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Comprehensive Utilizations of Red Mud with Emphasis on Circular Economy: An Approach towards Achieving the United Nations Sustainable Development Goals

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INFORMATION

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ABSTRACT

Red mud (Bauxite residue) is an industrial by-product (IBP) generated as a vast volume, mainly from aluminum industries. Disposal of red mud in open land leads to serious environmental hazards, occupies a vast land area, and incurs enormous economic and social costs. Storage and maintenance of red mud dumps are also costly, and their failures frequently flood vast areas, killing people and cattle and disrupting the ecosystem. Conversely, research data shows that the red mud has enormous potential to transform its valuable resources. Due to the growing demand for bauxite ore for aluminum industries, the volume of red mud has been increasing rapidly, causing an inevitable multidirectional consequence in the context of environmental and sustainability issues. On the other hand, the rising demand and resource crises continue to deplete natural resources; the gap of enormous resource availability has become a severe challenge for scientists, researchers, and institutional R&D to develop a process technology to re-generate resources through the recycling of wastes. Using red mud through the circular economy concept can replenish the depletion of virgin resources (mainly the construction sector) and extract valuable materials and metals from red mud. Recycling RM through the circular business model can increase the sustainability of natural resources, reduce environmental pollution, water contamination, and land pollution, increase land area, replenish the depletion of natural resources, enhance economic growth, and mitigate global warming and climate change.

1. Introduction

1.1. The Transition from Linear to Circular Economy

Globally, Interest towards applying of circular economy concept has surged in recent years, reflects new direction of research about wastes and the utilization of resources, it emerges the waste hierarchy (Fig. 1) and aim on higher order uses, while developing on the idea of continually reusing, recycling and recirculating of IBPs (Bose et al., 2024; Bose, 2024; Moustakas and Loizido, 2023; Bose, 2022; Bose et al., 2022a).

Recent endeavour to foster the concept of transition from waste to wealth and linier economy to circular economy have been manifested new direction to the Scholar, R&D experts and entrepreneurs to explore innovative idea to develop process technology to transform IBPs to a valuable products, which can be replenish the depletion of natural resources through the process of recycling (Moustakas and Loizido, 2023; Bose and Dhar, 2022; Bose et al., 2021; Bose et al., 2019; Pinjing et al., 2013).

In the process of linear economy, notion is that there is a continuous supply of natural resources for the processing of products, and after use, it has been disposed as a post-consumer waste, these wastes incur enormous amount of environmental, economic, and social cost. A circular economy has been propounded as a sustainable substitute to our present linear economic model, mainly by recycling and recirculating IBPs, post-consumer waste and discarded materials for the purpose of development new products, main focus on recirculation of resource in circular economy loop is to conserve value proposition as much as possible. (Bose et al., 2022b; Bose et al., 2021; Moraga et al., 2019). To make sustainability in natural resources and to prevent global population go to waste, we must "closing the circularity gap" as a model of circular economy instead of linear economy model. Fig. 2 presented a graphics of "Linier Economy Vs Circular economy".

Circular economy processes may be an integrated process for synergistic reutilization of Bauxite residues (Red Mud (RM)). Bauxite residue (RM) despite of waste, it may be a valuable input material for other products purposes if we can process it with the proper scientific way, on the other hand it may call as a "by-product of economic activity" (Uysal et al., 2023; Bose et al., 2019; Bose and Dhar, 2022; Lei, 2022; Swain et al., 2022; Wackernagel et al., 2002; Xie et al., 2020).

Initiatives towards a more circular economy could deliver several advantage and benefit such as increasing security of resource, replenish the depletion of natural resources, reducing GHG, decreasing waste volume, boosting economic growth and others benefit including employment opportunities and increasing competitive advantages for companies and leading to increase global sustainability (Bose et al., 2021; Sauvé et al., 2016; Esposito and Soufani, 2018; Corona et al., 2019).

