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Valorization of Iron Ore Tailing (IOT) Waste Through the Circular Economy Concept: A Sustainable Solution Towards Mitigation of Resource Crisis and Climate Change

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INFORMATION

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ABSTRACT

Worldwide exponential population growth causes tremendous resource crises leading to declining sustainable development in the global context; on the other side, massive waste materials generating worldwide, causing degrading biodiversity and loss of nature's regenerative capacity. Rapid population growth is a worldwide concern regarding fulfilling the resource demand and accelerating industrial growth. Among the different waste materials, iron ore tailing (IOT) is a valuable waste with a huge potential to reproduce secondary material and mitigate resource crises. Tailings are dumped mostly in specially made dams that occupy vast land areas and continue to pollute the surrounding environment. Failure of the tailing dam incurs enormous environmental, economic, human, and animal losses and declining sustainability in mining industries. Using tailing waste as an alternative to virgin resources through the circular economy process would be a sustainable solution to eliminate all associated hazards and impacts pertaining to tailing storage and maintenance. Worldwide, the circular economy concept is gaining acceptance; in this process, tailing waste can be recycled fully through the continuous circulation loop. This paper presented the opportunities and possibilities for recycling and valorization of the IOT for different applications. Recycling and valorizing IOT through the circular economy concept can replenish the depletion of natural resources, eliminates pollution, clean the environment, restore biodiversity, reduce the burden from the biosphere, mitigate global warming, and improve sustainability.

1. Introduction

The global population is growing significantly faster than at any time in history. Subsequently, minerals and metals consumption are growing faster than the population, as more demand is placed in the market for minerals and as the worldwide standard of living changes and improves; at the same time, processing of mining and minerals ore poses a tremendous negative impact on the environment and sustainability (Kesler, 2007; Tuokuu et al., 2019; Manhart et al., 2019).

Worldwide, mine tailings are the solid waste generated after separating valuable fractions from the uneconomic fraction of various minerals ore. Generally, tailing is the fine particles of crushed rocks and a mixture of low-value mineral residues. The estimated global tailing production was 14 billion tonnes in 2010 (Adiansyah et al., 2015), and the worldwide production rate of mine tailing has been assessed as a range between 5 and 7 billion tonnes per year (Edraki et al., 2014; Schoenberger, 2016).

Based on the evidence in the literature and records with regulatory officials, there are estimated to be more than 3500 appreciable tailings dams worldwide (Davies and Martin, 2000; Clarkson and Williams, 2020). Because of such a large volume of tailings waste produced and the nature of the chemical composition involved, the storage, handling, and maintenance of mine tailings is a significant environmental and ecological problem. It puts pressure on the biosphere and biodiversity. Among the important consequences of a large amount of tailing waste are the failure and disasters of the tailing dam.

During 1971-2009, worldwide 237 cases of serious tailings dam failure were reported (Adiansyah et al., 2015), such as the tailings dam failures in Brazil in 2019, the Cadia mine in Australia in 2018, and elsewhere, the Mount Polley mine in Canada in 2014, Philex Padcal in the Philippines in 2012 (Owen et al., 2020; Do Carmo et al., 2017; Lyu et al., 2019; Clarkson and Williams, 2020).

Tailing dam failure incurs substantial environmental, economic, human, and animal losses, declining sustainability in mining industries. Utilizing tailing as an alternative to virgin resources through recycling would be a sustainable solution to eliminate all associated hazards and impacts of tailing storage and maintenance. To eradicate the associated adverse effects of tailing dams, including storage and maintenance, R&D experts are striving and working on it, and technology has already been developed for the recycling of tailing in different applications.

At present, tailing has been utilized in many aspects, not per the proportion of the production level of tailing, so surplus tailing remains a burden for the environment and the biosphere. Based on the report of UNEA, with the global demand for sand and gravel standing at 40 to 50 billion tons per year, a new report by UN Environment reveals that aggregate extraction in rivers has led to pollution, flooding, lowering of water aquifers, and worsening drought occurrence (UN et al., 7th May 2019).

