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Possibility of utilizing red mud waste in industrial applications: A panoramic review

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Abstract

Red mud, a byproduct of bauxite processing for aluminum, poses environmental challenges due to its high alkalinity and substantial generation, exceeding 175.5 million tons annually and totaling around 4 billion tons by 2022. This hazardous waste threatens pollution and incurs significant liabilities for responsible companies. Despite studies demonstrating the potential for integrating red mud into ceramic materials, large-scale applications remain absent. This review provides a panoramic overview of the status of red mud production, including a comprehensive characterization of the globally available red mud to elucidate its material properties. Furthermore, the review underscores the potential hazards associated with red mud in relation to public health and environmental concerns. In addition, it aims to assess the viability of red mud applications across various domains, including its utilization in highway and road construction, incorporation as a component in ceramic and cement manufacturing, geotechnical applications, material recovery, and its roles in water, wastewater, and industrial gas treatment. The review also explores red mud's potential as a catalyst, coloring agent, foaming material, radiation-shielding material, and in agricultural applications. Effective market acceptance of red mud products hinges on addressing safety and environmental concerns, as well as raising public awareness of their benefits. Beyond application in construction industry, red mud can be utilized in recovery of materials. However, its economic viability depends on composition and recovery methods. Ongoing research and collaboration between academia and industry are essential to develop strategies that make red mud inert and enhance its mechanical performance. Properly utilizing red mud can reduce landfill waste, prevent contamination, and promote sustainable resource management, turning waste into valuable assets across sectors.

Keywords: Red mud. Environmental hazard. Reuse applications, Construction material. Environmental applications.

1. Introduction

Red mud, a byproduct produced during alumina extraction from bauxite ore, called as the Bayer process. The process consists of four main steps: digestion, clarification, precipitation, and

calcination (Figure 1). This material has become a focal point of concern due to its environmental impact and the potential for valorization. The production and management of red mud present significant challenges in many regions, leading to increased research into sustainable practices.

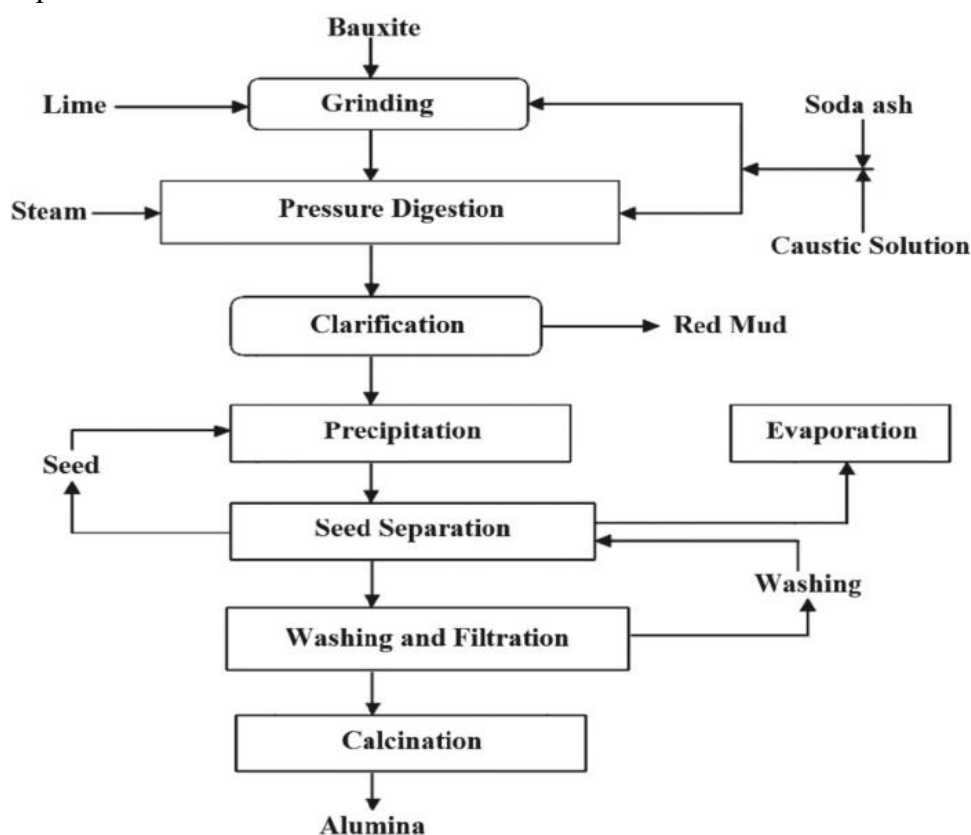


Figure 1: Simplified flowchart of Bayer process used for extraction of alumina from bauxite ore. Source: (Learnmetallurgy, 2024)

Red mud is arguably the most pressing issue associated with alumina production, primarily due to its caustic nature. While red mud can be stored in impoundments, researchers have explored various methods for its reuse following adequate treatment.

At present, the majority of red mud produced by alumina processing plants is either disposed of in landfills or dumped at sea. The associated disposal costs are substantial, constituting approximately 5% of alumina production expenses (Kumar et al., 2006). Despite efforts to manage its storage, red mud remains a hazardous material that poses serious environmental risks, including the contamination of surface and groundwater, which can adversely affect public health.

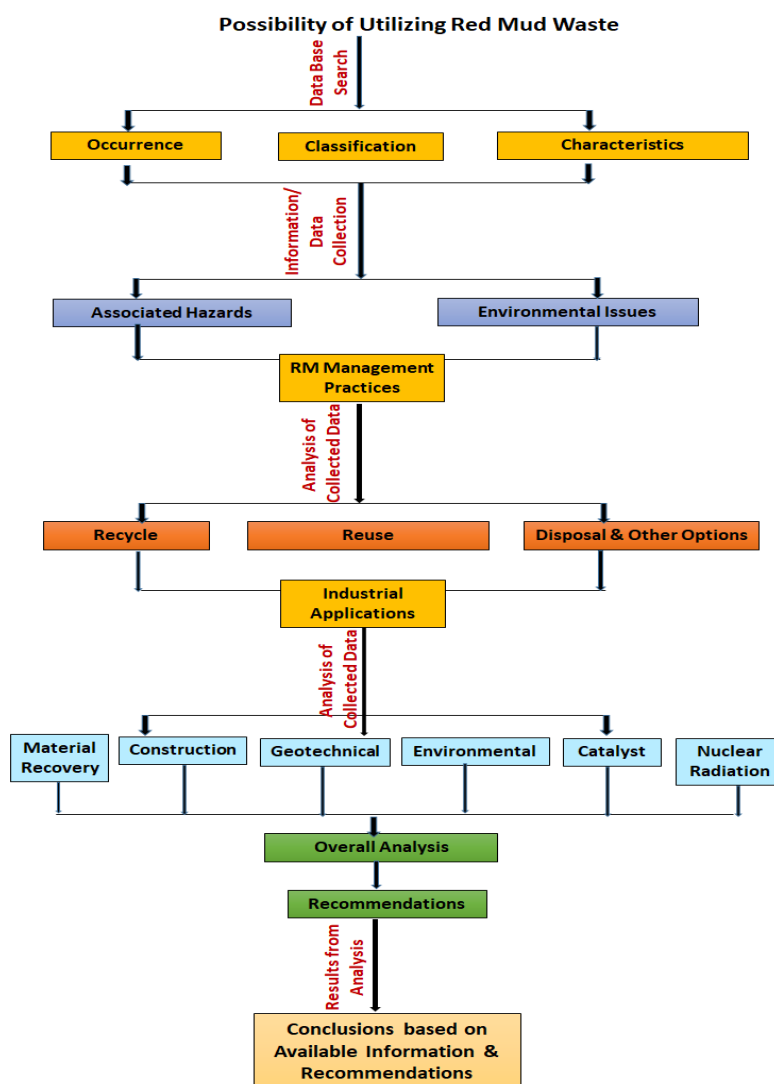
Efforts to repurpose red mud from industrial landfills are crucial for sustainable waste management. Investigations have substantiated its potential application in various construction materials, demonstrating enhanced mechanical properties, particularly increased strength. Moreover, red mud has been successfully utilized as an adsorbent for gas cleaning and wastewater treatment, as well as a catalyst for the purification of waste gases and liquids. However, the implementation of these technologies is hindered by the lack of supportive policies, leading to continuous accumulation of this waste and the expansion of occupied land areas. Effective policies are imperative to promote large-scale reuse.

