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Research article

Towards increased utilisation of tailings in Norwegian mining industry

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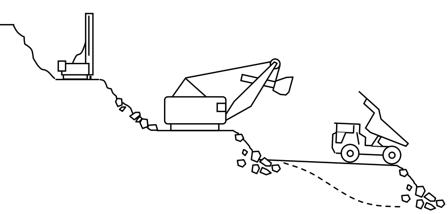
ABSTRACT

In this study, we investigate the barriers, and potential measures, for increased tailings utilisation in Norwegian mining industry. The purpose of this study is to explore the potentials for increased utilisation of mine tailings, contributing to seal the knowledge gaps by addressing major barriers for alternative tailings application, and finally, comment on aspects for a viable business model for tailings utilisation. The study was organised as a qualitative study, where 15 organisations across seven stakeholder groups were interviewed. In this empirical undertaking, we sought to answer the following research questions: (RQ1) What are the major barriers for increased tailings utilisation from Norwegian mining industry, and (RQ2) which measures can be introduced to overcome said barriers. We find that the main barriers for increased tailings utilisation are related to the lack of circular economy business models and mindset (A1-4), lack of knowledge of alternative applications and use areas (B3), logistics and transportation (D3) and lack of incentive measures (F3). Amongst the suggested measures are: i) allocation of mandate and resources in organisations to work with tailings utilisation, ii) information sharing across stakeholders and industries, iii) tailings screening tool, iv) application test facilities, and v) legislative measures. Our findings on major barriers for tailings utilisation are to a large extent mirrored in existing literature. And while the opposition towards submarine tailings disposal constitute a 'natural' incentive for the mining industry to work on this issue, we still find that stronger incentives and cross-industry partnerships are needed to succeed with tailings utilisation in Norwegian mining industry.



1. INTRODUCTION

With Today, one of the major controversies within Norwegian mining industry is tailings management and submarine tailings disposal (STD) in particular (Ramirez-Llodra et al., 2022; Skei, 2013). Opponents argue that marine deposition represents a great hazard to the marine environment, and that tailings should be managed in a more environmentally sustainable manner. Despite having all the required permits and licenses in order, tailings management is still a major issue for the mining industry, where especially new or planned mining operations experience a lack of societal licence to operate. Alternative uses for mine tailings may hence be a measure which will go a long way in securing a broader acceptance for future development of the Norwegian mining industry.

Despite having its controversies, the mining industry represents one of the world's major providers of raw materials needed to maintain the modern standard of living we have become accustomed to. Supply of minerals and metals are also considered essential for green technologies needed to reach the UNs sustainable development goals and fulfilling climate commitments of the Paris Agreement (Ali et al., 2017; Murray et al., 2017; Zhang et al., 2000). The transition to a low-emission society requires that greenhouse gas emissions are reduced, at the same time as the energy consumption in many regions of the world are expected to increase to cope with population growth and increased welfare standards. In this context, technologies for renewable energy production are an important prerequisite for successful transition, but solar cells, wind turbines and electric cars all require significant amounts of valuable minerals and metals. Minerals and metals are, however, finite resources, making the mining industry a significant contributor to the exploitation of the world's non-renewable resources. As put by Vidal et al. (2013, p. 894), this forms a trade-off where "a shift to renewable energy will replace one non-renewable resource (fossil fuel) with another (metals and minerals)".

The world's remaining mineral and metal deposits are getting increasingly less accessible with declining ore grades, resulting in increased costs and environmental impacts from mining activities (Esposito et al., 2017; Prior et al., 2012). However, following of a worldwide increase in demand for minerals and metals (European Commission, 2016) the previously unprofitable deposits have become profitable to extract. On the other hand, the increased extraction of low-grade and less-accessible deposits has led to a significant increase in the amount of waste materials generated per tons of metal produced. Such mining wastes primarily constitute waste rock and mine tailings, where the latter is crushed/ground materials typically deposited in onshore tailings facilities.

Tailings management have associated risks of both human safety and environmental concern, where dam failures (Rico et al., 2008) and acid mine drainage (Akcil & Koldas, 2006) constitute major concerns. Furthermore, the ongoing resource depletion and increasing worldwide demand, entails that the industry encompasses a sustainable management of all material resources, including today's unexploited resources regarded as waste. In this sense, the industry must adopt new approaches and methods for responsible production and consumption, one of which could be to apply the principles of circular economy (CE) (Gedam et al., 2021; Lèbre et al., 2017).

Few efforts have been made to introduce CE-practices into the mining industry, pointing at important knowledge gaps being a lack of CE-focus (i.e., it is not core business), lack of developed CE value chains, and lack of regulatory regimes to promote CE-measures. The purpose of this study is to further explore the potentials for increased utilisation of mine tailings, contributing to seal the knowledge gaps by addressing major barriers for alternative tailings application. To investigate this, we have conducted a stakeholder analysis based on qualitative data from workshop and interviews amongst mining industry, governance, research, innovation and development, industry- and environmental interest organisations, and other industries as potential end-users.

This work seeks to answer the following research questions: (RQ1) What are the major barriers for increased tailings utilisation from Norwegian mining industry, and (RQ2) which measures can be introduced to overcome said barriers. We aim to contribute to answering these research questions by analysing the findings from interviews with 15 organisations across seven stakeholder groups, and based on these, we comment on aspects for a viable business model for tailings utilisation. The paper is structured as follows: Section 2 introduces the background literature, section 3 describes the data acquisition and methodology, section 4 presents result from stakeholder interviews, section 5 includes the discussion, while section 6 gives some concluding remarks.

