

BAUXITE MINING AND REFINERY: INVESTIGATING PROSPECTIVE RED MUD MANAGEMENT STRATEGIES

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Abstract

The bauxite or aluminium industry continues to play an important role in the global economy. However, efforts are still needed in the sector in order to meet the objective of the millennium for sustainability. Serious environmental and health concerns are raised at every stage of the industry starting from the bauxite preliminary exploration to the mining activities as well as the alumina refining process. In addition to the excessive energy requirement, huge amounts of greenhouse gases including carbon dioxide (CO₂) and Perfluorocarbon Gases (PFCs) are emitted. Besides, large superficies of lands and forests are destroyed every year. Red mud obtained from alumina processing is among the world's biggest industrial wastes characterized by high alkalinity (about 2 to 3 g L⁻¹). Based on the type of bauxite, the waste might contain some radioactive and hazardous elements. The high iron content in bauxite and red mud is also a source of various environmental and social issues. Run out of red mud and dust emission are potential sources of ground and surface water severe pollution and public health issues. This review briefly describes the potential environmental and health risks associated with bauxite mining and its transformation processes into alumina. An outline of the available environmental management strategies is given with a focus on those associated with the bauxite residue.

Keywords: Bauxite, Bayer process, Red mud, Risk management, Sintering process.

1. Introduction

Bauxite mining is undeniably one of the world's fastest economic growth sectors. Practised in over 30 countries, the aluminium industry directly employs more than 1 million people together with numerous indirect jobs in downstream and service industries [1]. The world global production of bauxite has increased from 183 million metric ton (MT) in 2006 to about 262 MT in 2014 with nearly 53.5 MT of alumina produced. These values are even expected to reach up to 570 MT and 230 MT respectively for bauxite and alumina production as the demand for aluminium is likely to increase more than 2.5 times by 2025 [1-3]. However, despite this substantial contribution to the global economy, the bauxite industry is yet to meet the objectives of the millennium for sustainable development. Large superficies of forest are degraded every year via the creation of access roads and bauxite extraction sites. About 2% of the global electricity supply is consumed only at the primary stage of aluminium production [1]. Besides, the management of the by-product generated during bauxite processing into alumina is among the world's biggest environmental challenge. Processes including the Bayer process (invented by Karl Bayer in 1887) and the sintering process are the most economically effective and widely used techniques by alumina industries around the world. Residues generated from these processes are respectively called the Bayer and sintering red mud (RM) [4, 5].

The appellation "Red Mud" of these by-products is due to the high iron content [6]. RM is characterized by high alkalinity, which results in pH value usually greater than 10.5 and up to 13 depending on the technique adopted by the refineries [4, 7]. The Bayern RM generally contains a high concentration of hazardous compounds (e.g., As, Pb and Hg) as per comparison with the Sintering RM. However, the concentration of CaCO_3 is higher in the later. Both types of RM remain hazardous to the environment due to the presence of traces of radioactive isotopes [6, 8]. The physical and chemical properties of RM are determined by both the origin of the bauxite ore together with the refinery process applied.

Since the 1970s, there has been a positive shift away from marine dumping of RM to the land-based disposal method. However, marine dumping still represents about 20 to 30% of the global RM disposal, which may still affect the marine ecosystem [9]. Land disposal of high alkaline and radioactive red mud is likely a potential hazard to the surrounding environment (soil, air and groundwater). About 3 billion tons of RM has been accumulated up to now [10] and nearly 1 km² of lands are covered every five years [11]. Besides, dust generated from the surface of the dry residue may constitute a hazard to the surrounding biological system due to mostly the presence of sodium carbonate [12]. In case of heavy rain, run-off of from RM disposal areas may contaminate the closest water bodies as well as valuable lands downstream. The ore may contain a low level of toxic and radioactive compounds, depending on its origin [13]. Public health and environmental issues related the bauxite mining and alumina refinery requires eminent operational and management strategies by governments and bauxite companies. Factors such as high pH, salinity, exchangeable sodium percentage, and high soluble aluminium, present a constraint to reclamation and re-vegetation of RM disposal area [12]. Technologies and efforts have been featured to find environmentally friendly and cost-effective methods of RM management including its possible recycling-reuse as adsorbent (pollutant removal), building materials (brick, cement, glasses and concrete blocks), filling materials and neutralizing agent for acidic wastes. The recovery of mineral contains in RM has also been widely studied. However, not more than 40% of the global RM generated is reused [14].