This literature review aims to assess the global landscape of red mud production, focusing on its composition, environmental impacts, and remediation strategies. It examines the challenges of managing red mud, a hazardous byproduct of alumina extraction, and evaluates innovative reuse approaches in construction, wastewater treatment, and recovery of valuable metals. By

synthesizing research on these applications, the review seeks to identify opportunities for safe red mud integration into sustainable practices, reducing environmental harm and supporting circular economy initiatives. Additionally, it will highlight policy gaps and the need for frameworks that promote transitioning red mud from waste disposal to resource recovery in industrial processes.

2. Review methodology

This review employs a systematic approach to gather reliable and succinct information concerning the effective utilization of red mud. This process begins with an overview of the issues associated with red mud, highlighting its potential to reduce landfill waste, mitigate environmental contamination, and promote sustainable resource management by transforming waste into valuable assets across various sectors. The subsequent focus addresses specific scenarios and academic publications on the environmental impacts of red mud accumulation. This section assesses the feasibility of red mud applications across multiple domains, including highway and road construction, ceramic and cement production, geotechnical uses, material recovery, and its roles in water, wastewater, and industrial gas treatment, as depicted in Figure



2.

Figure 2: Review process to analyze the possibility of utilizing red mud for beneficial purposes

2.2. Source of Information

The review utilizes three major databases: Scopus, Web of Science (WoS), and DOAJ. These databases host extensive collections of peer-reviewed research abstracts and citations. A systematic search was conducted using Boolean operators along with relevant keywords, primarily targeting recent literature on the harmful effects, beneficial uses, and industrial applications of red mud published between 2000 and October 2024 as depicted in Figure 3.

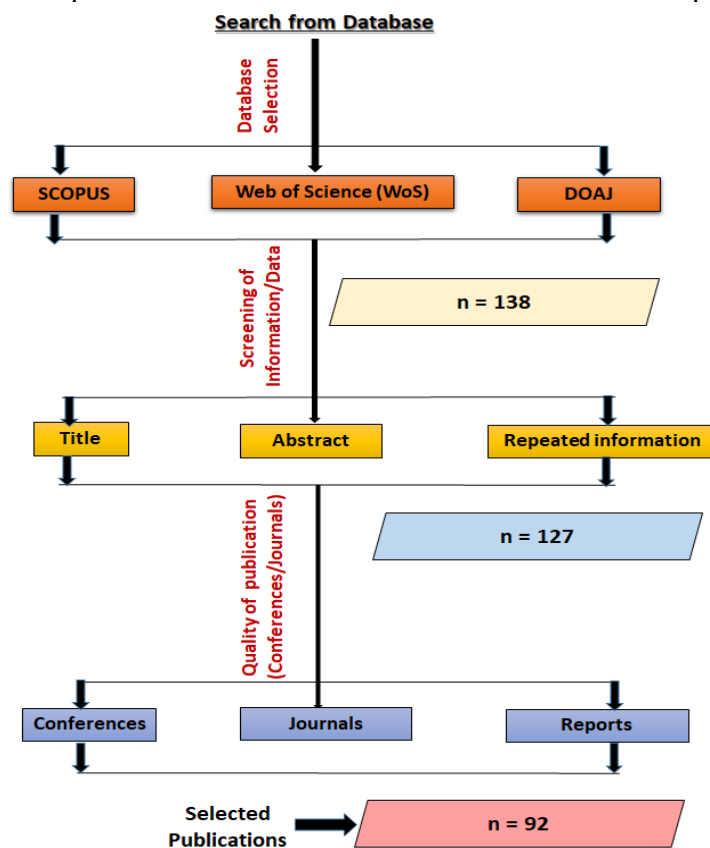


Figure 3: Review process and methodology

2.3. Review Methodology and Criteria

The literature review adhered to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework, delineated in the PRISMA flowchart (Figure 4).

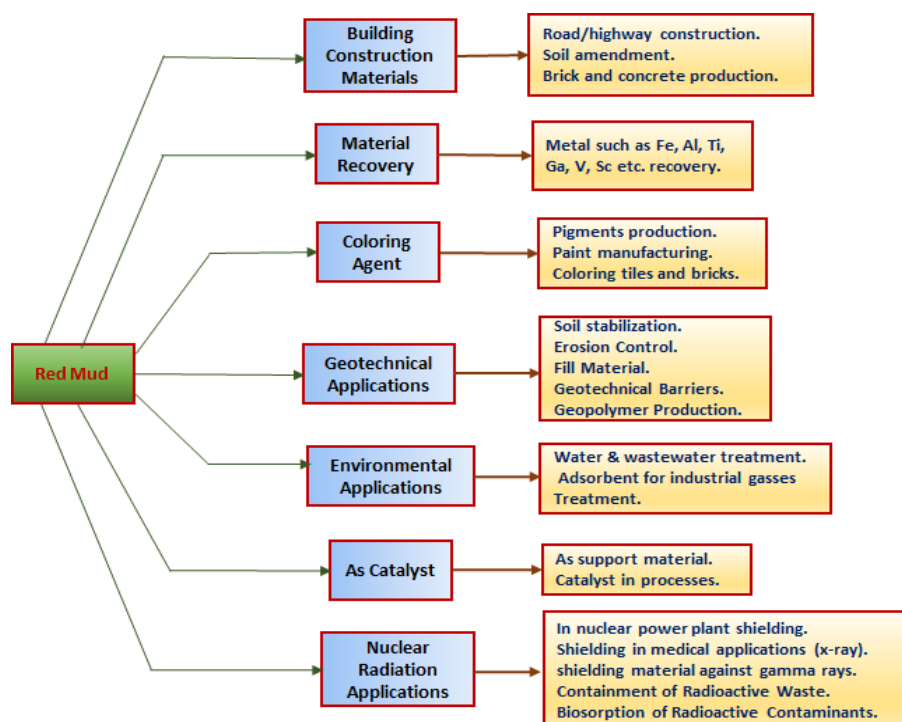


Figure 4: Possible areas for the application of red mud. Source: the authors

The methodology encompassed four key steps: identifying relevant documents, screening titles and abstracts for relevance, assessing the full texts for eligibility, and ultimately deriving selected literature focused on the hazards of red mud accumulation and contemporary methods for its beneficial use. This review aims to explore and recommend avenues for red mud utilization in industries, emphasizing enhanced material performance, reduced leaching risks inherent to bitumen's hydrophobic nature, and the economic feasibility associated with its application without the need for pretreatments.

Employing industrial by-products for the treatment of other wastes offers numerous economic and environmental advantages. The possible areas where red mud can be utilized are summarized in Figure 4.

As of now, applications of red mud have been largely limited to road construction, land reclamation, and cement production. However, novel applications are being explored, such as the recovery of metals like iron, aluminum, titanium, and other trace elements from red mud, as well as its use in ceramic production. Present review explores the global landscape of red mud production, highlighting its composition, environmental impact, current remediation strategies, and beneficial application in environmental and construction industry.