2. BACKGROUND LITERATURE

2.1 The controversies of tailings in Norwegian mining

As stated, submarine tailings disposal represents one of the most controversial topics in the Norwegian mining industry (Ramirez-Llodra et al., 2022; Skei, 2013). Areas of concern constitute, among other things, the seizure of large seabed areas, the risk of spreading fines in the water column, heavy metals and use of chemicals with uncertain long-term effects on the marine environment (Loe & Aagaard, 2013; Morello et al., 2016; Ramirez-Llodra et al., 2022; Ramirez-Llodra et al., 2015). Recently, the Norwegian Environment Agency was commissioned to study the consequences of a ban of sea deposition, where they concluded that it is not possible to determine in general which deposit solution (land or sea) entails the least environmental disadvantages (Norwegian Environmental Agency, 2019).

In a circular economy perspective, however, the deposition of tailings as a valuable resource would be considered unfavourable, regardless of tailings placement (land or sea). In this context, a joint mining industry in northern Norway represents a potential annual discharge of approximately 9 million tonnes of mine tailings each year (calculated from discharge permits, including planned mining operations not yet in operation). In other words, mine tailings represent a largely unused resource, as well as an environmental and societal issue with liabilities for further development of the mining industry. The latter refers to the increased opposition against sea deposition, where alternative tailings management can increase societal acceptance for mining activities in Norway.

Addressing the issue of tailings disposal is therefore an important part of ensuring the sustainable development of the Norwegian mineral industry, where stricter requirements for resource utilisation and environmental impact, as well as increased demand for minerals and metals, are met. And in contrast to less developed countries, where poor working conditions and unsatisfactory requirements for personnel safety and environmental emissions may be more prevalent (Bird, 2016; Hermanus, 2007; Von der Goltz & Barnwal, 2019), Norway, and the western world in general, have all the prerequisites to operate in the most environmentally friendly and safe way possible.

2.2 Mine tailings availability, characteristics, and potential applications

Information on expected tailings generation in Norway can be found from publicly available permits, and an overview has previously been reported in literature (Ramirez-Llodra et al., 2015). In addition, Kvassnes and Iversen (2013) reported an overview of marine deposits from Norwegian mining activities, including information on tailings deposits from terminated mines. However, such information may be outdated and do not provide detailed information on tailings properties, availability, or other characteristics. Furthermore, while landfills can function as a storage for future exploitation, the recovery of marine tailings will be more challenging, even unfeasible, from long-term terminated mines where tailings may have been irrecoverably lost to the environment.

While utilisation of mine tailings is a greatly researched area, there has been limited implementation on an industrial scale, at least in Norwegian context. There are, however, examples of mine tailings applications as covering-/filling masses and use in agriculture purposes. For instance, Rana Gruber AS's tailings have been applied for filling out large land areas for industrial purposes (Høgaas, 2016), and both Sibelco Nordic AS and Hustadmarmor AS have developed tailings-based products applied as soil improvement (Norsk Bergindustri & Norsk Industri, 2017).

In any case, for mine tailings to be used for alternative purposes, the tailings should satisfy different requirements related to the purpose. Such requirements presuppose that the physical and chemical composition of the minerals is suitable for the given purpose, and that the transportation costs do not exceed the tailings' value. Furthermore, because the generation and sale of tailings will not happen at the same time, there will be a need for temporary storage of tailings (Norwegian Environmental Agency, 2019).

With respect to tailings utilisation, one could further distinguish between direct or as-is use, and use of tailings as raw material for valorisation into new products. The former can e.g., comprise applications as partial replacement for virgin materials in established products like asphalt, cement, and concrete (Huang et al., 2013; Oluwasola et al., 2015; Shettima et al., 2016), while the latter will involve development of innovative products such as geopolymers (Ahmari & Zhang, 2012; Singh & Middendorf, 2020), ceramics, and lightweight aggregates (Cetin et al., 2015; González-Corrochano et al., 2009; Huang et al., 2007), amongst others.

2.3 The concept of circular economy

The concept of circular economy (CE) has gained a lot of attention in recent years across several nations, as well as by EU and the European Commission (see e.g., Geissdoerfer et al., 2017; Kirchherr et al., 2017; Korhonen et al., 2018). CE is an economic model aiming to increase sustainability of production and consumption patterns, by keeping products and materials within value chains and to preserve their value by closing the loops of materials (Geissdoerfer et al., 2017; Stumpf et al., 2021). The concept of CE is to an increasing extent considered a solution to series of challenges such as waste generation and environmental impact of linear production, scarcity in resources, and sustaining economic benefits (Lieder & Rashid, 2016). Building on the so called 3R principles (reduce, reuse, and recycle), the heart of CE is the circular and closed material flows, and the utilisation of raw materials and energy through several phases (Lieder & Rashid, 2016; Zhao et al., 2012).

2.4 Challenges and barriers for CE-adoption

The concept of CE has been criticized for having over-simplistic goals and having potential for unintended negative environmental consequences (Murray et al., 2017). One example is the increasing demand of biofuel that has contributed to massive areas of tropical forests being replaced by soy fields for bioproduction (Fargione et al., 2008). Another relevant example is the increasing demand for green technology, technology relying upon rare metals "which is mined at a considerable environmental cost" (Murray et al., 2017; see also Zhang et al., 2000).

Authors have also questioned the relationship between concepts of sustainability and that of CE, and further, the extent to which different aspects of sustainability are emphasized in CE (Geissdoerfer et al., 2017; Kirchherr et al., 2017; Murray et al., 2017). While sustainability in general aims to benefit the economy, the environment, and society at large (Elkington, 1997), “the main beneficiaries of the Circular Economy appear to be the economic actors that implement the system” (Geissdoerfer et al., 2017, p. 764). Even if CE is expected to affect the environment positively through resource efficiency and reduced pollution, the CE seems “to prioritize the economic system with primary benefits for the environment, and only implicit gains for the social aspects” (Geissdoerfer et al., 2017; see also Kirchherr et al., 2017; Murray et al., 2017).