Research has proven that mine tailing can be used as a virgin resource like sand, aggregates, and many natural resources, so utilization of mine tailing as an alternative to natural resources can replenish the depletion of natural resources and save the environment, ecology reduce the burden from the biosphere and increase sustainability as a whole (Wells and Collins, 2011; Gupta et al., 2017; Ivannikov et al., 2019; Paiva et al., 2019).

2. Global Perspective Towards Valorization of IOT

Materials like minerals and metals are essential for developing and functioning modern civilization and economy. Mining activities provide significant economic opportunities throughout the globe. However, the entire process of mining industries creates challenges and risks for the well-being of all living species, climate change, and the environment (Xu et al., 2019). A key challenge is to manage mining in a way that contributes to economic enhancement, societal development, and overall sustainability, and at the same time, it should not endanger the sustainability of the planet Earth (Lambert, 2001; Zhironkin et al., 2018; Monteirobet et al., 2019). Since 1984, mining activities and mineral production have been rising continuously at 17.7 BMT as compared to 9.6 BMT was 1984, a 45% increase during the span of 1984-2018 (World Mining Data, 2020), presented in Fig 1.

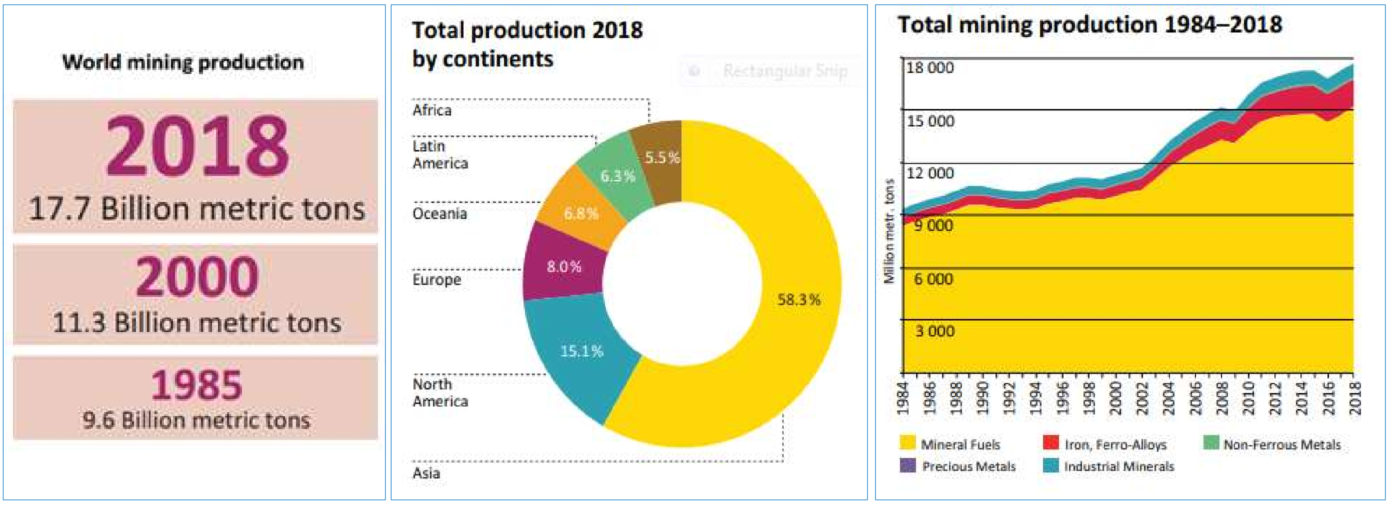

Fig. 1 Global mining production (1984-2018) (World Mining Data, 2020)

Due to the growing demand and the unprecedented rate of mining and mineral processing over the last few decades, the generation of mine waste, viz. IOT, etc., is increasing much faster, causing enormous environmental degradation, damaging biodiversity, and a substantial economic loss.

The mining and mineral process generates a large volume of residues which mainly includes waste rock, tailings, and slag, as shown in Fig. 2, that must be scientifically and strategically managed to combine with the demand for societal and environmental sustainability, economic efficiency, including resource optimization (Durucan et al., 2006; Gou et al., 2019).