3. Occurrence and characterization of red mud

The distribution of bauxite reserves highlights the concentration of resources in various regions, with Africa holding the largest share at 32%, followed by Oceania (23%), South America and the Caribbean (21%), and Asia (18%) (Georgitzikis et al., 2021).

The red mud is characterized by its highly alkaline nature and comprises salts and oxides of various elements including iron (Fe), aluminum (Al), titanium (Ti), silicon (Si), sodium (Na), and calcium (Ca), in addition to several trace elements. Typically, red mud contains approximately 15 to 20 different mineral phases. The production of red mud is significant, with around 1.5 to 2.5 tonnes generated for every ton of alumina produced. The specific quantity

depends on the source of bauxite and the efficiencies achieved in alumina extraction (Samal et al., 2013).

With the primary aluminum production reaching 47 million tons annually, the demand for raw materials (RM) has significantly increased. However, the production of aluminum also leads to the generation of substantial amounts of red mud, a byproduct of the bauxite refining process. Currently, approximately 4.6 billion tons of this red mud are stored in waste reserves, creating a considerable environmental challenge (Khanna et al., 2022).

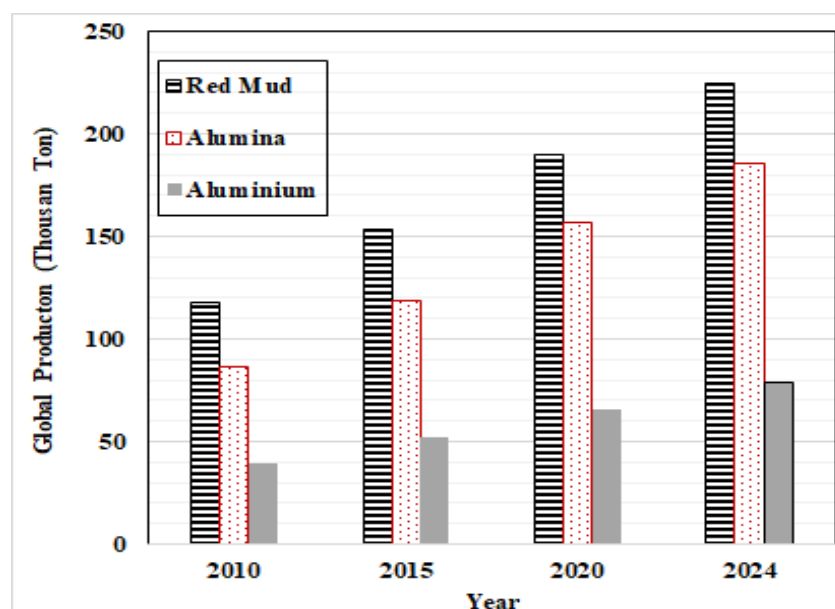


Figure 5: Global production of red mud, aluminum and alumina. (Source: Modified from Lima et al., 2017; Morsali and Yildirim, 2024)

Globally, red mud production is approximately 90 million tonnes annually, with Australia contributing about 30 million tonnes (Kumar et al., 2006; Archambo et al., 2021). In 2016, China was the top alumina producer, accounting for 55% of output, followed by Australia and Brazil. Red mud production in Brazil was 4.40 to 6.26 million tonnes, contributing to a global total exceeding 117 million tonnes, generated by over 85 refineries across 32 countries (Georgitzikis et al., 2021; Svobodova-Sedlackova, 2024). Global production of red mud, aluminum and alumina is depicted in Figure 5.

Increased aluminum demand has led to significant red mud accumulation, often stored unsafely in deforested areas, posing environmental risks. Effective management and innovative treatment strategies are essential to mitigate these impacts and enhance the sustainability of aluminum production (Silveira et al., 2021; Morsali and Yildirim, 2024).

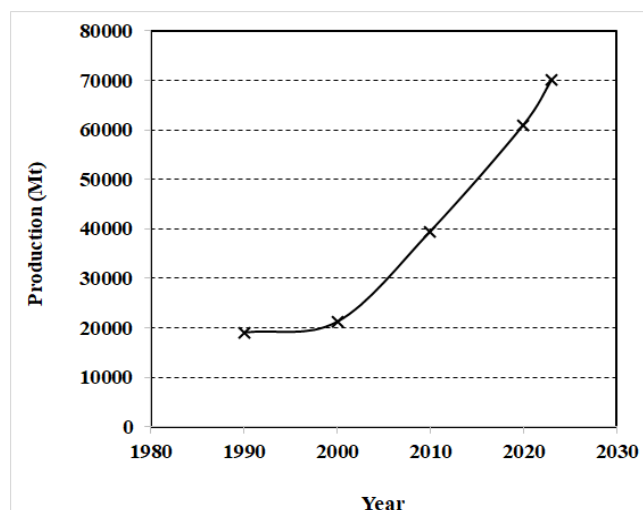


Figure 6: Global aluminum production during last 40 years. (Source: Modified from Silveira et al., 2021; Morsali and Yildirim, 2024)

4. Classification and characterization of red mud

The chemical heterogeneity of red mud poses a significant challenge for reutilization, demanding stringent process control and increasing costs. Classified as hazardous waste due to its caustic, saline, and sodic characteristics (Zhou & Haynes, 2010), red mud's fine particle size (typically $< 10 \mu\text{m}$) and the critical influence of basic site number and strength on catalytic activity (Busca, 2010) are key properties.

Physical Properties of Red Mud

Red mud exhibits a bulk specific gravity that varies between studies, with reported values ranging from approximately 2.13 g/cm^3 to 3.04 g/cm^3 (Han and Hwang, 2002). Specifically, the bulk specific gravity is commonly noted to be around 2.609 g/cm^3 . However, in the past literature Chandra indicated that the bulk specific gravity of red mud falls within the range of 2.5 to 2.7 g/cm^3 (Chandra, 1996).

The specific surface area of red mud, as determined by BET (Brunauer-Emmett-Teller) analysis, typically lies between 13.2 to $31.9 \text{ m}^2/\text{g}$ (Cornelius and Kamga, 2017; Yenial and Bulut, 2018). Huang and colleagues observed that Australian red mud has a specific surface area of approximately $22.71 \text{ m}^2/\text{g}$, which aligns closely with the findings of Han and Hwang who reported a value of $23.53 \text{ m}^2/\text{g}$ (Han and Hwang, 2002; Huang et al., 2008). It is noteworthy that the specific surface area may decrease when red mud is calcined at elevated temperatures (greater than 600°C). When utilized as a component in ceramic materials, red mud contributes positively to the surface finish (Singh and Chauhan, 2017; Al-Fakih et al., 2023).

Red mud, a fine particulate ($d_{80} < 50 \mu\text{m}$), demonstrates high surface area, facilitating effective wastewater treatment and heavy metal adsorption. Incorporation of its fine fraction ($d_{70} < 20 \mu\text{m}$) into bitumen may enhance the rheological properties and performance of bituminous materials in civil engineering applications. (Lima et al., 2017).

Effect of Physico-chemical properties of red mud

Red mud's distinct reddish color stems from its complex mineral composition, including hematite, goethite, rutile, aluminum oxides, quartz, and gypsum (Salim et al., 2023). It contains valuable nutrients like calcium and potassium, making it a potential soil amendment (Chao et

al., 2022). However, its high alkalinity (pH over 11) due to sodium hydroxide raises concerns about heavy metal leaching, requiring careful management to prevent soil degradation (Archambo and Kawatra, 2021).