In a recent study, lack of definitions and standards, lack of government enforcement and cooperation, and technical barriers were identified as the most important barriers that companies face in CE projects (Stumpf et al., 2021). Earlier studies have found cultural barriers (lack of consumer interest and awareness and a hesitant organizational culture) followed by market barriers (e.g., low virgin material prices, high upfront investment costs) to be the most significant (Kirchherr et al., 2018; Kirchherr et al., 2017). Stumpf et al. (2021, p. 11, p. 11) calls for regulatory barriers to be addressed more directly, e.g., by “imposition of sound quotas and targets” that balances associated trade-offs.

2.5 CE in mining industry

Only a few efforts have been made to get the circular economy concept operational in the mining industry (Lèbre et al., 2017). Pointing at the works of Zhao et al. (2012) and Balanay and Halog (2016), Kinnunen and Kaksonen (2019, p. 154) states that “circular economy in mining can be implemented at the company, mine area, mineral value chain and system levels” and that “mine waste utilisation can occur both at micro- and meso-levels”.

Several studies have reported the identification of barriers for adoption of circular economy principles to optimize resource use and minimize waste for industrial activities in general, and for the mining industry in particular. Such barriers are often structured in overlying categories with sub-barriers specifying concrete needs or challenges for CE-adoption. In their literature review, Edraki et al. (2014) points at relative conservativism within the industry as a challenge for change towards more circular business models. Singh et al. (2020) identifies the five major barriers for CE-implementation in mining as financial, market, government policies and regulations, organizational and operational barriers, further highlighting lack of stringent regulation, lack of promotion for CE & incentives and lack of products standardization market as the most pressing sub-barriers. Gedam et al. (2021) covered challenges to closed-loop systems and circular business models in the mining industry, identifying 17 CE-challenges where lack of governance measures and legislation policy emerge as a core challenges that influence all other challenges. Trade-offs between prices of virgin material and secondary waste materials is also highlighted as a major challenge for CE-adoption in mining, and the authors argue for adequate governance measures regarding closed-loops, which is vital to ensure sustainable balance between supply and demand.

Regarding tailings utilisation in particular, Tayebi-Khorami et al. (2019) identified five key areas comprising social, geoenvironmental, geometallurgical, economic, and legal/regulatory fields to overcome the many obstacles for tailings utilisation, amongst other todays' regulatory regimes and societal acceptance of products made from waste. The authors further highlight a knowledge gap on the industries that would use products made from mine tailings, as well as how the mining industry can connect with downstream users. Kinnunen and Kaksonen (2019) explored the opportunities and bottlenecks for tailings valorisation, finding that utilisation of mine tailings is still in its infancy. The big mining companies do not regard waste valorisation as core business, and the mining industry in general have not comprehensively evaluated the business opportunities for tailings utilisation. Knowledge gaps on tailings content and market price are identified, and the authors suggest databases on existing tailings to facilitate knowledge transfer on available resources. The authors further highlight a need for suitable business cases and SMEs to complement the value chain for tailings valorisation, while institutional influence may boost the circular economy transformation.

3. METHOD

3.1 Research strategy

This study was organised as a qualitative study, aiming to investigate the barriers, and potential measures, for increased utilisation of tailings from Norwegian mining industry.

3.2 Data Material

The methods for data collection included a workshop and semi-structured interviews with stakeholders. First, we arranged a preliminary workshop with mining company representatives (organisations n=4, participants n=4) and representatives from a research institution (organisation n=2, participants n=3). During this workshop, stakeholders were asked to give their input on relevant barriers and measures to be included in the interview framework, and a mapping of relevant stakeholder groups to be included. After the workshop, 15 semi-structured interviews were conducted, across seven different stakeholder groups (see Table 1). This included representatives from the mining industry and research institution that had participated in the workshop. The selection of organisations across these stakeholder groups were based on input from the conducted workshop. Other industry stakeholders consist of both established industries that can use tailings as substitute for current raw materials, as well as greenfield projects based on tailings as raw material for new products.

Table 1. Resumé of stakeholders interviewed (with acronyms used in Results section in parenthesis).

Stakeholder group	Organisations	Informants
Mining industry (MI)	4	5
Industry interest organisation (IIO)	1	1
Other industry, potential end users (OI)	5	8
Environmental interest organisations (EIO)	2	3
Research and development (R&D)	1	1
Innovation and development instrument (I&D)	1	3
Governmental (G)	1	3
Total	**15**	**24**

3.3 Data analysis

The workshop input was documented using Miro V 0.7.2. Interviews were transcribed and coded using Dedoose 9.0.46.

Prior of the data collection, themes and topics were synthesised and pre-prepared to a list of barriers dimensions, based on previous research with emphasis on the works of Kinnunen and Kaksonen (2019) and Gedam et al. (2021). This list of six different dimensions constituted a starting point for the data analysis: i) circular economy models and value chains, ii) technology/knowledge, iii) social, iv) economic, v) environmental, and vi) legislation and regulation.

During the preliminary workshop, these themes were elaborated and saturated by the stakeholders. The preparation of the stakeholder's input resulted in the framework of barriers that was used to structure the interviews (Table 2). During these interviews, informants were asked to comment on the list of barriers (RQ1), and further, what measures that could be introduced to overcome these barriers (RQ2). The list of barriers was also developed further based on the informant's statements, resulting in minor adjustments of the barrier list. Thus, the barriers list is a result of processing and synthesizing of literature and interview data combined. In Table 2, we present the final list of barriers.

Table 2. Barriers for tailings utilisation in the present study.

