing green buffers around mining sites.

Circular Economy and Industrial Symbiosis

The principle of circular economy is gradually being embedded into alumina production. One notable example is Runaya's state-of-the-art facility in Jharsuguda, which converts dross, a byproduct of smelting, into calcium aluminate. With an annual capacity of 12,000 Mt, this plant exemplifies how industrial waste can be transformed into a high-demand input for the steel industry. This approach aligns with the concept of zero waste and contributes to reducing landfill pressure and environmental hazards [9].

In addition, ongoing research explores the potential uses of red mud in the construction sector (as bricks and tiles), ceramics, and as a raw material in cement production. These avenues can transform red mud from a liability into a resource, reducing the ecological footprint of alumina refining [10]. Adopting circular economy models ensures that waste from one process becomes input for another:

- *Industrial Symbiosis Parks:* Alumina plants can be co-located with cement, brick, and metallurgy industries that utilize red mud, fly ash, and other byproducts.
- *Co-Processing of Waste:* Integrating waste streams from steel, power, and alumina industries allows for mutual sustainability benefits.

STRATEGIC IMPLICATIONS FOR ODISHA

Odisha is poised to emerge as a global leader in sustainable alumina production by aligning technological advancement with strategic policy interventions. Adopting green innovations can provide multifaceted benefits:

1. *Regulatory compliance:* Implementation of environmentally friendly processes ensures adherence to stringent pollution control norms and facilitates the acquisition of environmental clearances.
2. *Economic competitiveness:* Efficient use of energy and raw materials leads to cost savings, enhancing the global competitiveness of alumina producers.
3. *Employment and community development:* Renewable energy projects and circular economy initiatives support local employment, especially in rural areas, and foster positive community relations.
4. *Resource security:* Efficient utilization of medium- to low-grade bauxite deposits ensures resource longevity and reduces the pressure on high-grade reserves [7].

The cumulative impact of these initiatives will reinforce Odisha's vision of achieving a sustainable, inclusive, and economically robust industrial ecosystem [8].

POLICY AND COLLABORATIVE FRAMEWORKS

Technology alone is not enough. Regulatory frameworks, financial incentives, and institutional alignment are essential.

- *Extended producer responsibility (EPR):* norms can hold refineries accountable for waste management.
- *Carbon credits and green financing:* Alumina plants adopting energy-efficient practices may earn carbon credits, unlocking international green finance.
- *Academic-industry collaborations:* Institutions like NALCO's R&D centre, IITs, and universities in Odisha are working closely with the industry to develop scalable solutions.

Government support plays a crucial role in promoting sustainable practices. Incentives for adopting green technologies, such as tax benefits, subsidies for renewable energy, and support for R&D, are essential.

Public-private partnerships (PPP) are also gaining traction. Joint ventures between refineries and academic institutions such as IITs can accelerate the commercialization of research. Moreover, industry forums and knowledge-sharing platforms are facilitating the diffusion of best practices.

Establishing a dedicated "Green Refining Mission" under the Ministry of Mines or the Ministry of Environment could help in standardizing sustainability benchmarks and monitoring industry-wide performance [9].

CONCLUSION

The aluminium industry in Odisha stands at a crossroads, where the need for industrial growth must be balanced with environmental stewardship. Embracing sustainable technologies offers a pathway to achieve both. With a focus on reducing red mud, improving energy efficiency, integrating renewable sources, and capitalizing on waste-to-wealth opportunities, Odisha can transform its bauxite wealth into a sustainable advantage. Continued collaboration among stakeholders, policy innovation, and a commitment to green practices will be pivotal. This transformation is not only crucial for Odisha's future but can serve as a model for sustainable mining and refining globally. Odisha, blessed with rich bauxite reserves and a growing ecosystem of research and industry players, is well-positioned to lead this transformation. By embracing innovations, both technological and social, India can not only meet its domestic aluminium demand but also emerge as a global hub for sustainable alumina production. In this journey, collaboration is key, between policymakers, industry leaders, researchers, and communities. The goal is not just to refine alumina, but to refine our approach to development: one that is smart, sustainable, and future-ready.

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