Red mud's thermal properties can enhance concrete's mechanical performance, but its high alkalinity requires neutralization to mitigate environmental risks. Understanding its physicochemical properties promotes sustainable practices and valorization across industries, supporting environmental sustainability (Rai et al., 2017).

Chemical properties

Red mud typically comprises several chemical constituents, including alumina (Al_2O_3), quartz (SiO_2), iron oxide (Fe_2O_3), calcium oxide (CaO), titanium dioxide (TiO_2), and sodium oxide (Na_2O). A variety of red mud compositions sourced from various locations worldwide are presented in Table 1. Generally ferric oxide (Fe_2O_3) is the major constituent of red mud and gives it its characteristic brick red colour. Significant variations in the chemical composition of red mud have been reported, as noted by Wang et al. (2012). Bauxite's varied mineral composition causes red mud variations. These differences depend on bauxite source, processing, and storage, leading to compositional changes even within the same site (Liu et al., 2007).

Table 1. Typical composition of red mud found in various countries reported in the literature.

RM Source Country								
Components (% wt.)	Al_2O_3	Fe_2O_3	SiO_2	TiO_2	Na_2O	CaO	Other (e.g. K_2O , Sc_2O_3 , V_2O_5 , Nb_2O_5)	Reference
Australia	25.45	34.5	17.06	4.9	2.74	3.69	3.16	Lima et al., 2017
Africa	26.6	48.4	5.50	2.80	2.40	26.6	-	Lima et al., 2017
Brazil	35.5	37.16	2.34	6.18	8.49	1.23	-	Lima et al., 2017
China	17.89	33.88	19.43	0.72	12.18	2.66	0.47	Hu et al., 2019
Canada	37.60	32.45	3.67	4.12	6.78	3.45	4.70	Lima et al., 2017
Greece	16.25	42.34	6.97	4.27	3.83	11.64	1.49	Cardenia et al., 2018
India	36.26	16.58	8.32	17.1	6.0	1.43	1.43	Khanna et al., 2022
Russia	11.8	36.90	8.71	3.54	0.27	23.80	0.42	Valeev et al., 2019
South Korea	19.87	22.21	15.12	5.24	14.92	7.1	1.20	Do et al., 2019
Spain	19.80	39.23	8.77	10.09	5.02	4.54	2.04	Pérez-Villarejo et al., 2012
Ukraine	12.9	48.6	4.8	5.3	-	10.1	2.50	Krivenko et al., 2017

USA	18.40	35.50	8.50	18.40	6.10	7.70	-	Khairul et al., 2019
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Red mud's high alkalinity and compounds of iron, aluminum, and silicon make it useful for recycling and waste management. It can be used in cement production, soil conditioning, and metal recovery, presenting innovative solutions for wastewater treatment and environmental remediation, positioning it as a valuable resource.

5. Hazardous associate with rm

Red mud, characterized by its alkaline pH (10-13) and heavy metal content, poses significant environmental and health risks, compromising aquatic ecosystems and human well-being. Poor disposal management may lead to catastrophic incidents, necessitating stringent regulations and effective mitigation strategies to safeguard public health and the environment (Mayes et al., 2016).

Pathways for RM causing Environmental Damage

Red mud can transport through air, water, soil and sediments into the environment and its information and mobilization is important from environmental protection point of view. The environmental impact of red mud spills, particularly concerning air quality, water contamination, and soil effects, has been assessed through various studies (Mayes et al., 2016).

Air Quality:

The red mud's particle size is mostly in the PM10 range, around 3–8 micrometers, with few particles in the PM2.5 and PM1 categories. This distribution resembles urban dust, indicating minimal risk. A study on the Ajka red mud spill in Hungary found that PM10 levels were consistently within air quality limits over a year, except for seasonal increases due to domestic biomass burning in winter (Mayes et al., 2016).

Water Contamination:

Red mud leachate poses environmental risks due to high solubility of contaminants like aluminum and arsenic in alkaline conditions. Bioavailable elements such as phosphorus and vanadium exceed aquatic life standards, impacting the Torna Stream and Marcal River, while elevated phosphorus may cause long-term nutrient enrichment (Mayes et al., 2016).

Land and Soil Contamination:

Red mud adversely impacts soil and sediment quality (Ruyters et al., 2011). Over time, its pH decreases due to carbonation, affecting trace element mobility. Although red mud contains contaminants like arsenic, chromium, and nickel, studies show these remain less bioavailable at near-neutral soil pH (Gräfe and Klauber, 2011). Speciation indicates that chromium and arsenic are primarily in less toxic forms, while vanadium remains reactive in its pentavalent state, similar to leachates.

Red mud degrades soil and sediment quality, lowering pH and affecting trace element mobility. While contaminants like arsenic and chromium can be less toxic at near-neutral pH, concerns over water and soil contamination persist. Effective monitoring and management are essential to mitigate these ecological risks (Mayes et al., 2016).

6. Management for red mud disposal, recycle, reuse and other options

Red mud disposal is challenging for alumina plants. Traditional methods like ponds and landfills raise environmental concerns (Rai et al., 2012). Dry stacking is increasingly adopted for its reduced land use and improved stability. Sea disposal is rare, practiced by only seven out of 84 alumina plants globally due to land limitations (Samal et al., 2013).

In the U.S., red mud is mostly landfilled, with 10% recycled for metal extraction or brick production. (Archambo and Kawatra, 2021). Most of the red mud generated in Japan is neutralized before being disposed into the deep-sea (Zouboulis and Kydros, 1993). Additionally, researchers noted that Japanese aluminium manufacturers have developed pre-treatment techniques for bauxite to minimize red mud discharge (Samal et al., 2013; Archambo and Kawatra, 2021).

7. Using red mud for beneficial applications

Red mud from aluminum production can be repurposed for concrete, bricks, ceramics, soil improvement, and wastewater treatment, promoting sustainability and circular economy principles (Yu et al., 2024). Red mud's mineral richness enables the creation of lightweight bricks, offering a sustainable building material alternative. Its adsorption properties make it useful in wastewater treatment by removing heavy metals. Additionally, it can be utilized as a soil conditioner to improve fertility and support plant growth in agriculture (Xue et al., 2016; Wang et al., 2019; Irfan-ul-Hassan et al., 2024).

Red mud is underutilized in construction due to inadequate performance options, leading companies to prefer storage over valorization. Its applications include construction, neutralization, and metal recovery (Samal, 2021). Red mud is a low-cost alternative in construction, with significant applications in Brazil such as road construction, cement production, and ceramics (Al-Fakih et al., 2023). Key beneficial uses include four main areas, particularly in construction and manufacturing, as shown in Figure 7.

Highway and Road Construction

Red mud shows promise as a road construction material, particularly when dewatered, compacted, and mixed with a binder. Studies, including Kehagia's on a mixture with fly ash, highlight its quality and cost-effectiveness, urging further research on pretreatment benefits (Lima et al., 2017). (Kehagia, 2014; Lima et al., 2017).