Dimension	Barrier	Summary
Circular economy, value chains and mindset	A1 Tailings utilisation is not core business	Utilisation of mine tailings is not regarded as core business and is thus not prioritized by the mining industry
	A2 Lack of information sharing	There is insufficient information and/or information sharing on tailings available for alternative use
	A3 Incomplete value chain	There is a lack of industry/competence/SMEs who can utilize and make new products from mine tailings
	A4 Market uncertainty	There is a lack of knowledge on which actors who can use products made from mine tailings
	A5 Need for high-volume applications	The sheer amounts of tailings prerequisite that new applications represent high-volume potentials
	A6 Untailored infrastructure	The current infrastructure is not tailored for CE-adoption and tailings utilisation
	A7 Conservative mindset	Potential end-users (industries) are reluctant to adopt new material fractions into their production (conservative mindset)
Technology and knowledge	B1 Technology scale-up	There is a lack of scalable technology to process mine tailings into new products
	B2 Research needs	There is a need for fundamental research to develop new products from mine tailings
	B3 Applications	There is a lack of knowledge on what type of applications/products the tailings can be used for
	B4 Tailings content	There is a lack of knowledge on tailings content
	B5 Inhomogeneous materials	Mine tailings are inhomogeneous materials with varying characteristics, i.e., not a standardized product
Societal	C1 Potential stakeholder conflicts	Application of tailings prerequisite that new industry is established, which can be in conflict with other stakeholders (e.g., area use)
	C2 Lack of CE-culture	There is a lack of culture for utilizing mine tailings, and waste materials in general
Economy	D1 Investment costs	Large investment costs and long pay-back times for establishing new industry to recycle mine tailings
	D2 Competition with other materials	Competition with other materials (virgin and wastes) prerequisite that new tailings applications must be high-quality products
	D3 Transport and logistics	Significant transport and logistics costs in rural areas
	D4 Price of virgin materials	Trade-off between prices of virgin material and secondary waste materials
Environment	E1 Impurities and heavy metals	Tailings may contain heavy metals, chemicals and impurities which limit alternative applications
	E2 Intermediate storage pending use	Intermediate onshore storage of tailings pending use may cause environmental issues
	E3 Altered effluents characteristics	Partial utilisation of tailings can alter the remaining effluents characteristics causing environmental issues
Legal and regulations	F1 Regulations/standards limiting use (environmental)	There are standards/regulations which limits alternative use based on tailings content of heavy metals, chemicals and/or impurities
	F2 Regulations/standards limiting use	There are standards/regulations which limits alternative use based on the tailings' chemical and physical properties
	F3 Lack of incentive measures	There is a lack of incentive measures to use mine tailings over virgin materials.
	F4 Challenging to establish new industry	Establishment of new industry to utilize mine tailings is a demanding task
	F5 Land use for intermediate storage	Lack of intermediate storage areas pending use

As the foundation for the framework barriers list is based on previous research on CE in mining industry and tailings valorisation specifically, and further, quality assessed in a workshop with representatives from the mining industry (together with R&D representatives), the list is somewhat biased towards the perspective of the mining industry. Not surprisingly, the mining industry informants were more capable to provide comments to all barriers. However, the other stakeholder groups did comment on all six dimensions of barriers, which in total provided us with a complementary picture of how the various barriers are effective, and what may potentially contribute to overcome these barriers.

The interview data were then structured in a table where stakeholders' statements towards the presented barriers were aggregated to group level and weighted: (++) and (+) marks the respectively very important and important barriers, while (-) marks barriers that were pointed to as not important. Blank spaces indicate that the barrier was not commented or pointed to as important in either direction.

4. RESULTS

In this section, we present the findings from the conducted interviews. In Table 3, we present a summary of how the different stakeholder groups weighted the barriers for utilisation of tailings across the six dimensions. Stakeholder groups are presented with acronyms (see Table 1 for identifiers for each group).

We find that the main barriers for utilisation of mine tailings are related to the lack of circular economy business models and mindset (A1-4), lack of knowledge of alternative applications and use areas (B3), logistics and transportation (D3) and lack of incentive measures (F3). However, the case of tailings utilisation within a CE-business model is a complex topic and, as emphasised by the stakeholders, several of the barriers are interrelated, in some cases quite heavily, to the extent that they cannot always be entirely separated. This seems to be the case for the barriers within category A, circular economy business models and mindset, in particular. In fact, barrier A1 Tailings valorisation is not core business, is pointed to as more of a meta-barrier that is made relevant in several of the contexts that were discussed by the interviewees, across all groups. In the following sub-sections, we present the results that lead to the findings presented.

4.1 Circular economy business models and mindset

According to the mining industry, one of the most important barriers for increased tailings utilisation are related to lack of SMEs that can utilize the tailings (A3). It is, however, unclear if the barrier is limited to lack of knowledge of SMEs, or if it is an actual lack of SMEs which are capable and interested in using mine tailings as raw material for new products (A4 Market uncertainty). Either way, there is a lack of information sharing across companies and industries (A2), where, traditionally, the mining industry have not actively shared information on their tailings (quantities, chemical and physical properties, etc.) to external actors. Today, the external sharing is more prevalent, but, still, there is no joint arena where such information is shared. Instead, the information sharing takes place through direct inquiries that the mining companies receive, for instance through R&D projects. Other stakeholder groups, amongst others the potential end users, also acknowledge the usefulness of an open information sharing arena. In addition, the stakeholders would welcome a screening tool for preliminary assessment of tailings' suitability towards given applications.

The mining companies admit that utilisation of mine tailings has not received much attention in the past, but rather has become increasingly important in recent years (A1 Tailings utilisation is not core business). They justify this with being increasingly concerned with raw material efficiency and waste reduction, and in fact draws parallels to the global focus on sustainability and reduction of greenhouse gas emissions. In addition, the environmental concerns with sea deposits which threatens the societal license to operate, has led to an increased focus on tailings utilisation. However, while mine tailings utilisation may have received greater attention in recent years, we are left with a feeling that it still might be a significant bottleneck for increased tailings valorisation. This does not imply that the mining actors have not attempted to find new uses for their tailings; in fact, our informants have participated in several such projects. However, we still find that the companies, for various reasons, have not prioritized tailings utilisation, i.e., it has not been regarded as core business. In this regard, one miner claims that their corporate management is not particularly concerned with mine tailings utilisation, among other things because "… now that the profitability is good, there is no pressure on us to create added value from waste streams". The miner further highlights the importance of internal allocation of both mandate and resources to work with tailings utilisation, which is supported by a second miner who claims, "there is a lack of both external and internal initiators to succeed with tailings utilisation". In other words, the mining industry recognise that this is something they need to start prioritizing to better the reputation of the industry.