In order to evaluate the strength and weakness of actual available practical and experimental management strategies adopted by bauxite companies, a brief review has been done on major environmental and social impacts caused in the bauxite sector via case studies. A focus is made on available environmental management strategies associated with the bauxite residue.

2. Mineralogy and Chemical Characteristics of Bauxite and RM.

Bauxite ore is characterized by its high concentration of iron oxide and alumina, along with various other mineral and chemical structures. Alumina occurs in 3 principal phases, depending on the origin and type of the ore. These are Gibbsite or Hydrargillite ($\gamma\text{-Al(OH)}_3$), Boehmite ($\gamma\text{-AlO(OH)}$) and Diaspore ($\alpha\text{-AlO(OH)}$) [15]. The occurrence of bauxite in some key producing countries is given in Table 1 [16].

The mineralogical composition of the ore is important in the choice of the alumina processing method. The Bayer process consists of digesting bauxite ore by washing with a hot solution of sodium hydroxide (NaOH), at 175 °C and high pressure to convert the aluminium oxide content into soluble sodium aluminates (NaAlO_2) [17]. The sintering process is used for bauxite ores that are hardly digestible with the Bayer process. The method is based on the “dry digestion” of aluminium oxides with caustic soda (Na_2CO_3), along with burnt lime (CaO) or calcium carbonate (CaCO_3) at a mole ratio of 1:0.20:0.25 respectively. A high temperature is required, usually between 800 to 1200 °C [18]. Beside the elements from the bauxite source, calcium and sodium present in RM are introduced during the treatment process [17]. Table 2 presents the chemical composition of the Bayer (1) and Sintering (2) RM. Iron content in the Bayer red mud is about half of its total weight, whereas CaO and SiO_2 contents are higher in the Sintering RM [8, 16]. The small particle size fraction content in red mud results in a very negligible settling property. RM has a specific gravity of about 2.18 with a particle size distribution similar to fly ash [19]. Table 2 clearly shows that hazardous traces are higher in the Bayer RM. Both, the Bayer and the Sintering red mud contain radioactive elements like ^{226}Ra and ^{232}Th , with an average concentration of 360 (150-700) $\text{Bq}\cdot\text{kg}^{-1}$ and 292 (102-506) $\text{Bq}\cdot\text{kg}^{-1}$ respectively.

Table 1 Type of bauxite from some producing countries.

Cristallography	Origin countries
Gibbsitic	Australia, Brazil, Guyana, India (Eastern Coast), Indonesia, Jamaica, Malaysia, Sierra Leone, Suriname, Venezuela
Boehmitic	Australia, Guinea, Hungary, Russia, Yugoslavia, India (Central part)
Diasporic	China, Greece, Guinea, Romania, Turkey

Table 2. Chemical composition of Bayer and sintering RM.

	Main chemical %										
	Fe₂O₃	Al₂O₃	SiO₂	CaO	Na₂O	TiO₂	K₂O	Sc₂O₃	V₂O₅	Nb₂O₅	TREO
1	26.41	18.94	8.52	21.84	4.75	7.40	0.068	0.76	0.34	0.008	0.012
2	7.95	10.36	17.29	40.22	3.53	7.14	0.053	0.16	0.024	0.020	0.31
	Trace of hazardous elements (ppm)										
	As	Pb	Hg	Cd	Cr	Ba	Zn	Cu	Mn	Ni	
1	267.3	56.6	67.3	27.1	537.8	212.0	103.2	78.2	187.5	984.9	
2	246.7	48.0	58.7	14.4	416.9	197.2	76.3	213.6	146.3	578.6	

1= Bayer RM and 2= Sintering RM Source (adapted from [8]).