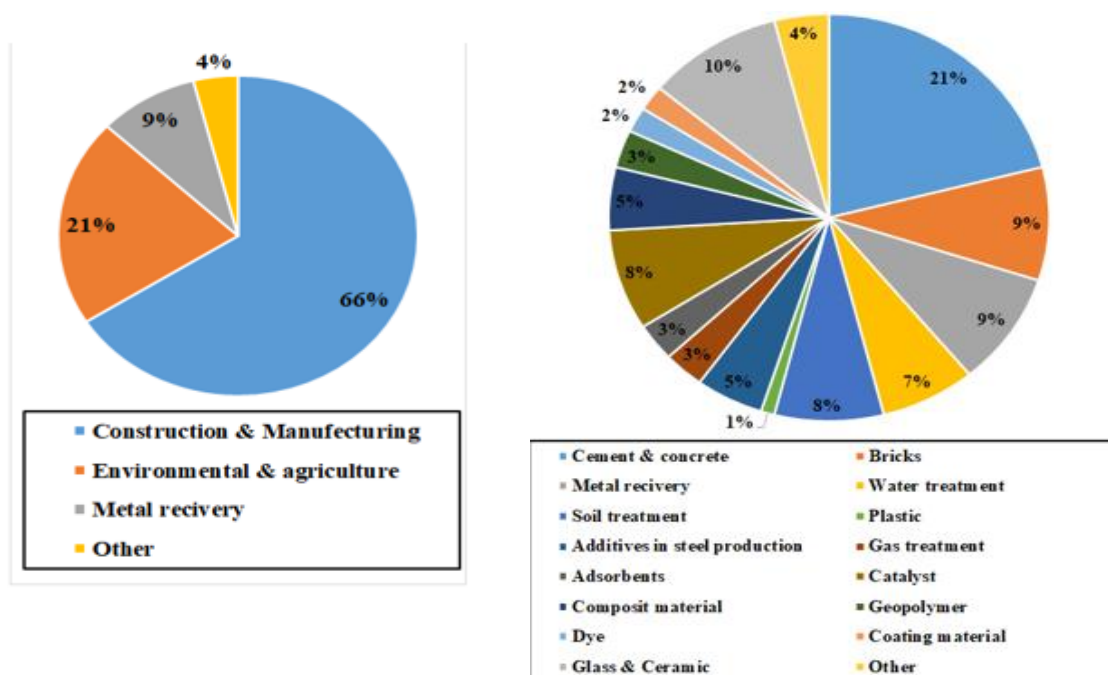


Figure 7: Application of red mud in beneficial applications (a) Broad applications (b) Detailed applications. (Source: the authors)

Research by Jitsangian and Nikraz demonstrated that a pozzolanic mixture of 70% red mud, 25% fly ash, and 5% lime met Australian Standards for unconfined compressive strength (UCS) of 0.6 to 1.0 MPa, outperforming conventional materials in stability (Jitsangian and Nikraz, 2013). Additionally, studies in Brazil found that adding red mud to bituminous mixtures improved their resistance. Performance varied with the amount of red mud used, with higher filler content typically increasing bitumen consumption (Lima et al., 2017).

Tests on permanent deformation showed that mixtures with higher red mud content outperformed conventional mixtures, all meeting French guidelines (<10% deformation). The enhanced performance is attributed to lower bitumen content in red mud mixtures, which increases viscosity without greatly affecting thermal susceptibility (Lima et al., 2023). Therefore, red mud presents a promising resource for road construction, showing improved engineering properties, cost-effectiveness, and sustainability potential across various applications. However, further exploration and systematic study are necessary to fully harness its benefits.

Ceramic Material and Cement Production

Incorporating alkaline substances from red mud in ceramics can reduce sintering temperatures, save energy, and improve resistance (Mi et al., 2021). Research shows that red mud significantly enhances ceramic strength; for example, Lu et al. (2022) found that increasing red mud content improved the mechanical strength of non-sintered blocks due to hydration reactions. Successful uses of red mud in cement include achieving optimal crushing strength with 10% addition, and developing a high-strength cement mix with 35% red mud, among other components, fired at 1250 °C (Samal et al., 2013).

Other studies have shown that mixing red mud with limestone at 1150–1200 °C can produce iron-rich cement with strengths up to 200 kg/cm² (Archanbo and Kawatra, 2021). Studies reported that glass ceramic tiles have been manufactured utilizing red mud and fly ash, achieving various shades with good scratch resistance. The strength of these materials can be adjusted by altering the mixtures of red mud, fly ash, and other additives (Mishra and Gostu,

2017; Bajpai et al., 2020). In a study, Qin and Wu used the red mud to mitigate self-glazing effects in ceramic materials (Qin and Wu, 2011).

Application in Soil Stabilization

Studies show that blending red mud, cement, and clay improves unconfined compressive strength, decreases hydraulic conductivity, and reduces swelling in compacted clay liners. This approach effectively stabilizes clay liners for geotechnical applications, presenting a cost-effective solution for using red mud as a waste material (Alam, 2018).

Various applications in geotechnical engineering, such as backfill and road sub-grade materials, have been investigated. Experimental studies suggest that red mud can effectively stabilize soil when mixed with fly ash (Pandey and Prakash, 2020). In another study, a mix of 30% RM, 67% soil, and 3% fly ash showcased favorable bearing strength characteristics. This mixture provided an increase in bearing strength by 7.354% due to the inclusion of RM and fly ash (Mukiza et al., 2019; Kan et al., 2022).

Enhanced Iron and other Metal Recovery

The recovery of metals from red mud is critical for enhancing material utilization and reducing waste (Wang et al., 2021). Red mud typically contains a significant amount of iron oxides (Fe_2O_3), aluminum oxide (Al_2O_3), titanium dioxide (TiO_2), silica (SiO_2), and sodium oxide (Na_2O), varying based on the bauxite's composition and treatment methods. Given that iron oxides are often the predominant component, strategies to recover iron have garnered considerable research interest (Yadav and Fulekar, 2020; Naykodi et al., 2023). Research indicates that red mud can recover 95% iron as hot metal, but only 50% TiO_2 , insufficient for synthetic rutile, leaving 12% TiO_2 in the slag. The study also indicated effective smelting of red mud and pig iron at 1600 °C to produce cast iron (Khanna et al., 2022).

Various methods for extracting titanium and iron from red mud have been explored. One successful technique involves blending red mud with coke and smelting in an electric arc furnace at 1600-1700 °C, achieving a 90% iron recovery rate. Other methods include using a blast furnace with sintered red mud, optimizing it for pig iron and titania-rich slag, and reducing red mud in a rotary kiln with hydrogen at 1050-1300 °C to produce sponge iron (Shah and Gararia, 1996). Overall, these investigations highlight the potential for efficient metal recovery processes from red mud, contributing to both resource recovery and waste reduction initiatives.

Water and Wastewater Treatment

Red mud has garnered attention for water and wastewater treatment due to its constituent components. However, its application necessitates caution due to the potential leaching of metal ions and organic compounds. Leaching tests are crucial prior to implementation. Previous studies offer valuable insights into red mud's utility in diverse water treatment areas.

Use as Coagulant

Coagulants like Fe^{3+} and Al^{3+} compounds are essential in water treatment. Due to the high Fe and Al content in red mud, it presents a promising alternative for producing coagulants. Researchers highlighted that red mud-based coagulants outperform ferric chloride and polyaluminum chloride in from economic point of view (Wang et al., 2019). Advantages of red mud coagulants include a simplified one-step process, minimal pH changes, effective removal of cationic and anionic species, extended dosage for multiple cycles, low heavy metal leaching, and safe transport and handling (Orešcanin et al., 2006).

Use as Adsorbent

Groundwater and wastewater contain various harmful pollutants, necessitating their removal for safety (Wang et al., 2019). Adsorption is a cost-effective treatment method, though activated carbon is expensive to produce and regenerate (Fahim et al., 2006; Saleem, 2017; Wu et al., 2020; Niu et al., 2021; Coker et al., 2023; Saleem, 2024). Recent research focuses on developing low-cost adsorbents from industrial and agricultural waste. Notably, red mud has gained attention as a promising, affordable material with significant adsorption capacity for removing contaminants (Tsamo et al., 2018; Du et al., 2019; Kyrii et al., 2023).