Table 3. Stakeholders' ranking of barriers for increased tailings valorisation.

Dimension	Barrier	MI	IIO	OI	EIO	R&D	I&D	G
Circular economy, value chains and mindset	A1 Tailings utilis. is not core business	+	+		++	+	+	
	A2 Lack of information sharing	+		+	+			+
	A3 Incomplete value chain	++	+			+	++	
	A4 Market uncertainty	++				+	++	
	A5 Need for high-volume applications		+	+		+		
	A6 Untailored infrastructure	+		+				
	A7 Conservative mindset				+			
Technology and knowledge	B1 Technology scale-up	-			-			
	B2 Research needs	+		+		+		
	B3 Applications	++	+			++	++	++
	B4 Tailings content	-					-	
	B5 Inhomogeneous materials		+	+				+
Societal	C1 Potential stakeholder conflicts	-					+	
	C2 Lack of CE-culture				++		+	
Economy	D1 Investment costs							
	D2 Competition with other materials					++	+	
	D3 Transport and logistics	+	+	++		+	+	
	D4 Price of virgin materials			+		+	+	
Environment	E1 Impurities and heavy metals	-			-	-		
	E2 Intermediate storage pending use				-			+
	E3 Altered effluent characteristics							+
Legal and regulations	F1 Regulations/standards limiting use (environmental)							
	F2 Regulations/standards limiting use			++		+		
	F3 Lack of incentive measures	++	+		++	+	++	++
	F4 Challenging to establish new industry			+				
	F5 Land use for intermediate storage							

The barrier of tailings utilisation not being core business (A1) is also pointed out by other stakeholder groups as a significant barrier. For instance, the industry interest organisation (IIO) claims that incentives to work with tailings utilisation already exists, but questions "how much effort has been made [historically], by each company, and by the industry itself", while at the same time acknowledging that the focus on tailings utilisation has increased significantly in recent years. The environmental interest organisations (EIOs) argues that the barrier is not specific for the mining industry, but rather something that applies to most industries when it comes to waste issues. They claim that lack of core business "is precisely why we need requirements, policies, and incentives to ensure tailings utilisation, despite not being part of the industry's core business". The innovation and development stakeholder (I&D) also acknowledge this barrier, stating that tailings "often become something you 'get rid of' in the most favourable way, within what is legal".

Mining stakeholders practicing sea deposition do not greatly emphasize the need for tailings valorisation to be profitable and would welcome any volume of tailings utilisation, i.e., they do not stress a need for high-volume applications. Regarding business potential and profitability, moderate quantities could potentially be sufficient, but in terms of lightening the environmental concerns related to sea deposition, moderate amounts would not have significant impact when compared to the vast amounts which are deposited each year. Thus, while the need for high-volume applications (A5) is not regarded as an important barrier for implementation of new applications, the sum of alternative uses should concern large material quantities to increase the industry's reputation and societal acceptance.

An additional barrier for miners, is that the process plants are not tailored for extraction of tailings for alternative use (A6). This encompasses a lack of infrastructure for storage and drying of tailings, as well as lack of systems for accessing specific subfractions of interests (e.g., fine, or coarse tailings). This is, however, not a technology-related issue, but rather an issue in terms of on-site implementation. The extraction of tailings on an ad hoc basis is therefore challenging and would easily fall in disfavour of more accessible virgin materials. However, this barrier also applies for potential end users in established high-volume industries like concrete and cement production (A5). Hence, with respect to direct ("as-is") use of Norwegian mine tailings, there is a need for more flexibility on both sides of the table, where miners lack flexible systems for tailings extraction, and potential end users lack tailored systems for incorporating tailings into their production.

4.2 Technology and knowledge

Overall, informants from R&D and the mining industry emphasise the need for development of products able to compete in the market (B2) (technology push, market pull). That is, one cannot sell products there are no demand for. This is a fundamental issue, related to all barriers within this dimension. The mining industry, in this sense, highlights a lack of knowledge on the area of use (B3) for their tailings as one of the most important barriers for increased tailings utilisation. They describe a general lack of ideas, solutions, competence, and actors to establish new industry based on mine tailings as raw material. One miner state that because they do not know which product the tailings can be valorised into, they also don't know the actors or SMEs interested in using them. The governmental stakeholder has a similar reflection, although linked to legislative measures, stating that "one cannot demand a product to be made from the waste materials if there are no products to make. And in mines, there is a lot of waste that is not used". In this regard, the miners do not recognize a lack of technology for processing tailings into new products. Instead, they emphasize the need to identify potentials and industrial concepts for tailings utilisation: "there are a myriad of methods, processes, and techniques available, but to find suitable applications, given the tailing's content and market/customer aspects, that's where the challenge lies".

Both miners and the IIO highlight that the potentials for tailings utilisation will be case specific, thus, assessment of each case is necessary. In this regard, the stakeholders further emphasize a need for better infrastructure to examine material potentials, i.e., a lack of institutions or companies with facilities for performing application tests on their tailings. This is related to several barriers (B2-B3). In general, it is mentioned by several stakeholders that tailings are inhomogeneous materials that don't come with a product specification or declaration and will have greater variations compared to virgin materials (B5).