3. Environmental and health risks associated with bauxite mining: Cases in Malaysia, Hungary and Australia

The physical and chemical composition of red mud and its massive production made its management one of the world's biggest environmental and health concerns.

Exploitation techniques of bauxite (open land or underground exploitation) depend on the geographical location of the ore. Regardless of these techniques, the damages are considerable on the biophysical environment as well as on the community living around the mining sites. Vegetation loss, noise, runs off and contaminated dust is generated at many steps of the mining process including scraping, drilling, blasting, excavating, hauling, crushing, and conveying.

3.1. Malaysia

In Malaysia, though bauxite mining activities have been practised in the state of Johor since 2000 without much issue, in 2013 serious environmental and health issues have been observed around Bukit Goh, Gebeng and the Kuantan Port in the state of Pahang [20, 21]. This is due to an increase in the mining production (from 200,000 tons in 2013 to nearly 20 million tons in 2016), which is mostly based on open-cast technique [22]. The open mining practice requires huge land clearings and excavations that seriously impact the ecosystem. It was even decided by the Malaysian government to temporarily suspend any mining activities for at least a period of three months since January 2016 [21, 22]. Lack of defined mining zones (sometimes very close to community living areas) and uncontrolled mining activities further exaggerate the pollution level. Furthermore, a survey performed in December 2015, showed that the air quality in the mining zones constantly approached the PM10 level (between 164 to 277 $\mu\text{g m}^{-3}$), values beyond the Malaysian National Ambient Air Quality Standard 2015. This is due to the emission of particulate red dust from the bauxite extraction, transportation and stockpiling activities, resulting in substantial loss of economic potentials and public health issues [21]. Roads and rivers are covered with dust deposition during the dry period. Streams contamination becomes even worst during heavy rains due to bauxite washout run-off. The bauxite in Kuantan is characterized by high aluminium and ferric oxide content ranging from 14.4 to 50% depending on the zone [21]. It is also believed that dust and run-off from the mining zones may contain toxic metals particles such as As, Hg, Cd, Pb, Ni and Mn, which are potential roots of cancer.

Consumption of aluminium would lead to serious bone diseases in children over the period [21]. Malaysia Nature Society (MNS) has gained the trust of the community to assess the water supply quality [22]. A study performed by Kusin et al. [23] showed that the water was polluted in some sites within the bauxite mining zone in Kuantan, Pahang, Malaysia. Water quality index was found to be in the range of 66 to 74 characterized as class III slightly polluted. The most polluted water samples were those collected near the bauxite mine stockpiling areas and had a slightly acidic pH value. In addition, based on the Malaysian recommendation guideline and international standards on drinking water quality, the study showed that the concentration of Mg, Na, Al, Fe, As, and Pb in water was above the norms at some sampling zones. The Kuantan Environmental-Public Health Tracking System (KEPTS) from the Health Department of Pahang State ensures continuous monitoring of food and drinking water quality and public health in the bauxite activity area [21]. Another aspect of concern within the Pahang community is their

exposure to noise and vibrations from the transportation and excavation activities, which increase possibilities of hearing loss, mental and behavioural stress on people, including students [21].

3.2. Hungary

The largest environmental catastrophe related to the management of RM was recorded in October 2010 in Hungary, where a huge quantity of caustic and metal-rich Bayer RM from wet disposal facility was accidentally released into the environment. The incident raised a global concern on the environmental and public health issues associated with RM and its disposal management [24]. The Ajka's spill drained about one million m³ of RM over 120 km downstream, inundating 40 km² of agricultural and urban land, killing about 10 people and severe injuries [25].