Out of the various waste generated from mineral processing, IOT is one of the highly risk-oriented wastes in the mining industries in respect of storage and maintenance of tailing dams; the annual production rate ranges between 5 and 7 billion tonnes per year (Edraki et al., 2014; Schoenberger, 2016). Due to the catastrophic failure of a tailing dam at Brumadinho, Brazil, 259 people have been confirmed dead, and 11 remain missing; this was a remarkable human and environmental tragedy regarding tailing dam failure. On 5th August 2020, the initiative of ICMM and UNEP launched "The Global Industry Standard on Tailings Management" with the ultimate aim of preventing catastrophic failure, the safety of tailing storage facilities, zero harm for humans and living species, and protecting the environment (https://globaltailingsreview.org/).

From the perspective of sustainability in natural resources, future strategies of mining industries and ore processing may compound the risk and challenges for managing tailing waste, as ore grade of lower economic value increases the ratio of tailing waste produced for a given unit of the mineral resource and emphasize the priority and need for the mining industry to adopt new approaches (Ali et al., 2017). New innovative strategies and technologies to reduce risk in managing tailing storage facilities, such as thickened tailings, dry stacking, and paste backfill, have significantly reduced the risk and increased the sustainability in mining industries as well as meet the future challenges to sustainable development (Franks et al., 2011; Adiansyah et al., 2015; Schoenberger, 2016). Many literatures emphasize and proposes to implement an adequately strict policy, regulation in the regime and proper enforcement are the keys to avoiding and eliminating the hazards of tailings dam collapses (Schoenberger et al., 2016).

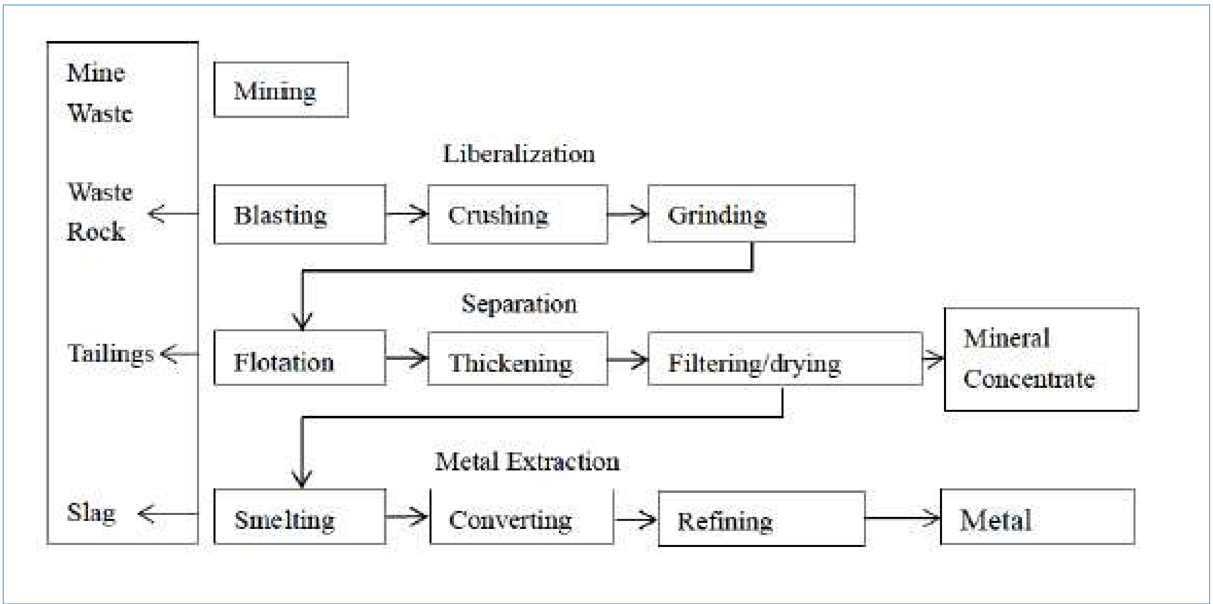

Fig. 2 Waste generation during mining, mineral, and metallurgical processes (Gou et al., 2019)

Despite storage and maintenance for the accelerating volume of tailings produced annually, there should be more emphasis on research for the comprehensive utilization of tailings for a broader range of applications. Recycling and valorizing tailing waste can replenish the depletion of natural resources, reduce the volume of tailing dams, increase the land area, and increase the sustainability of mining industries and natural resources.