The R&D stakeholder draws on experience from lab testing, where it has been challenging to extract value from a single tailings material, which can appear either too fine or too coarse, or with unfavourable composition (B2-B3). For instance, tailings too fine for use as building material, appear too coarse for production of lightweight aggregates and thus require further processing. In this regard, and more specifically on grain size and composition, the R&D stakeholder states that "it is difficult to process past nature", meaning that one operates on the mercy of the conditions and qualities of the material. And while it is possible to alter for instance a tailing's particle size by grinding and crushing, by doing so you are not fully exploiting the advantage of tailings having already undergone expensive and energy-intensive crushing.

4.3 Social conditions

In addition to submarine tailings disposal, the industry's land use is one of todays' conflict areas where especially indigenous people are concerned (C1). However, the mining stakeholders do not regard area requirements for tailings utilisation as a significant barrier, mainly because any additional area use will likely be situated on land they already possess which is regulated for industrial purposes. The I&D stakeholder, however, argues that the sheer volume of tailings to be put to alternative use may seize significant areas, which warrants closer consideration. Related to circular economy mindset in barrier-category A, and barrier A1 in particular, several informants mentioned lack of culture (C2) for circular thinking, also within what was sometimes described as a rather conservative business sector (A7), and in Norwegian industry as such. Here, the conservativism is in terms of reluctance to change, as well as rigorous standards and demands for materials which take time to change. The EIOs emphasise this as a central barrier, both for the mining industry, and other (manufacturing) industry as such. The I&O also points to this barrier when they in relation to barrier A1 point to tailings being viewed as something one just 'get rid of' (see section 4.1).

4.4 Economy

Mine tailings tend to fall in disfavour of other fine materials (both virgin and waste rock) due to being less accessible or more expensive (D2-D4). In this regard, we find that while tailings may have appropriate characteristics for some low-grade or as-is applications, there is an existing surplus of comparable fine grade materials suitable for such applications. An additional barrier in that sense, is that the fine grade materials only constitute a minor part of the total material mix, thus limiting the potential for high-volume utilisation in such applications. The R&D stakeholder stresses this issue and suggests looking at developing high-value products instead.

In an economic perspective, an industrial utilisation of mine tailings is, in large, regarded by the stakeholders as similar as other types of industrial initiatives; it can be costly, requires planning and will have a relatively high level of uncertainty and risk associated with it (D1). Thus, a significant investment should generate an equivalent significant income. However, if only minor investments are needed, the mining industry can accept low-income or even (limited) economic losses, given that reduced sea deposition provides added value in terms of societal acceptance. One miner (without STD) points out that utilisation of tailings would reduce costs of landfill and potentially help in legitimizing an industrial investment. EIO argues that the economics/investments needed for utilisation of mine tailings should be accounted for when granting operation licenses to new mining activities.

Transport is regarded by many as a potential barrier for tailings utilisation (D3), especially since most mining activities are situated in rural areas. Many stakeholders therefore argue that any utilisation of mine tailings should happen in proximity to where the tailings are generated, for instance through a next-door factory. However, one thing is where the products are produced; another aspect is where the market for said products is. Therefore, it is also stressed by the stakeholders that the product's value will determine how expensive the transport can be, i.e., high-value products would allow longer transports. However, for more direct use, an expensive transportation service could see tailings fall in disfavour of other fine grade materials. In this regard, both concrete and cement producers, as well as other potential end users, already use waste materials from other industries, and transportation costs are mentioned as a significant barrier for incorporating tailings into their production.

4.5 Environmental

One of the proposed environmental barriers for tailings utilisation, is that the tailings' potential content of heavy metals, chemicals, impurities, etc., may restrict alternative use (E1). In this regard, it is pointed out by several stakeholders that each tailings' characteristics will depend on its origin and extraction method. And while such contents may restrict how tailings can be disposed of (e.g., land or sea disposal), it is not regarded as a major barrier for alternative utilisation of tailings. The R&D stakeholder, in this regard, claims that "the issue with impurities, pollution and heavy metals, it is manageable; it is a matter of processing". In fact, none of the proposed environmental barriers for tailings utilisation are highlighted as major showstoppers by any of the stakeholder groups.

Some potential issues are, however, pointed out. The miners are concerned with labelling or defining the tailings as waste related to how this may restrict future use of tailings in alternative applications. The governmental stakeholder points out potential environmental hazards from onshore intermediate storage pending alternative use (E2), as well as how partial extraction of tailing may change the remaining effluents characteristics (E3). The latter is primarily concerned with an increased share of fines in tailings, which will spread more easily in the water column. One miner has experienced dust-related issues from onshore intermediate storage and highlights the need for watering systems to avoid dust dispersal. The EIO, on the other hand, argues that intermediate onshore storage will be favourable over permanent marine deposition, which will make tailings unavailable for future application. However, miners acknowledge the possibility of extracting marine tailings (e.g., by dredging), but stresses the potential environmental issues caused by stirring up finer particles.

4.6 Legislations and regulations

While having decision-making power to introduce incentives for increased tailings utilisation from Norwegian mining industry, the governmental stakeholder seems reluctant to do so without a realistic alternative to todays' practice of land or sea disposal. The I&D mentions that requirements to handle tailings and work on tailings utilisation are embedded in concession or licence, thus argues that mining companies already have incentives “to ensure in every way that the requirements in the discharge permit are complied with”. The IIO also acknowledges that the mining industry already has incentives to work on tailings utilisation, referring to the increasing opposition towards STD. The EIOs, on the other hand, argue that one of the major barriers for tailings utilisation is precisely the lack of public incentives to do so (F3). They encourage the authorities to take a greater role in facilitating for circular economy in mining, and argue that tailings utilisation, as well as resource utilisation in general, must be an integrated part of running an industrial business, not "something extra" which is handled on the side.