Removal of metal and toxic materials from water and wastewater

Thermal activation of red mud has been explored for the removal of contaminants like arsenate, vanadate, and molybdate (Guo et al., 2014). Red mud, is recognized as an effective adsorbent for removing toxic metals such as lead (Pb^{2+}) and chromium (Cr^{6+}) from water and wastewater (Gupta et al., 2001). Islam et al. (2023) effectively adsorbs chromium from wastewater, achieving over 98% removal, showing feasibility across various metal ion concentrations. Moreover, studies elsewhere confirm that red mud is suitable for industrial wastewater treatment, with metal, nonmetal and other toxic pollutants removal (Bhatnagar et al., 2011). Carvalheiras et al. (2023) demonstrated the effectiveness of metakaolin and red mud-based geopolymer monoliths for lead removal from wastewater, achieving a capacity of 30.7 mg/g. By optimizing various parameters, the monoliths were successfully regenerated for multiple reuse cycles. This innovative method highlights the potential of clay-derived geopolymers in wastewater treatment and promotes sustainable recycling of red mud waste, offering a promising solution for efficient and eco-friendly heavy metal removal.

Red mud has emerged as a cost-effective adsorbent for removing toxic substances from wastewater, including Congo red dye (Wang et al., 2019). Its adsorption capabilities have been enhanced for phenol and its derivatives, achieving removal efficiencies of 94-97% for certain chlorophenols (Bhatnagar et al., 2011), with a notable removal order of 2,4-dichlorophenol > 4-chlorophenol > 2-chlorophenol > phenol. Column experiments demonstrated up to 98% removal rates, primarily through diffusion (Bhatnagar et al., 2011). Additionally, red mud effectively removes procion orange dye, acid violet, and fluoride, with adsorption influenced by pH (Pepper et al., 2017). This research highlights red mud's versatility in wastewater treatment applications.

Use in Industrial Gas Treatment

Flue gases from industrial processes often contain harmful pollutants like H_2S , SO_x , and NO_x , raising environmental concerns. Recent research by Liu et al. (2022b) demonstrated that red mud slurry can effectively remove NO_x and SO_2 with efficiencies of 97.9% and 100%, respectively. Previous studies on coal gas desulfurization with a clay-red mud mixture in a fixed bed reactor showed low attrition loss and strong performance regarding sulfur capacity and durability (Rai et al., 2017; Archambo, M., & Kawatra, 2021).

Application in Catalysis

Catalytic processes are vital across industries, leading to a focus on effective catalysts. Recently, utilizing red mud, a by-product of alumina production, as a catalyst source has gained interest due to its iron oxide content, despite potential sintering from sodium and calcium oxides at high temperatures (Mi et al., 2022). Sulphided red mud, due to its iron sulphide content, is an active hydrogenation catalyst and has been employed in the hydrogenation of organic compounds, as well as in coal and biomass liquefaction (Liu et al., 2007; Rahman et al., 2021). Red mud effectively catalyzes transesterification of vegetable oil for biodiesel,

achieving over 94% yield. Its use not only recycles waste and reduces costs but also presents eco-friendly potential for other base-catalyzed organic reaction. (Liu et al., 2022).

Coloring Agent

Carneiro et al. (2018) researched red mud valorization by sintering it at temperatures between 1100°C and 1350°C, analyzing the mineralogical changes through XRD, UV-Vis spectroscopy, and CIELab metrics. Red mud sintered at 1300°C showed lower coloring power than commercial hematite but superior color stability in glazes fired at 1100°C, suggesting its potential as a hematite substitute. Similarly, Sglavo et al. explored red mud as a coloring agent in clay-based ceramics, finding that up to 50 wt% could be added without compromising mechanical properties, yielding promising results (Sglavo et al., 2000).

Arruda and team explored red mud's potential in new building materials, creating pozzolanic pigments through calcination and grinding with kaolin waste, which improved mortars' mechanical strength and color stability over traditional inert pigments (Arruda et al., 2022). These studies collectively highlight the promising applications of red mud as a coloring agent in various materials, emphasizing its potential to contribute to sustainability and resource efficiency in construction and ceramic industries.

Foamed Concrete

Badanoiu et al. studied using red mud and glass cullet in foamed geopolymers. They found that 25% red mud caused softening, enhancing volume. Compressive strength ranged from 2.1 to 8.6 MPa, decreasing with increased porosity. The materials show promise as lightweight, cost-effective thermal and sound insulators (Badanoiu et al., 2015). Dong and Wu developed foam blocks using red mud, magnesium powder, and additives, identifying an optimal mix. Their research highlights the potential for creating value-added materials with economic and environmental advantages. (Dong and Wu, 2011). Guo and colleagues enhanced glass ceramic foams' compressive strength by using red mud and fly ash with CaCO₃, improving mineralogical properties and structure through their analyses (Guo et al., 2014).

Reinforced Red Mud Polymer and Radiation Shielding Material

Researchers created organic-inorganic composite films using red mud (RM) waste from aluminum production, reinforced with polyvinyl alcohol (PVA) via the sol-gel method, and examined the effects of sodium lauryl sulfate (SLS) as a compatibilizer. Characterization through UV absorption, X-ray diffraction, FTIR, SEM, and EDX revealed strong bonding and compatibility between RM and PVA. The composites showed an increase of 194.88% in tensile strength and 71.48% in swelling degree, while elongation at break and solubility decreased by 98.07% and 78.07%, confirming RM's role as a filler and SLS's effectiveness as a compatibilizer (Daw et al., 2019).

Recently, Vishwakarma and colleagues explored the potential of red mud for radiation shielding, leveraging its metal oxide-rich content. They produced X-ray shielding sheets through a solution-casting technique with PVA as a binder for red mud particles. The material effectively shielded diagnostic X-rays at 60 kVp, 90 kVp, and 120 kVp. Structural analyses of the fabricated samples were conducted using SEM, XRD, RAMAN, and FTIR. The results indicated that the best formulations containing 70 and 80 wt.% RM demonstrated significant UV shielding capabilities alongside X-ray protection (Vishwakarma et al., 2024).

Use in Agriculture as Fertilizer and Chemical Stabilizer

Feigl et al. conducted a two-year study on red mud's effectiveness in stabilizing contaminated mine waste and agricultural soil. Their results showed that a 5% addition of red mud (pH 9.0) reduced cadmium (Cd) mobility by 57% and zinc (Zn) mobility by 87%. In a laboratory

lysimeter, leachate concentrations of both metals decreased by about two-thirds without increasing soil toxicity. This amendment resulted in an 18-29% reduction in Cd and Zn uptake by the plant *Sinapis alba*, suggesting its potential for safe soil remediation (Feigl et al., 2012). Gautam and Agrawal examined the effect of combining red mud with cow dung manure on the growth of *Brassica juncea* cultivars, Kranti and Pusa Bold. Their results showed that higher concentrations of red mud in manure-amended soil increased total metal content but decreased phytoavailable metal levels. Notably, 10% red mud led to significant improvements in plant growth and seed yield, with Pusa Bold's yield increasing by 140.5% and Kranti's by 120.3% (Gautam and Agrawal, 2019).

Researchers have also recently developed a one-step process using KOH for hydrothermal treatment of red mud and fly ash, creating potassium-rich fertilizer while extracting Al_2O_3 . This method enhances material utilization and reduces environmental impact (Chao et al., 2022).

Extensive research has been conducted to explore the beneficial applications of red mud in a cost-effective manner across various fields. Table 2 provides a comprehensive summary of the principal studies that have been undertaken to investigate the advantageous uses of red mud in the past. This compilation not only highlights the diversity of applications but also underscores the potential of red mud as a valuable resource in sustainable practices. The findings from these studies contribute significantly to the understanding of red mud's role in environmental remediation, construction materials, and other innovative uses, thereby facilitating the transition toward a circular economy.