3. Circular Economy Approach Towards Valorization of Tailing Waste

Discharging waste, such as tailing from mining industries, causes severe environmental degradation, including air, water, and soil pollution (Dudka and Adriano, 1997). The impact of tailing waste also damages ecology and biodiversity and badly affects the flora, fauna, and other inhabitants (Sun et al., 2018). Storage and maintenance of the tailing dam also incur enormous economic and social costs. Recycling and utilizing tailing through the scientific process and appropriate technology is challenging and requires considerable revenue.

To eliminate the associated hazards from the tailing waste, including severe catastrophic failure of the tailing dam, valorization of tailing waste is one of the best options. Since the last few decades, stakeholders are taken initiatives to recycle tailing waste for different applications; however, most of the mining industry manages their tailing waste with the linear economy model (Kinnunen and Kaksonen, 2019).

The application of the circular economy can boost up the valorization of tailing waste and increase sustainability in mining industries (Golev et al., 2016). The transformation toward a circular economy needs to identify the barriers and future possibilities and address the issues to accelerate the business opportunities for recycling and utilization of tailing waste (Zhao et al., 2012; Kinnunen and Kaksonen, 2019; Tayebi-Khorami et al., 2019).

According to Bechtel et al. (2013), the reluctance to think is one of the significant factors and barriers to transformation towards a circular economy for the valorization of tailing waste. Typically, there is a mixed factor, which may be favorable or hinder the adoption of the circular economy concept in the context of mining industries presented in Fig. 3 (de Jesus and Mendonça, 2018; Kinnunen and Kaksonen, 2019).

Most of developing countries, waste recycling is considered to improve global sustainability, and they overcome many barriers concerning circular economy, such as integrated solid waste management, environmental policies, public awareness, and favorable investment policies. In contrast, the same has become a significant issue in economically weak countries (Ferronato et al., 2019).

Knowledge gaps on potential utilization of tailing and business opportunities for valorization are the primary Bottleneck; in most cases, the lack of initiatives among the stakeholders makes valorization of tailing challenging. Online platforms and exchange facilities for knowledge sharing, resource availability, and a data bank for “tailing generation, storage, and utilization" business and investment opportunities can accelerate the valorization of tailing (Kinnunen and Kaksonen, 2019; Almeida et al., 2020).

The circular economy strategy is gaining interest as an effective way to achieve a low-carbon footprint through waste recycling and industrial symbiosis. The concept of the term 'circular economy' would be the most suitable approach for recycling and utilization of every bit of tailing waste which now remains treated as unwanted waste in most cases, as closing the gap of resource utilization and increasing sustainability is one of the concepts of the circular economy model (Zhu et al., 2019; Singh et al., 2020).

Despite having the potential for tailing valorization, viable both economically and technically, there still needs to be more knowledge and information available with the mining companies. A database of tailing resource status such as generators, processors, recycling facilities, and market opportunities can enhance the recycling of tailing waste and close the gap in the circular economy. To accelerate the implementation of the circular economy concept in mining industries needs to form a firm policy, regulation, and initiative by the stake holders and national authorities.

Through the circular economy model, recycling and utilization of tailing can be boost up, reducing the volume of the tailing waste, increasing the land area, reducing the burden of the biosphere, and can be possible to eliminate the repeated catastrophic failure of tailing dam as well (Singh et al., 2020).