Australian Government has published five principles on "Applying circular economy principles for waste, recycling and resource recovery" which is available in the source as (Australian Government, National Waste Policy, Department of the Environment and Energy, 2018).

2. Global Perspective

Globally, the drives of manufacturing lightweight components in the automobile industry to increase fuel efficiency and reduce CO_2 emission as well as other relevant uses has led to much wider use of aluminium. (Miller et al., 2000; Green, 2007; Hirsch, 2014; Tisza and Czinege, 2018). Global primary aluminium production in 2018 was 65 million metric tonnes, (Wong and Lavoie, 2019). Due to the growing demand for aluminium globally, the total volume of aluminium smelting crossed 60 MT in 2018 (Rodionova, 2020) and subsequently, the bauxite demand also increasing substantially. Global productions of the bauxite country-wise from different sources are summarized in Table 1.

Globally, approximately 117 million tons of RM is generated annually (Lima et al., 2017). Disposal of RM causing serious hazards. Utilization of RM as construction material such as backfilling, road construction, cement production, brick & concrete, tiles, aggregates and recovery of rare earth & valuable metal, etc. seems inevitable (Kalkan, 2006; Yarbaşı et al., 2007; Nadaroglu et al., 2010; Nadaroglu, H., Kalkan, E., 2012; Cozzolino et al., 2023; Borges et al 2011; Ashok and Sureshkumar, 2014; Agrawal et al., 2015; Borra et al., 2016; Kim et al., 2017; Nikbin et al., 2018; Wang et al., 2018; Akcil et al., 2018; Khairul et al., 2019; Mukiza et al., 2019a).

Table 2 presented the resource status and inventory of eight major bauxite producer country.