Numerous eco-toxicological studies have been performed across the Marcal catchment (Hungary) after the incident. Klebercz et al. [26] performed an integrated assessment of biological activity together with an ecotoxicity analysis of fluvial sediments alongside the Marcal river catchment (3078 km²). An analysis of the released RM sediment revealed the presence of traces of hazardous compounds (e.g., As, Co, Cr, V) and high exchangeable Na from the NaOH content. The most toxicological effect of these toxic compounds was observed on inhibition in bioluminescence *Vibrio* fishery. Furthermore, *Lemna minor* bioassay, *Sinapis alba* root and shoot growth were witnessed at RM depositional hotspots. Ujaczki et al. [12] perform a different study based on lab-scale microcosm experiment to evaluate the maximum amount of RM admissible without adverse effects on the soil and in addition assess the mid-term environmental risk related to this mixture. Though the mixture of 5 % RM with the soil did not exceed the Hungarian soil quality criteria, a significant increase of total As, Cr, Ni, Pb and Na content was observed. Furthermore, it was found by Misik et al. [27] that the area of Kolontar, was highly affected by the presence of vanadium and its effect on essay plants (generally used for environmental monitoring) was apparent. Even though there is little research on biological response to Vanadium pentoxide, classified as group 2B of possible human carcinogen agent by the International Agency for Research on Cancer in 2006 [25].

Several remote sensing reports were reviewed by Mayes et al. [28] on the extent and thickness of the spilt RM, frequent quality monitoring of streams and air, as well as speciation studies on important contaminants in the RM-affected sites in a detailed analysis on the environmental risks of RM after the Ajka Spill in Hungary. Hungarian RM catastrophe is discussed by Gruiz et al. [24] besides the results of priority assessment and decision making on relevant risk reduction measures of the 2010.

3.3. Australia

Dust emission was perceived to be a general issue within the community surrounding the Pinjarra Refinery owned by Alcoa in Western Australia. Based on the Bayer process, the refinery capacity was approximately 3.5 million tons per annum of alumina in 2007 [29]. RM is generated by the refinery at a rate of approximately two dry tonnes per ton of alumina produced and is primarily composed of alumina, silica and iron oxides and a fraction of sodium carbonate. Dust generated from it would also have a similar composition. The sodium carbonate crystallizes on the surface of the residue as moisture evaporates. Improper management of the dried residue surface led to dust emission, which can be entrained by excessive wind speeds of 23 km h⁻¹.

The transportation of fine particles over long distance depend on factors such as the atmospheric conditions, the size, shape and mass of the particles as well as the surrounding infrastructure such as roads, embankments and drains. It was predicted in 2004 that wind speed above 50 km h⁻¹ could be the largest source of dust from the refinery, constituting a potential risk of airborne dust emission around the disposal area plant. It was observed that some of the 14 residential locations within the Alcoa industrial zone were exposed to the dust emission. A 1-hour maximum and highest annual average volatile organic compounds (VOC) concentrations were observed in one location and considered as the worst case exposure to emissions from the refinery. The potentially high VOC exposure within the immediate area was also to be considered [29].

4. Strengths and weaknesses of red mud management techniques

RM-management and storage generally depend on factors such as the age of the alumina plant, land availability or proximity to sea, presence of local features (such as old mines), climate, logistics, nature of the residue, and regulations [30].

4.1. Red mud disposal

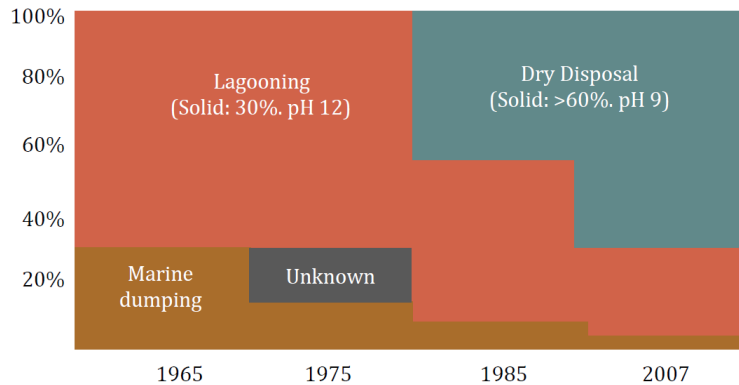
Land disposal of RM is the first choice of the majority of bauxite companies around the world. The method includes dry (dry disposal or dry stacking) and wet (lagooning or damming) disposal. RM dumping into deep sea is also adopted by few alumina processing companies [31]. Figure 1 shows RM disposal practices by 17 refineries representing 44% of global alumina production in 2007.