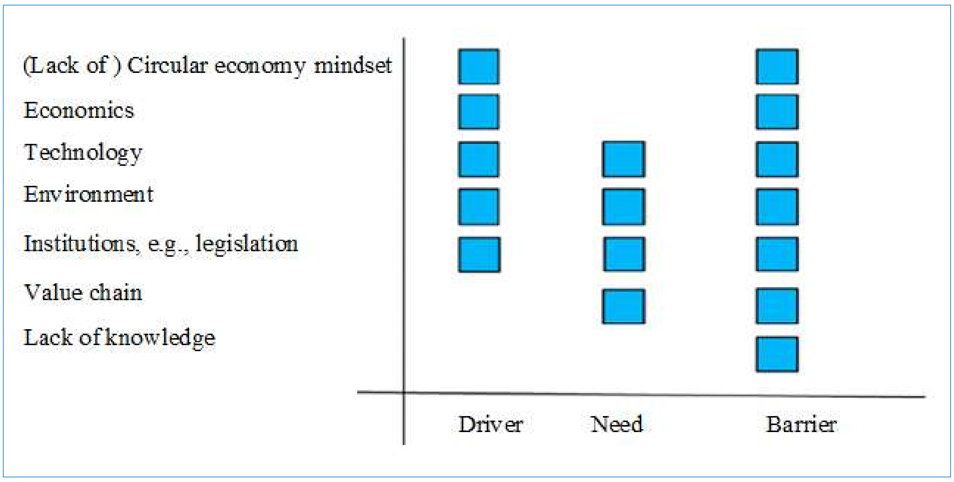

Fig. 3 Complementarity and mutual inclusiveness of categories of drivers, needs and barriers (de Jesus and Mendonça, 2018; Kinnunen and Kaksonen, 2019)

4. The disposal and Environmental Impacts of IOT

Despite technological development and advances in mineral extraction and processing, mining industries still need help to store and maintain tailing waste. Increasing stringent policy and regulations, strategy on environmental protection, and social demands is the primary key to adopting clean technology in mining industries, especially in the tailing disposal method. Because of different agendas on global sustainability and resource optimization, tailings storage facilities (TSFs) come under scrutiny; generators and operators are looking at alternative tailings management technology and strategies. Integrated tailings management is the best option for tailing disposal and storage facilities. Traditional tailing disposal method has led to heavy metal contaminated sites with serious impact on the ecosystems and risk to human health, including severe catastrophic failures of tailing dam. Instead of the conventional tailing disposal method, thickened tailing disposal technology results in less environmental impact than most other systems used in the mining industry today for the best way to manage tailing materials (Ozkan et al., 2002; Hatje et al., 2017).

The initial investment and operating costs for “thickened tailing disposal” systems are slightly higher, and the system can be implemented in any given topography. The most damaging aspect of tailing waste disposal is seepage into the surrounding land, and the environment creates leachate. It pollutes the entire surrounding area leading to soil and water pollution.

In the conventional method of tailing disposal, seepage can only be prevented partially, but the thickened tailing disposal system creates less contamination than traditional methods. It maximizes evaporation, optimizes runoff, and eliminates dusting, including air pollution. The significant advantage of "Thickened tailing disposal” systems over the conventional tailing disposal method (Mudd and Boger, 2013) is presented in Table 1.

5. Chemical Compositions of Tailing Waste

Several studies have determined the chemical composition of IOT waste in different locations; a few of them are presented in Table 2.

6. Main Policy Guidelines, Standards or Rules Governing the Management of IOT waste

When designing specific policies to promote the recycling process, it is essential to understand all potential bottlenecks, needs, barriers, and inefficiencies in such processes and how such bottlenecks, obstacles, and inefficiencies can be overcome through public policy intervention. Recycling is an important economic sector for employment, turnover, and investment. The recycling policy pertaining to IOT waste utilization shall guide and establish an appropriate legislative, administrative, and institutional framework (Bose et al., 2021; Bose et al., 2022: Bose, 2022; Bose and Dhar, 2022).