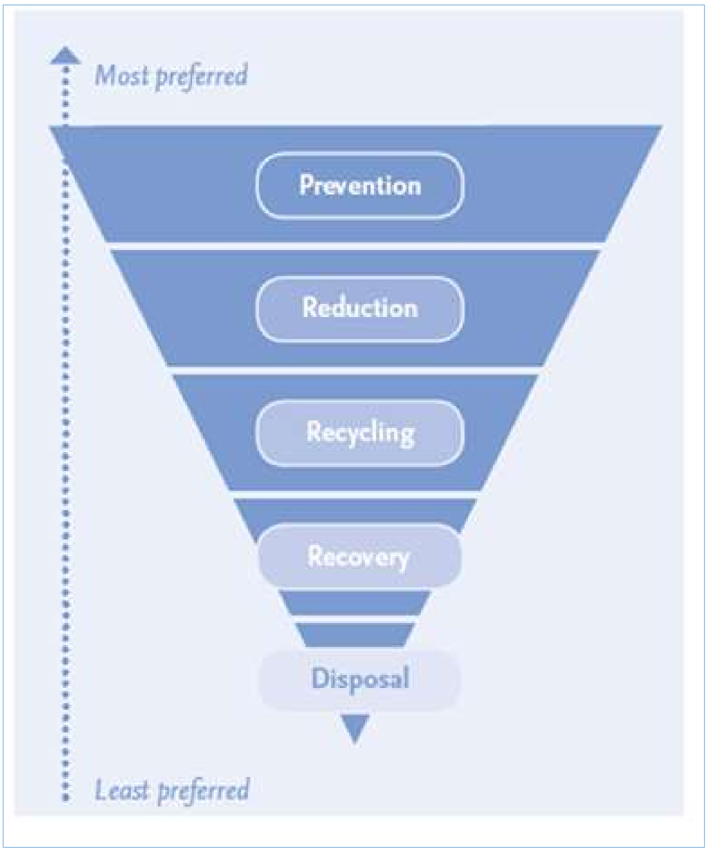

Fig. 1. The waste management model (UNEP, 2011). Towards a green economy

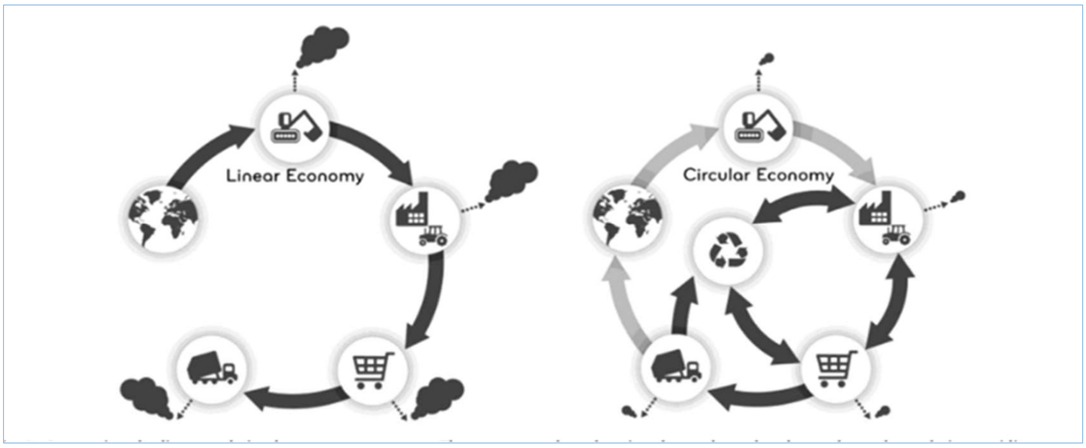

Fig. 2. Graphical flow line “Linier Economy vs. Circular Economy” (Sauvé et al., 2016)

Research finding of RM studies shows that it is very suitable and worthy for recycling or reuses as a raw material in a wide range of commercial and other relevant applications using cost-effective procedures. (McConchie et al., 2002; Sutar et al., 2014; Wang et al., 2018; Zhang et al., 2018; Rubinos and Spagnoli, 2019; Mukiza et al., 2019b).

Table 3 presented the utilization of RM in various applications (worldwide).

Table 1. Country-wise bauxite production (2013 & 2014) (Patel and Pal, 2015)

Country	Mine production (X1000 tonne)		Reserves
	2013	2014	
Australia	81,100	81,000	6500,000
Brazil	32,500	32,500	2,600,000
China	46,000	47,000	830,000
Greece	2,100	2,100	600,000
Guinea	18,800	19,300	7,400,000
Guyana	1,710	1,800	850,000
India	15,400	19000	540,000
Indonesia	55,700	500	1,000,000
Jamaica	9,440	9,800	2,000,000
Kazakhstan	5,440	5,500	160,000
Russia	5,320	5,300	200,000
Suriname	2,700	2,700	580,000
Venezuela	2,160	2,200	320,000
Vietnam	250	1,000	2100,000
Other countries	4,570	4,760	2400,000
World total	283,000	234,000	28,000,000

Many R&D organizations have been evaluated the different applications of RM and gained global acceptance. Between 1964 and 2008, 734 patents have been registered for utilizations of RM for various applications worldwide (Morsali and Yildirim, 2023; Khanna et al., 2022; Leiva et al., 2022; Lima et al., 2017), summary of the registered patent presented in Table 4.

4. The Disposal of RM and its Environmental Impacts

Worldwide, aluminium industries are facing major challenges with the storage and disposal of RM. Presently dry stacking method considering as secure disposal of the RM with the constraint of land requirements scenario (Swain, 2022; Prasad et al., 1991). Damaging effects of RM waste on the environment and ecology are quite extensive, dumping of RM occupies the vast land area, polluting land, air, and groundwater respectively (Prasad et al., 1991; Wong and Ho, 1994; Kogel, 2006; Gelencsér et al., 2011; Gura, 2010). Maintaining of storage dam for RM is costly and their failures frequently flood vast areas, killing people, cattle, and disrupting the ecosystem (Boily, 2012; Wen et al., 2016). Table 5 presented few serious incidents due to the storage systems of RM waste in open land and the dam respectively.