Table 2: Overview of major studies on the beneficial applications of red mud.

Area of application	Detail of application	Outcome of study	Reference
Construction materials	Use of RM in pavement material economically	RM with fly ash (97% & 3%) provides cost-effective material with similar mechanical properties.	Kehagia, 2014.
	Use mixture of RM, fly ash, and lime for good compressive strength.	Mixture of 70% red mud, 25% fly ash, and 5% lime achieved compressive strength of 0.6 to 1.0 MPa.	Jitsangian and Nikraz, 2013
	Adding RM to bituminous mixtures for improved properties.	Improved bonding with higher filler content achieved.	Lima et al., 2021
	Use of RM as a partial replacement of cement in concrete.	Achieved optimal crushing strength with 10% addition of red mud, and developing a high-strength cement mix with 35% red mud, among other components, fired at 1250 °C.	Samal et al., 2013
	Blended RM & limestone at 1150 -1200 °C to get high strength cement	By mixing RM with limestone at 1150–1200 °C can produce iron-rich cement with strengths up to 200 kg/cm ² .	Archambo and Kawatra, 2021
	Evaluated red mud's impact on masonry block properties	Industrial scale blocks showed a 202% strength increase and met ASTM and ACI standards.	Irfan-ul-Hassan et al., 2024
Soil Stabilization	Tested RM for enhanced strength, low hydraulic conductivity, and swelling in clay liner.	RM enhances clay liners' strength, reduces hydraulic conductivity and swelling, offering a cost-effective geotechnical solution.	Alam, 2018
	Mixture of RM, soil, and fly ash used to evaluate bearing strength as a soil stabilizer.	A mixture of 30% RM, 67% soil, and 3% fly ash increased bearing strength by 7.354%..	Kan et al., 2022
	Investigating nano-SiO ₂ -RM modified stabilized soil's strength for potential roadbed material use..	The 7-day unconfined compressive strength of red mud-stabilized soil exceeded 2 MPa, meeting roadbed strength requirements.	Chen et al., 2023

Removal of contaminant from wastewater	Use red RM as a cost-effective coagulant source.	Red mud's high Fe and Al content makes it a viable, cost-effective alternative for producing coagulants.	Wang et al., 2019
	Magnetite nanoparticles (RM-NPs) used to remove carbamazepine from real wastewater.	Regenerated magnetite RM-NPs are cost-effective, easy to use, and outperform commercial adsorbents in removing psychiatric drugs from wastewater.	Aydin et al., 2021
As Adsorbent for gases & liquid effluent treatment	Modified RM for enhance ion removal from wastewater and gases..	Modified RM can be used as a cheap adsorbent for removing various pollutants from water and gases	Wang & Liu, 2021
	Adsorption of Cr ⁶⁺ on RM activated by H ₂ O ₂ at 500 °C tested.	ARM effectively removes Cr ⁶⁺ from water, achieving a removal rate of 87.65% across various concentrations.	Sahu, et al., 2011
	Explored the removal of Pb from aqueous solutions using RM.	At 20 °C, 30 °C, and 40 °C, Pb ²⁺ removal rates were 60.4%, 82.6%, and 60.4% respectively.	Yu, 2015
	Explored the removal of Cu from aqueous solutions using RM	Cu ²⁺ concentration decreases over time, while pH rises, with a maximum removal rate of 87% reached at higher pH.	Yu, et al., 2015
	RM used as adsorbent for Fe with Na ₂ SiO ₃ ·9H ₂ O, CaO, and carbon.	Converted RM balls showed an adsorption capacity of 0.47 mg/g, achieving a 98% fluoride removal rate.	Li et al., 2017
	Investigated rhodamine B, fast green, and methylene blue dye removal from wastewater using RM.	The removal rates of the tested compounds were 92.5%, 94.0%, and 75.0%, respectively, and the optimal pH values for the compounds were 1.0, 7.0, and 8.0, respectively.	Gupta et al., 2004
	Used RM to absorb and purify SO ₂ flue gas,	Results demonstrated SO ₂ flue gas, and the SO ₂ absorption efficiency is more than 98%.	Liu, et al., 2013
	Used RM to remove Cd in wastewater by electrostatic attraction.	RM exhibits an excellent adsorption performance to Cd ions, efficiency reaches 95.32%.	Guo, et al., 2010
	Used RM to absorb CO ₂ .	Sowed good adsorption and after carbonization, the total alkalinity decreased by 85% and 89%.	Alharthi, et al., 2016
Agriculture	Evaluate the effectiveness of red mud in stabilizing contaminated mine waste and agricultural soil.	A 5% RM(pH 9.0) amendment reduced Cd and Zn mobility and plant uptake, aiding soil remediation and crop yield.	Feigl et al., 2012
	Studied combining RM with cow dung to enhance soil properties and Brassica juncea growth.	Higher concentrations of RM manure-amended soil increased total metal content, but decreased phytoavailability, improving plant growth by 120-140%.	Gautam and Agrawal, 2019
Material recovery	Studied the recovery of metals from RM, economically.	Efficient recovery of metals can be achieved from RM, enhancing material utilization and reduce the waste accumulation.	Wang et al., 2021
	Researchers tried to recover iron and TiO ₂ and produce cast iron.	RM recovers 95% iron as hot metal, but only 50% TiO ₂ , leaving 12% in slag; effective smelting occurs at 1600 °C.	Khanna et al., 2022
	Study targeted to recover iron. They also produced sponge iron by using RM.	Blending RM with coke in an electric arc furnace at 1600-1700 °C, achieves 90% iron recovery, while rotary kilns with hydrogen produce sponge iron.	Shah and Gararia, 1996
Additives & Composites Materials	Investigated the mechanical properties of polymer composites with various percentages of RM.	RM composites provide an eco-friendly option, improving hardness while reducing tensile and flexural strength with higher red-mud content.	Akinci, et al., 2008
	Utilized RM as an additive reinforced with PVA using sol-gel, exploring SLS's role as a compatibilizer.	Swelling and tensile strength increased 71.48% and 194.88% respectively, while elongation at break and solubility decreased by 98.07% and 78.07% respectively versus virgin PVA.	Daw, et al., 2019

Coloring Agent	Explored RM as a coloring agent in clay-based ceramics with economical and improved properties.	Study showed that up to 50 wt% RM could be added without compromising mechanical properties, yielding promising results.	Sglavo et al., 2000
	Red mud used to create pozzolanic pigments with kaolin waste..	Study showed that, created pozzolanic material improved mortars' mechanical strength and color stability over traditional inert pigments.	Arruda et al., 2022
	Investigated the feasibility of utilizing RM in the polymer matrix with coconut sheath (CS) fiber.	20 wt% RM enhanced the tensile, flexural, and impact strength of fiber composites while reducing void formation.	Vigneshwaran et al., 2020
Glass and ceramic production	Four types of RMs were used to enhance ceramic tile properties.	Four formulations with 40 wt% red muds achieved excellent properties at a low firing temperature of 940°C.	Xu, et al., 2019
	Ceramsite was made with fly ash, red mud, and bentonite using a two-stage sintering process.	The ceramsite exhibited a high compressive strength of 21.01 MPa, 1-h water absorption of 1.21%, and bulk density and apparent density were 994 and 1814 kg/m ³ , respectively.	Mi et al., 2021
	Using RM to enhance strength of ceramic.	Increasing RM content to 23% significantly enhanced the mechanical strength of non-sintered blocks through hydration reactions.	Lu et al., 2022
	Used RM to mitigate self-glazing effects in ceramic materials with high strength.	Result showed reduction self-glazing effects in ceramic materials. The bulk density obtained was 2.94 g/cm ³ with compressive strength, up to 78.12 MPa.	Qin and Wu, 2011
Reinforced RM Polymer and Radiation Shielding Material	Researchers made composite films with RM and PVA via the sol-gel method.	Composites increased tensile strength by 194.88% and swelling degree by 71.48%, while elongation and solubility decreased by 98.07% and 78.07%.	Daw et al., 2019
	Explored the potential of RM for radiation shielding, leveraging its metal oxide-rich content.	Formulations with 70% and 80% RM effectively shielded X-rays at 60, 90, and 120 kVp, and offered UV protection.	Vishwakarma et al., 2024