Table 1. The significant advantage of "Thickened tailing disposal" systems over the conventional tailing disposal method (Mudd and Boger, 2013)

Sl No	The significant advantage of "Thickened tailing disposal" systems over the conventional tailing disposal method
1	Reclaim water, process reagents, and energy
2	Maximize the density of tailings
3	Minimize tailings storage facility footprints
4	Render tailings suitable for mine backfill
5	Reduce the potential for acid drainage (by removing water available for leaching, decreasing permeability and oxygen diffusion) and minimizing (or eliminating) risks.

Table 2. Chemical compositions of the tailing from different locations

Chemical composition (%)	Wu et al., 2020	Osinubi et al., 2015	Perumal et al., 2019	Perumal et al., 2019	Perumal et al., 2019
SiO_2	57.20	45.64	32.99	72.52	78.44
Al_2O_3	9.11	3.36	7.09	16.43	12.57
CaO	11.30	0.607	12.92	0.05	0.30
MgO	-	0.393	17.27	0.82	0.14
Fe_2O_3	3.03	47.7	7.99	1.90	0.51
TiO_2	0.34	0.24	-	-	-
SO_3	-	-	-	-	-
P_2O_5	9.86	-	-	-	-
Na_2O	0.11	0.405	0.71	0.08	4.44
MnO	-	0.067	-	-	-
K_2O	2.11	0.607	5.53	3.05	2.80

7. Zero Waste Concepts Through Circular Economy Policy in the Context of Tailing Waste Valorization

The mineral processing unit generates a large volume of tailing waste annually. The tailing materials can be converted into value-added products with less effort and energy. The circular model of tailing materials can compensate for all resources, energy, and GHG through a circular economy process, clear policy framework, and regulation that can increase the tailing utilizations rate. The following Bottlenecks need to be considered while forming the policy, framework, and regulations for enhancing the utilization facilities of tailing materials presented in Table 3.

Table 3. Bottlenecks needs to be considered while forming the policy, framework, and regulations for enhancing the utilization facilities of tailing materials (Bose et al., 2021; Bose et al., 2022: Bose, 2022; Bose and Dhar, 2022)

SI No	Bottlenecks needs to be considered while forming the policy, framework, and regulations for enhancing the utilization facilities of tailing materials
1	Lack of initiative by governments and private agencies for processing tailing materials to valuable resources
2	Lack of proper policy framework and amendment of existing policies of the new policy to deal with tailing materials
3	Bridging the gap between industry and government
4	Government should make a policy regarding sustainability context for tailing recycling and utilization
5	To make realizing that tailing material is wealth
6	Policy formation for circular economy instead linear economy
7	Understanding of hazardous and non-hazardous waste for common people and organizations
8	Lack of adequate and attractive scheme for the entrepreneur who can open a startup for recycling processing plant for utilizations of tailing waste
9	Introduce code and standards for the products developed by recycling tailing waste
10	A dedicated data bank hub is necessary for the accountability of natural resources in the country, such as analysis of demand and supply in construction, the infrastructure sector, and other areas
11	Policy correlation within tailing recycling and utilization, sustainable development, and mitigation of climate change

8. Difficulty or Bottleneck Preventing Bulk Usage of Tailing

Among the different literature, bottlenecks were categorized under new value chains, technological, environmental, institutional, economic, and knowledge bottlenecks (Cezarino et al., 2021). The specific needs and barriers must be addressed appropriately to speed up the transformation from a linear economy to a circular economy towards managing bulk usage of tailing waste. Major bottlenecks towards managing bulk usage of IOT waste have been presented in Table 4 (Bose et al., 2021; Bose et al., 2022).