Further, the EIOs highlight that today's regime with no fees on tailings deposition do not encourage the mining industry to work intensively on this issue. The I&D actor has a related statement, claiming that "knowledge and technology are enabling [factors]. The economic aspects are fundamental. But laws and regulations, requirements, this trumps everything”. The mining industry confirms that there are currently too weak incentive measures addressed to them for utilisation of tailings but would rather see positive incentive measures for increased utilisation, mentioning, for instance, subsidies per ton of tailings put to alternative use, public procurements, and increased allocation of R&D-funding for exploring potential tailings applications. The mining industry stakeholders argue for this statement, based on the barriers of incomplete CE-value chain (A3) and market uncertainty (A4), stating that it would have limited accuracy to add negative incentives (e.g., taxation of tailings disposal) when there are no existing alternative use areas for the tailings. That is, the mining industry stakeholders acknowledge that such incentives would affect their motivation to focus more on tailings utilisation but argues that the issue is not so much a lacking will to do so, but rather a lack of knowledge about the use-areas and thus the possible end-users, calling for more knowledge sharing and research. The EIOs acknowledge the need for increased R&D-funding, but stress that the general purpose must be to support an environmentally sustainable development.

One of the OIs representing a greenfield project finds that the major barriers are related to regulations and challenges concerning use and certification of their product (F2). Introduction to market is especially challenging because their product is in direct competition with an established and well-known product, where today's regulatory regimes complicate introduction of alternative products.

4.7 Suggested measures for increased tailings valorisation

As described in section 4.1, the stakeholders in general acknowledge the need for tailings valorisation to become a prioritized issue by the mining industry themselves, but also by the government. However, the mining industry stakeholders emphasise that prioritizing of this issue needs to be accompanied by a top-down mandate and dedicated resources, from within the respective businesses, to make this a priority. The EIOs, on the other hand, encourage authorities to take greater responsibility to ensure better utilisation of tailings, regardless of it being a part of the industry's core business or not. More specifically, the EIOs propose that measures for sustainable mine tailings management should be an integral part of granting operation licenses to new mining activities.

The lack of information sharing (A2) could be comprehended by an open database and visualisation platform, where relevant information of tailings resources is made available to the public. The measure could alleviate several other barriers as well, for instance barrier A3 and A4 by connecting mining industry with potential end users, and barrier B3 by incorporating a screening tool for alternative uses based on tailings' content. A broader collaboration is also mentioned in relation to barrier B3, which governs a joint effort across professional environments to gather ideas and knowledge on industrial concepts for alternative tailings applications. In relation, a tailings terminal for collection, storage, and development of new products from mixtures of different tailings has been suggested by the R&D stakeholder. Structured as a stand-alone company, the tailings terminal could function as a joint test facility for development of innovative products based on waste residues across industries.

The majority of stakeholder groups highly emphasize a lack of incentive measures (F3). Disposal fees are often pointed to as an example of possible incentive measure that could stimulate an increase in tailings valorisation specifically, but also more sustainable or circular practices in general. However, the informants mentioned several alternatives to this type of measure. For instance, informants representing the governmental stakeholder commented that taxation of area use as an alternative that could have the same desired effect. This would also reach beyond the specific case of tailings, as it would create incentives "for CE" in general (more caution on using virgin materials in general). Other suggested incentives are to leverage the use of tailings over virgin materials, for instance through public procurements or subsidies per ton material put to alternative use.

5. DISCUSSION

5.1 Main barriers for tailings utilisation

From our findings, we confirm STD as a controversial topic, as this practice affects the mining industries social licence to operate, and further, act as a source for potential conflicts between different stakeholder groups. At the same time, there seems to be few realistic and environmentally sustainable alternatives to STD. Thus, the controversies related to STDs constitutes itself as an important driver to the development and implementation of more sustainable utilisation of mine tailings in the Norwegian context.

Several of the major barriers pointed to by our informants are mirrored in existing literature. For instance, barriers related to circular economy business models and mindset (A1-A4) is widely acknowledged in the reviewed literature (Kinnunen & Kaksonen, 2019; Tayebi-Khorami et al., 2019).

Regarding managerial conditions, we find that barrier A1 is also touched upon by other researchers (Kinnunen & Kaksonen, 2019; Lèbre et al., 2017). Kinnunen and Kaksonen (2019) points at how the mining industry in general have not comprehensively evaluated the business opportunities for tailings utilisation. This can also be related to the cultural barriers that have been pointed to in previous research, related to conservative organizational culture, lack of awareness or interest by the involved stakeholders (Edraki et al., 2014; Kirchherr et al., 2018; Kirchherr et al., 2017).

Related to the barrier of A2, A4 and B3, our findings support previous research findings concerning the knowledge gap in mining industry regarding the downstream value chain, that is, SMEs and business cases that would use tailings in their production or products made from mine tailings, as well as the lack of arenas to connect and share information with these potential downstream users (Kinnunen & Kaksonen, 2019; Tayebi-Khorami et al., 2019). These findings can also be related to lack of interest and awareness by consumers or end users, which is pointed to as a barrier by other researchers (Edraki et al., 2014; Kirchherr et al., 2018; Kirchherr et al., 2017). Rather, we find that e.g., the OI stakeholders are generally interested in considering alternative raw materials that could provide them with a greener profile. The challenge lies in incorporating these in already established systems and recipes/mixtures, both in terms of material characteristics, and logistics, etc.

Sticking to the notion of market barriers, other previous studies have also pointed to aspects like investment costs and low prices on virgin materials as important barriers for tailings utilisation (Gedam et al., 2021; Kirchherr et al., 2018; Kirchherr et al., 2017). While such considerations regarding the price of virgin materials were present also in our data material, investment costs were not pointed to as a barrier by any of the stakeholder groups, which is an interesting finding. That is, investment costs are considered, but they do not seem to act as a showstopper for moving forward with CE practices in general, and increased tailings utilisation or upgrading the production site, specifically.