The wet stoking consists of transporting red mud to the disposal area as slurry then stocked into dams after precipitation. Solid content is about 30% and the remaining 70% consists of the caustic solution with pH varying between 12 and 13 [6]. There is, in this case, a need for leachate water management, which may result in high risk of seepage of alkaline solution to groundwater. The risk of surface water contamination is also of concern due to the overflowing of high alkaline water after heavy rains. In the case of a dry stoking method, desiccative red mud (for dry stocking) is transported to a disposal point for accumulation after getting dried by the effect of wind and solar [32]. The risk associated with alkalinity may be low in this case. However, dust containing corrosive metals may cause burning and respiratory tracts injuries [6]. Dry stocking requires less landscape for disposal compared to the wet disposal. Qiao [33] reported an alternative “mixed disposal” technique. The method combines the advantages of both the wet and dry disposal techniques [16, 33] and claimed to be cheap and efficient technique. Deep sea disposal of RM was practised at a small scale. Although studies carried out in both the Mediterranean and the Pacific Ocean showed that the method has a minimal adverse effect on the marine environment, the method is progressively being phased out [30]. Table 3 summarizes the key information on RM disposal by eight plants operating in Western Europe [17].

*Estimated as 1.5-times the alumina production rate; **bauxaline patent; *** in the last part of the indicated period, the amount of waste discharged into the sea was progressively reduced in favour of dry disposal; *****2009 bauxite residue (BR) production; n.d.: no data available. This is adapted by Dentoni et al. [17].

Table 3. Characteristic of the RM disposal plants in the EU.

Refinery	Disposal period	Percentage of reuse	Disposal method	RM production rate (KT/year)*	RM disposal area (ha)
Ludwigshafen Stade	1976-2014	0%	Dry stacking	n.d	6.5
	1973	0%	Lagooning	1500	150
Gardanne	1893-2012	0%	Sea discharge	690	29.4
	2012-2014	30%**	Sea discharge/dry stacking	n.d.	29.4
San ciprian	1981-2014	0%	Dry stacking	2175	84
Aughinish	1983	0%	Dry stacking	3000	121
Mytilineos group	1966-2012	0%	Sea discharge/dry stacking	1200***	19
	2012-2014		Dry stacking	830	
Eurallumina	1977-2009	0%	Lagooning/dry disposal	1200****	120



Source: CSIRO DMR-3608 May 2009, reported by Szepevolgyi [34].

Fig. 1. Disposal practices by 17 refineries representing 44% of global alumina production in 2007.

4.2. Red mud neutralization

An important aspect for the management of RM is its neutralization. The strategy is intended to reduce not only the environmental impact of the alkaline material but also the need for further management of disposal impoundments post-closure. The neutralization of red mud can also facilitate its reuse for many purposes as described in section 4.3.

Gypsum is been applied to RM disposal area during remediation, allowing a decrease in the pH of the environment. This is usually done in order to facilitate the revegetation of the site after disclosure [35]. However, seawater and carbon dioxide neutralization remain the principal techniques used to neutralize red mud residue at a big scale. Other methods for partial or complete neutralization of RM include; acids (sulfuric or hydrochloric acid), sulfur dioxide and concentrated brine (Virotec process) [30]. Furthermore, acidifying bacteria are a good alternative for a green neutralization of RM. Acetic or citric acid producing bacteria can be grown in the residue by adding their natural substrates [16].