Table 4 Major bottlenecks towards managing bulk usage of the tailing waste

SI No	Major bottlenecks towards managing bulk usage of the tailing waste
1	Knowledge gaps on the potential utilization of tailing and business opportunities for tailing valorization
2	Unfavorable market forces, lack of investment opportunities for value chain establishment
3	The presence of an informal market
4	Lack of proper infrastructure facilities for processing bulk amounts of tailing waste
5	Consumer forces and commodity prices
6	Lack of infrastructure for collection, storage, and processing of tailing waste
7	Unfavorable market forces affecting the recycling process
8	Lack of legal and policy initiatives for the recycling process
9	Lack of political support for recycling, low level of awareness of environmental, economics and sustainability aspects
10	Most of the cases, recycling is not considered a priority in government programs and budgets
11	Lack of support for collection systems to ensure that the demand for recycling is met
12	Legislation is not enforced, and policy decisions must be consistent with legislation
13	Development or revision of legal instruments
14	Adoption of supportive policies
15	Measures to raise awareness among politicians, the private sector, small enterprises and civil society
16	Strengthening enforcement through global and regional networks and partnerships
17	Strengthening of cross-border cooperation
18	Different national regulatory requirements for the management of recyclable materials
19	Engagement through global or regional trade agreements
20	Possible approaches to support capacity building and funding
21	Legal, policy, and governance challenges at the international, national, and sub-national levels
22	Disposal capacity and process
23	Most of the cases, there is no strict law or regulations for preventing landfilling by tailing waste
24	Critical barrier on transporting tailing to a different location in respect of cost, safety, environmental issues, etc.
25	Lack of government initiative in respect of promoting mission zero waste (tailing)
26	Delay in necessary approval and responses from the official pertaining to dealing with tailing waste
27	Lack of policy frameworks, especially in the context of managing tailing waste
28	Transparency of information systems
29	Introduce code and standards on the secondary product from tailing materials so users can use the products

Table 5. Prerequisites for managing the bulk amount of tailing waste

SI No	Good practices and prerequisites for managing the bulk amount of IOT waste
1	Sufficient storage and disposal capacity for tailing waste generated annually
2	Characterization and analysis of chemical and physical properties of tailing waste
3	Proper and plane-wise investment
4	Startup facilities and funding scheme
5	Exclusive policy, regulation, and guidelines in the context of managing the bulk amount of tailing waste
6	Transparency of information systems among the stakeholders and Industry partners
7	Initiatives to introduce code and standards on the products developed from tailing (cement, concrete, brick, etc.)
8	Tariff and non-tariff barriers to using tailing waste
9	Building networks and partnerships to promote a harmonized approach to recycling and utilization of tailing
10	Development of internationally accepted criteria for recyclability of tailing waste
11	Technical capacity building and funding

9. Good Practices in the Mining Industry and Sustainable Management of Tailing Waste

Good practices that can be followed for sustainable management of tailing waste, prerequisites towards managing the bulk amount of IOT waste, presented in Table 5 (Bose et al., 2021; Bose et al., 2022: Bose, 2022; Bose and Dhar, 2022).

10. Way Forward

Worldwide, a vast amount of tailing waste has been discharged, and billions of tons of tailing remain in the tailing dams. There is an opportunity to extract exceptional residual mineral values from the stored tailing in the dam, which could minimize the risk of tailing dam failure and eliminate associated environmental issues while generating additional economic values. Through recycling, miming companies can set the strategy to transform huge amounts of tailings waste from a liability into wealth. With a strong commitment towards a more sustainable vision in mining industries, mining companies around the globe are looking for more sustainable solutions and strategies for reducing tailings materials generated during mineral processing activities. From the circular economy perspective, there is strong business potential for recycling tailing materials. Still, the identified factors, hinders, and barriers are the main issues that must be addressed early to accelerate the transformation.

Recycling and reusing tailing waste through the circular economy model is a viable and sustainable solution that helps minimize risk in terms of tailing dam failures, related environmental issues, and resource optimization and delivers a valued return on investment by the mining companies and stakeholders.

11. Concluding Remarks

The transformation from a linear economy to a circular economy needs significant initiatives and changes in policy and regulation and filling the knowledge gap of the factors that affect the existing process for mineral resource consumption and valorization of tailing waste. The valorization of tailings waste in the mining industries is still significantly lower. Still, the commitment towards sustainability goal, in the future, the mission "zero waste" would be the main focus to all concerns. Mining companies need more knowledge about the valorization process of tailing waste. To make a transformational change to managing tailing waste through the circular economy concept, all the factors and barriers needs to be address appropriately, which will make the most feasible and sustainable business model towards the valorization of tailing waste and will succeed in the mission of "Zero waste."

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