8. Discussion

This systematic review covers the information and work conducted during the last two decades and the results obtained revealed the significant environmental challenges posed by red mud, a byproduct of alumina production, which generates approximately 175.5 million tons annually. The effective management of this hazardous waste is critical, as improper disposal can result in severe ecological and health risks. The need for the proper management is raised since last three decades as mentioned in official report submitted by Ernő Kiss who addressed the issue with the Hungarian policymakers (Kiss, 1984). Present review identifies promising avenues for the valorization of red mud, showcasing its potential applications across various industries, particularly in construction and environmental remediation.

Studies reveal that the red mud's unique physicochemical properties enable its use in multiple applications, including as a sustainable alternative in Civil Engineering field such as; highway construction, ceramic production, and as a soil amendment. The literature suggests that red mud can enhance the durability and performance of construction materials, reduce sintering temperatures in ceramics, and improve soil quality, thereby contributing to a circular economy model. Moreover, its effectiveness as a low-cost adsorbent for wastewater treatment underscores its value in mitigating water pollution, particularly in removing heavy metals and dyes.

Despite these advantages, the large-scale application of red mud remains constrained by safety and environmental concerns, which necessitate comprehensive treatment and neutralization

strategies. A recent study conducted in China by Li and coworkers supplements the present study. Studies indicate that research on the comprehensive utilization of resource materials (RM) predominantly centers on three areas: metallurgy, construction, and environmental management. They highlight the key challenges hindering large-scale RM production in China, including unclear responsibilities, high technical costs, an absence of policies and standards, and inadequate interdisciplinary collaboration (Li et al., 2024). To address these issues, several recommendations for enhancing the utilization and development of RM have been put forward. Present review calls for increased collaboration among academia, industry, and policymakers to facilitate research into effective recovery methods and improve public awareness of red mud's benefits. Developing frameworks that prioritize safe integration into production cycles will not only alleviate landfill pressures but will also promote sustainable resource management.

Although research on treatment of red mud and material recovery is in progress, this review recommends further research to optimize metal recovery processes and explore innovative methods for treating red mud, thereby enhancing its economic viability. Additionally, there is an immediate need to cover the policy gaps to support large-scale implementation and establishing standards for red mud utilization will be crucial in transforming it from a liability into a resource. By advancing these initiatives, stakeholders can harness red mud's potential to contribute to environmental sustainability and drive the transition towards a more circular economy across sectors.

9. Conclusions and recommendations

The literature review highlights the environmental hazards of improperly managed red mud, a byproduct of bauxite processing. Conversely, its incorporation into various industrial applications offers opportunities for environmental sustainability and circular economy advancements. Red mud's suitability for road construction and infrastructure projects is promising, leveraging its chemical similarities with conventional fillers. However, market acceptance is contingent upon mitigating safety and environmental concerns. Additionally, potential applications in building materials and metal recovery are contingent upon the specific red mud composition and recovery methodologies employed. Effective utilization necessitates a nuanced understanding of these factors.

To effectively address the environmental challenges posed by red mud, it is recommended that ongoing research collaborations between academic institutions and industry stakeholders should be prioritized. To address red mud's environmental challenges, collaborative research between academia and industry is essential. Prioritizing innovative strategies to inert red mud, reduce leaching, and enhance its mechanical properties will maximize environmental and economic benefits. Industry should actively incorporate red mud in construction, like road building, transforming it into a valuable resource. Public awareness campaigns highlighting the environmental advantages and sustainability of red mud-derived products are necessary to facilitate market acceptance and societal embrace, fostering sustainable resource management. This study significantly advances the field by providing a comprehensive re-evaluation of red mud, challenging its conventional perception as a mere environmental liability. By characterizing its material properties, the research illuminates red mud's dual nature, addressing potential hazards while simultaneously unlocking its potential as a valuable resource in construction, manufacturing, and material recovery. The study advocates for collaborative, economically feasible strategies to integrate red mud into sustainable practices, fostering its transformation into a secondary resource and contributing to a circular economy paradigm. This shift promotes sustainable resource management by emphasizing red mud's beneficial reutilization.

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12. References

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إمكانية استخدام مخلفات الطين الأحمر في التطبيقات الصناعية: مراجعة شاملة

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الملخص

البازلت الأحمر، وهو منتج ثانوي لعمليات معالجة البوكسيت لإنتاج الألمنيوم، يشكل تحديات بيئية، بسبب قلوته العالية وكمية إنتاجه الكبيرة، التي تتجاوز 175.5 مليون طن سنويًا، وتبلغ حوالي 4 مليارات طن، بحلول عام 2022. وهذه النفايات الخطرة تهدد بالتلوث وتكبد الشركات المسؤولة عنها التزامات مالية كبيرة. وبالرغم من الدراسات التي تثبت إمكانية دمج البازلت الأحمر في المواد الخزفية، فإن التطبيقات . على نطاق واسع . لا تزال غائبة. ويوفر هذا الاستعراض نظرة شاملة على حالة إنتاج البازلت الأحمر، بما في ذلك توصيف شامل للبازلت الأحمر المتاح على مستوى العالم لتوضيح خصائصه المادية. علاوة على ذلك، يبرز الاستعراض للمخاطر المحتملة المرتبطة بالبازلت الأحمر فيما يتعلق بالصحة العامة والمخاوف البيئية. إلى جانب ذلك، يهدف إلى تقويم جدوى تطبيقات البازلت الأحمر عبر مجالات مختلفة، بما في ذلك استخدامه في إنشاء الطرق والطرق السريعة، ودمجه بوصفه مكونًا في تصنيع السيراميك والأسمنت، والتطبيقات الجيوتقنية، واسترداد المواد، وأدواره في معالجة المياه، ومعالجة مياه الصرف الصحي، ومعالجة الغازات الصناعية. كما يستكشف الاستعراض إمكانية استخدام البازلت الأحمر بوصفه عاملاً محفزًا وملونًا، ومواد رغوية، ومواد للحماية من الإشعاع، وفي التطبيقات الزراعية. ويعتمد قبول السوق الفعال لمنتجات البازلت الأحمر على معالجة المخاوف المتعلقة بالسلامة والبيئة، فضلاً عن زيادة وعي الجمهور بفوائدها. وإلى جانب استخدامه في صناعة البناء، فيمكن استغلال البازلت الأحمر في استرداد المواد. ومع ذلك، فإن جدواه الاقتصادية تعتمد على التركيب وطرق الاسترداد. وتعد الأبحاث المستمرة والتعاون بين الأكاديمية والصناعة ضرورة لتطوير استراتيجيات، تجعل البازلت الأحمر غير نشط وتعزز أداءه الميكانيكي. ويمكن أن يسهم الاستخدام المناسب للبازلت الأحمر في تقليل نفايات المدافن، ومنع التلوث، وتعزيز إدارة الموارد المستدامة، وتحويل النفايات إلى أصول قيمة عبر القطاعات .

الكلمات المفتاحية: الطين الأحمر، خطر بيئي، تطبيقات إعادة الاستخدام، مواد إنشاء، تطبيقات بيئية.