Neutralization of RM with carbon dioxide (CO₂)

Gaseous CO₂ or CO₂-containing flue gas can bubble through RM suspension (aqueous slurry) to form carbonic acid, which reacts with alkaline compounds of

the slurry. This, therefore, lowers the pH of the slurry [35, 36]. Sahu et al. [7] successfully neutralized RM on laboratory scale through CO₂ gas sequestration cycle (3 cycles) at ambient conditions. CO₂ sequestration was mainly dependent on NaOH concentration in RM. Energy-dispersive X-ray (EDX) revealed that the concentration (w/w%) of Na, C, O and Si were higher in the carbonated filtrate compared to that in RM. The amount of CO₂ sequestered per 10 g of RM was 26.33, 58.01, and 55.37 respectively for the 1st, 2nd and 3rd cycles of carbonated filtrate.

The pH of RM decreased from 11.8 to 8.45 and alkalinity from 10,789 to 178 mg L⁻¹. Furthermore, an experiment was performed in batch mode for alkali removal from RM through the dissolution of CO₂ in aqueous solution. Low alkaline RM was obtained at a constant flux of CO₂ dissolution in distilled water for about 3-2.7 hours at 4-75 °C. Alkali removal process from RM was a function of Na(I) concentration, contact (treatment) time, temperature and partial pressure of CO₂ [37]. Moreover, Alcoa of Australia Limited [29] performed a small scale experiment in 1996 in order to reduce the pH of RM slurry prior to “dry” stacking. An optimum rate of 25 kg CO₂ per m³ of residue slurry (48% solids) allowed the pH to decrease up to 9. Leachate collected from the carbonated bed remained steady at around 10.5 compared to that from a non-carbonated bed, which was consistently greater than 13. The technique was then successfully applied at a large scale in 2000 at the Kwinana refinery where the pH was lowered to about 8.5. However, a slow rise of pH up to 10.5 was observed when CO₂ overpressure was removed. This was probably due to the dissolution of alkaline solid phases that become soluble in this pH range [9].

Neutralization of RM with seawater

Seawater neutralization of red mud is done through soluble Ca²⁺ and Mg²⁺ content. On average one litre of seawater contains 965 g of water and 35 g of salts (i.e., 3.5% salinity). Seawater contains concentration of various salt ions including: 55% Chlorine (Cl⁻), 30.6% sodium (Na⁺), 7.7% sulphate (SO₄⁻²), 3.65% magnesium (Mg²⁺), 1.17% calcium (Ca²⁺), 1.13% potassium (K⁺) and 0.7% other elements [36]. Partial neutralization of RM is therefore possible with sea water where the high alkaline raw material is converted into a weak alkaline suspension. An excess of the quantity of seawater can neutralize red mud down to approximately pH 8.5 depending on the pH of the starting solution [35]. However, this kind of treatment will result in a high saline environment, which might require treatment (e.g., flush with fresh water) for further use in activates such as vegetation.

Neutralization of RM with mineral acids

Several techniques have been reported in the literature regarding the neutralization of RM with acids [4, 38]. Dealkalization of red mud was studied through active roasting of RM and water leaching [39]. ICP-AES, XRD, TG-DSC, SEM-EDS and leaching kinetic were used to analyze the mechanism of dealkalization, which rate reached 82% at 700 °C for 30 min. Water leaching was performed at four different stages. A liquid to solid ratio of 7 mL g⁻¹ was obtained at leaching temperature of 90 °C for 60 min reaction time. Furthermore, alkalinity was removed from RM solution via neutralization and precipitation of mineral acid after the addition of soluble calcium or magnesium salt, resulting in the formation of bicarbonate. The pH was reduced to 10 either by suppressing the

solid phase alkalinity (Ca/Mg) or by dissolved (acid). The reaction kinetics of the neutralization process was inhibited by mass transfer limitations (acid processes) and a sustainable presence of a soluble excess (Ca/Mg processes). The alkalinity of the RM solution was reduced to less than 1% of the initial. This was far greater compared to the use of carbon dioxide where only 40% of alkalinity was removed from the RM solution [35].

Bio-neutralization of RM

Bio-neutralization of RM can be done by adding natural organic substrate to red mud. This allows the growth of microorganisms for the production of different organic acids and CO₂ (in some cases), which can neutralize RM. Among the commercial substrates used to perform the production of acetic acid are grape wine, fermented apples, barley or cereal malt and rice starch. The substrates used for the production of citric acid are glucose, fructose, sucrose and lactose. 12-18% sucrose, whey and 3% 1, 2-propanediol are used as a substrate for production of lactic acid.