4.1. Chemical Compositions of RM

Properties of RM are mainly dependent on the category of bauxite ore using and refining processes. For several considerations, the RM appears to be potential resources for various applications and alternatives. Chemical composition is one of the important considerations to determine the utilization pattern of RM in different applications and uses respectively. Chemical compositions of some RM from different companies are presented in Table 6 respectively (Liu et al., 2007, 2017).

Table 2. Country-wise production of bauxite, alumina, and aluminium smelter (U.S. Geological Survey, 2018)

Country	Bauxite (Tonne)	Alumina (Tonne)	Reserves (Tonne)	Aluminum Smelter (Tonne)	Aluminum smelter year-end capacity (Tonne)
China	68,000	72,300	1,000,000	32,600	44,500
Russia	5600	2800	500000	3600	3900
India	27000	6170	830000	3200	3600
Canada		1570		3210	3270
USA		1500	20000	740	20000
Australia	83000	20600	6000000	1490	1720
Norway				1220	1550
Brazil	36000	11000	2600000	800	1400

Table 3. Utilizations of RM (worldwide)

Description	References
Extraction and Recovery of Valuable Metals [SiO_2, CaO, Fe_2O_3, Al_2O_3, Na_2O, TiO_2, K_2O]	Zhang et al., 2018; Xakalashe and Friedrich, 2019; Rai et al., 2019
Recovery in Component in RM	Liu and Wu, 2012; Zhu et al., 2020
Recovery of Rare Metals from RM	Zhang et al., 2019; Qu et al., 2019; Zhang et al., 2020
Production of Construction material from RM	
Geopolymers	Yan et al., 2023; Zhang et al., 2010; Li et al., 2019
Clay-based products	Yang et al., 2009; Babisk et al., 2020
Cement	Ribeiro et al., 2010; Liu et al., 2020
Brick	Yang et al., 2008; Zhao et al., 2020
Glass	Peng et al., 2005; Zhao et al ., 2019
Aerated concrete block	Bo et al., 2005
Utilization of RM as filling materials	
Road base materials	Mukiza et al., 2019a
Mine filling	Chen et al., 2020
Application in Pollution control	
Wastewater treatment	Hofstede, 1994; Wang et al., 2019
Soil improvement by RM	Ciccu, 2003; Chen et al., 2019
Treatment of waste gas containing sulphur by RM	Nie et al., 2019

5. Policy Relevance in the Current Context

The right model for policy and regulatory framework pertaining to managing IBPs is an urgent need at the national and state level. Various countries have taken lot of initiatives to form different of policies and guideline for managing waste. In the year of 2013, Asian Productivity Organization Resource recycling in R.O.C, (2013) has been published a report on policy implementations by Taiwan Government on "Utilization of Industrial Waste" has described following two major concept on managing Industrial waste through a proper flow chart are as follows.

- The best practices and policy implementation for recycling Industrial by products (IBPs) (Fig. 3).
- Operation of resource recycling management fund presented (Fig. 4).

Table 4. RM applications: registered patents (1964-2008) (Lima et al., 2017)

RM applications	Ratio
Civil construction	33%
Water treatment	13%
Soil treatment	12%
Ceramic composition	12%
Recovery of metals	11%
Additive for metal production	7%
Gas remover	4%
Adsorbents	4%
Other elements	4%