Lactose and glucose are used for the production of propionic acid [16]. The use of the microorganisms depends on their stability and resistance to the standard characteristics of RM. The microbial conversion of abundant and renewable cellulosic biomass to organic acids offers an attractive alternative to the neutralization of red mud. Cellulosic biomass is available in enormous quantities as waste from agricultural, industrial, forestry and municipal activities. The microbial conversion of these wastes to generate value-added products can also alleviate pollution problems. The direct conversion of cellulosic biomass to acetic acid by single step fermentation can be economical over the expensive multi-step process in which, fungal cellulases, yeasts and acetogenic bacteria are used [40, 41].

4.3. Beneficial use of red mud

The key to solving red mud stockpiling is to develop a comprehensive utilization technology that consumes red mud or converts it into a secondary resource. Since the 1950s, scientists have carried out research projects that explore the disposal and utilization of red mud, according to the unique physical and chemical properties of red mud [16]. There exist several attempts and methods for the utilization of red mud taking into account environmental and economic aspects. From many literatures, red mud can be used as adsorbents for pollutant removal, building materials (brick, cement, glasses and concrete blocks), filling materials in mining and reagents for neutralizing acidic wastes [11, 31, 33, 42, 43]. Red mud itself can be used as a neutralizing agent.

For instance, a study was conducted to test the long term potential of RM combined to brine for the neutralization of acid mine draining [44]. The results showed that red mud could rather lose its alkalinity by mixing with the acid mine. However, the addition of Brine helped RM to keep its neutralization potential over several cycles of leaching. Some of the potential utilization of red mud for integrated management and reduction of environmental degradation could be used in various industries such as chemical industry, metallurgical industry, construction industry, glass and ceramic industry, agriculture, water supply and environmental protection [31]. In terms of material recovery from red mud, a study showed that copper (Cu) contained in red mud, could be tightly retained by a CaCO₃-dominated red mud compared to boehmite-dominated red mud [45]. The conclusion made by

the authors was that the heterogeneity of red mud marked influences on its capacity to immobilize water-borne Cu and maintain the long-term stability of the immobilized Cu species. Another study based on laboratory findings and finite element analysis [46] offered the possibility of using red mud in the construction of the tailing dam. Moreover, Liu and Poon [19] demonstrated that RM has good pozzolanic activity similar to that of fly ash (FA) and can be used in self-compacting concrete (SCC). Using XRF and XRD, SiO₂, Al₂O₃ and CaO were found to be the major oxides contained in RM. Crystalline phases were mainly gismondine, goosecreekite and epistilbite (zeolite family).

Even though a slight decrease was observed in the hardness of SCC with increasing RM content, the similar content of RM to that of FA (30%-40%) favoured an enhanced compressive strength and splitting tensile strength of SCC after 90 curing days' observation. The drying shrinkage in SCC was also reduced in the presence of RM, probably because of the internal curing effect. It was demonstrated, therefore, that there is a possibility of using around 10%-40% of RM to replace FA in the production of SCC. Similarly, Molineux et al. [47] looked at the potential of using RM for the fabrication of lightweight aggregate as an alternative to Pulverized Fuel Ash (PFA). Interestingly, the use of 44 % RM was used as an alternative to replace the PFA in the production of aggregates with high water absorption capacity, making them suitable for urban greening applications. High water absorption property was observed for aggregates with high density, probably because of their open pore structure as a result of gases released at high temperatures. Concentrations of heavy metals in the resulting materials were below the regulatory target limits. Further investigations could be performed on the possible utilization of RM above 50 % while testing the crystallography and pozzolanic characteristics of the aggregates. Investigation on lowering the water holding capacity of RM-based aggregates could also be very interesting as well as the possible use of RM in the manufacturing of concretes and other materials of construction.

Despite its high alkalinity and salinity, low hydraulic conductivity, trace toxic elements, and deficiencies in organic matter and nutrition concentrations, various studies have been reported on the possible use of RM for land rehabilitation for green environment [48]. Depending on the origin of the bauxite ore, RM may contain Rare-Earth Elements (REEs), which can be recovered. For instance, the recovery of scandium from RM has particularly attracted some interests. Borra et al. [49] carried a leaching experiment on RM in Greek by taking into account different concentrations, liquid to solid ratio, leaching times and temperature, where successful extraction REEs was achieved through leaching in HCl solutions. Up to 80% of the REEs were recovered. Sodium and calcium were completely dissolved during the leaching. In addition, the dissolution of iron was high (60%) compared to aluminium, silicon and titanium, which dissolution was between 30% and 50%. Data showed a very close association of scandium with the iron oxide phases. Activation and heat treatment of row red mud was studied in a parallel experiment for the recovery of phosphate (PO₄-P) [50]. Furthermore, the recovery of titanium with citric and sulfuric acid from red mud was put forward to strengthen acid leaching efficiency. It was found that the combination of 5% citric acid with sulfuric acid could increase between 65% to 82% recovery of titanium [51]. Iron oxides/hydroxide content is more than half of RM composition, which would make its recovery a great advantage in the management of RM. Different physical and chemical techniques have been

intensively studied such as direct magnetic separation, acid leaching, smelting in a blast furnace and solid-state reduction magnetic separation.

Considering the above routes, low-level recovery, high energy consumption, long process and secondary pollution are the main limitations of large-scale industrial applications. Alternative methods like selective flocculation have been explored for iron recovery from red mud (a solid-solid separation process) [14]. A technique of iron mineral recovery was carried out applying humics flocculants on red mud based on selective flocculation desliming process [14]. The bioleaching of other valuable metals (Ga, Ge, V, Sc, La, Eu, Yb) from red mud was also examined [52]. An efficient and environmentally friendly aluminium leaching from red mud was done using various species of filamentous fungi, from which, *Penicillium crustosum* G-140 and *Aspergillus niger* G-10 showed excellent results [41].

Another analysis was done based on thermodynamic modelling and laboratory experiments and a semi-industrial Electric Arc Furnace (EAF) experiments. The analysis proved that a reductive smelting of red mud at 1600 °C, using carbon as a reducing agent and appropriate fluxes to regulate the composition of the generated slag, can produce pig iron and a viscous slag, which could be converted into glassy fibres suitable for mineral wool production [53].

5. Conclusions

In this mini-review, red mud characteristics have been reviewed together with environmental issues related to its disposal and reuse. Some case studies on risk assessment and management of red mud have also been highlighted. Due to its chemical composition, production method and its large production, effective management strategies, which addresses the hazards accompanying the process are required to minimize the risk of environmental pollution by red mud.

Although, the hazards of RM are generally common, however, the treatment and reuse methods might vary depending on many factors. In Malaysia case, Kuantan bauxite mining sites are scattered, and in some cases, near residential areas. Bauxite mining is also causing dust, noise and water pollutions in the areas of mining. On the other hand, the major issue faced by Pinjarra Refinery in Australia was dust pollution. However, the refinery is facing other challenges, which some are similar to Malaysian cases such as noise and water pollution. Various management strategies could be applied to tackle this range of pollutants. The best practice will be in providing a solution, which promotes sustainable development. Recycling of wastewater and dust is an example of such practice. The water could be used in running the facilities, while the dust could be used in making construction materials. It is important to note that the reuse of some of RM waste might not be positively received by some due to the possibility of the presence of radioactive compounds.

Further considerations including the geographical location, design structure, transportation system, and stockpiling method of RM must be taken into account to avoid large scale environmental incidents from disposal facilities failures. The environmental quality monitoring should focus on surface water, groundwater, agricultural lands and air, to ensure close environmental monitoring and take appropriate measures even before a pollution signal is detected. Continuous evaluation of the environmental performances of bauxite companies by relevant authorities is essential to ensure the application of regulations is in place.

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