Table 5. RM incidents in different countries

Date	Place	Incident
26-May-2012	Guangxi Huayin, China	Leaking of disposal pond
12-Jan-2012	Rusal, Ireland	Fine dust contamination
10-Dec-2011	Alcoa, Virgin Island	General pollution
17-Oct-11	Venezolana de Guayana, Venezuela	RM discharge into Orinoco River
2-Jun-2011	Rusal, Italy	Spills of RM
16-May-2011	Vedanta, India	Pollution after heavy rain
3-Mar-2011	Rusal, Ukraine	Fine dust contamination
22-Oct-2010	Alcoa	The United States Fine dust contamination
4-Oct-2010	MAL Hungarian, Hungary	Dam break
27-Jun-2010	Vedanta, India	Fine dust contamination
1-Feb-2010	Rusal, Jamaica	Clouds of toxic dust
27-Apr-2009	Norsk Hydro, Brazil	RM discharge into Murucupi River
20-Aug-2008	Rio Tinto, Canada	RM discharge into the river
21-Feb-2008	KAP Aluminum	Montenegro fine dust contamination
6-Apr-2007	Rio Tinto, Canada	49 tonnes released into Saguenay River
14-May-2006	Alcoa, Australia	Poisonous dust emission
6-May-2002	Alcoa, Australia	Disposal of RM onto local farmland
1966-Present	Rio Tinto, France	RM discharge into the ocean

Table 6. Chemical composition of RM from different companies' worldwide

Composition (%)	ALUNORTE Brazil	ALCOA Brazil	CBA Brazil	ALCAN Canada	ALCOA Australia	ALCAN Africa
Al_2O_3	35,5	35,67	36,7	37,6	25,45	26,6
Fe_2O_3	37,16	33,78	29,89	32,45	34,5	48,4
SiO_2	2,34	3,45	6,78	3,67	17,06	5,5
TiO_2	6,18	4,56	5,67	4,12	4,9	2,8
Na_2O	8,49	9,67	7,89	6,78	2,74	2,4
CaO	1,23	2,34	1,2	3,45	3,69	-

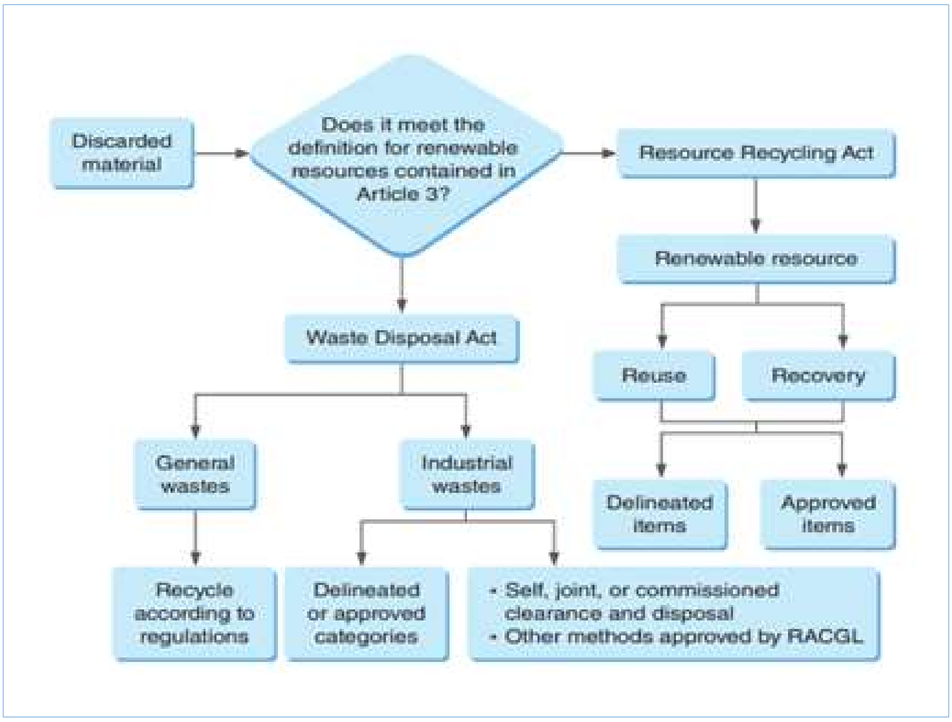

Fig. 3. The process for identifying the relevant regulations for recycling Industrial Waste (Asian Productivity Organization. Resource Recycling in R.O.C, 2013)

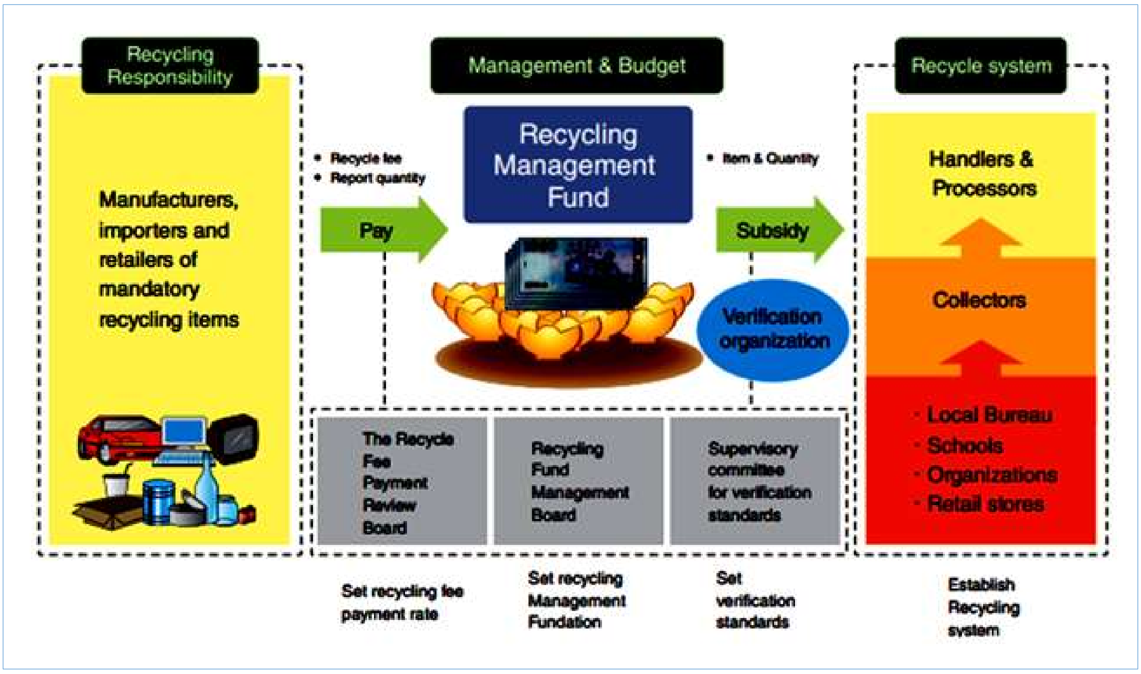

Fig. 4. Operation of Resource Recycling Management Fund presented (Asian Productivity Organization. Resource Recycling in R.O.C, 2013)

To get succeed, actors all along the systems of IBPs management will have to co-operate each other's for the sake of sustainable development reach to a mission of zero waste. Only at that point will we achieve meaningful positive impacts. With the holistic vision and cooperation among Government, R&D partner, industry, public and private sector, bauxite residues (IBPs) can be managed more efficiently and effectively. Through collaboration and cooperation, new concept of business models (with the coupling of circular economy) and incentives can be enhancing the process to maximize value from recycling of IBPs, leading to expanded and robust markets for products and resources recovered from bauxite residues (IBPs). Creating common platforms for collaboration, cooperation and technology & knowledge transfer, best practices can be adopted and implemented. This Joint and collaborative action plan leading to a way forward for innovative and sustainable approaches for recycling and utilizations of bauxite residues (IBP).

7. Conclusion

Mission zero waste challenges all stakeholders to eliminate IBPs through recycling and recirculation by coupling the circular economy model. This pushes them to redesign their existing practices, policies, and norms and direct them towards greater sustainability. The adequate disposal and storage of bauxite residues (RM) from aluminum industries remain challenges for both corporations and the government; it is probably a direct consequence and impact of inadequate practices long past for managing IBPs, which in turn produced a negative impact on environmental, ecology and economy as well. Recycling bauxite residues (RM) through the circular economy model can partially replenish the depletion of virgin resources, reduce pollution, increase land area, and improve sustainability.

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