Regarding legislative barriers, that is, lack of governance measures, legislation policy, institutional influence, lack of standards and definitions, and lack of stringent barriers that balances trade-offs associated with e.g., virgin materials versus secondary waste materials (Gedam et al., 2021; Kinnunen & Kaksonen, 2019; Stumpf et al., 2021; Tayebi-Khorami et al., 2019), our findings support this as a major barrier for tailings utilisation and valorisation. The stakeholders' statements place great emphasis on the need for legislative or regulatory measures, balancing positive and negative incentives in a way that ensures an appropriate and adequate distribution of different trade-offs.

Previous studies have criticized CE business models for prioritizing economic rationale at the expense of environmental and social aspects of sustainability (Geissdoerfer et al., 2017; Kirchherr et al., 2017; Murray et al., 2017). Our findings does not provide a clear basis for supporting previous research pointing to financial or economic aspects in general as a main barrier for increased tailings utilisation (see e.g., Singh & Middendorf, 2020). Economic considerations, however, are made relevant by the interviewed stakeholders in different ways. Making profit on the tailings utilisation does not seem like a primary concern for the interviewed mining industry stakeholders. Rather, they state that it would be sufficient to break even, and some would even accept minor expenses, if this contributes to an increase in societal acceptance.

A major barrier to increased tailings utilisation is the issue of logistics and transportation of tailings between locations (D3). First, this is obviously an economic concern. In addition to this question of the economic feasibility and viability in transporting tailings a certain distance (ref. barrier D3 and conditions related to barrier A5), this is also a question of at what point the environmental effect of tailings utilisation is devaluated.

Further, some of our findings provided us insights that were somewhat opponent to the findings of previous studies, thus elaborating and adding to the knowledge on barriers for mine tailings utilisation. For instance, in contrast to the findings of

Kinnunen and Kaksonen (2019), we find that there's no significant knowledge gap on tailings' content, granted there has been a development in recent years to seal this gap. This applies for the mining industry stakeholders, regarding their own tailings. From the stakeholder interviews, we instead find that the gap is more concerned with information sharing rather than knowledge. Furthermore, authors like Stumpf et al. (2021) highlights technical barriers associated to tailings utilisation. Our findings do not provide any evidence that technical aspects represent any barrier for increased utilisation of tailings. On the contrary, aspects like technology scale-up (B1, see Table 3) were even highlighted as not being an issue at all – the technology is considered to be, more or less, there. That is, the stated research needs (B2) are not associated with technical knowledge gaps, but rather related to the development of new products. This includes the need for sustainable and predictable balance between supply and demand, product standardisation and societal acceptance for such products, findings also supported in previous studies (see e.g., Singh & Middendorf, 2020; Tayebi-Khorami et al., 2019).

5.2 Possible measures

5.2.1 Mandate and resources to prioritize tailings utilisation

A top-down allocation of mandate and resources is closely linked with barrier A1 and making tailings utilisation a greater part of the mining industry's core business, representing both an anchoring and obligation from the stakeholders to work with the issue at hand. Several of the mining stakeholders acknowledge a need to invest more time and resources to work on waste issues, while other stakeholder groups emphasize that this applies for other industries as well.

Inspiration can be found in other industries, where Elkem's success with microsilica is a great example of how top-down allocation of mandate and resources resulted in new business areas from yesterday's waste. Over 300 million Norwegian NOK (in 1985 NOK) were spent for R&D and marketing, exploring 300 potential uses for microsilica (NTVA, 2022). Years of testing have resulted in several established commercial applications for microsilica, turning what was previously regarded as a waste material into a very profitable business. Elkem's work on microsilica is a highly successful story that will be hard to follow, but nevertheless shows what can be achieved by large corporations with desire and willingness to turn waste into value.

5.2.2 Information sharing arena

While the mining industry has become increasingly willing to share tailings information, they do not have an arena to do so. Granted, some information on Norwegian mine tailings have been reported in literature (Kvassnes & Iversen, 2013; Ramirez-Llodra et al., 2015), and discharge permits are publicly available from The Norwegian Environmental Agency. However, these overviews are not necessarily precise or up to date, and more importantly, they only provide limited tailings-specific information, apart from the amount and location of tailings generation.

A welcomed measure, across stakeholder groups, is to enhance information sharing across stakeholders and industries, for instance through an open database and visualisation platform. Such an information sharing arena should not be made exclusively for the mining industry, but rather include other industries that generate waste rock or other residues, thus facilitating for cross-industry cooperation and application.

Outreach to potential end users should be emphasized as well, where the database seeks to connect supply and demand, creating a marketplace for mine tailings and other waste materials. The information sharing arena's usefulness may extend to exploring business opportunities and partnerships, as many of our mining stakeholders are explicitly willing to partner with other organizations to develop new products from mine tailings. This is in line with Kinnunen & Kaksonen (2019) who also argue that because these challenges are so complex, it is hard to find solutions without networking (see also Lebre et al., 2017). Related, Tayebi-Khorami et al. (2019) points at a lack of knowledge on how the mining industry can connect with downstream users, which is precisely one of the issues a joint information sharing arena could remedy.

5.2.3 Tailings screening tool

A tailings screening tool is suggested by mining stakeholders to mitigate the lack of knowledge on tailings utilisation (B3). The tool should offer an initial screening of suitable applications based on the tailings' content, while not having to provide a definite answer on how the tailings should be utilized, but rather be able to exclude certain areas of use. One example would be suitability for LWA-production given by the phase diagram of Riley (1951); another, the limitation on alkali content for use in ordinary Portland cement.

By encompassing the possibility of combining different materials, the screening tool would further allow examination of material mixes, e.g., the combination of mine tailings with other waste materials. In addition, one would be able to assess the need for additives, which might be necessary to enhance material properties for use in construction purposes (Almeida et al. 2020). Developing the screening tool as an integral part of an information sharing arena (chapter 5.2.2) would make characteristics of many waste materials available with the opportunity to examine interesting material mixes towards certain applications.

5.2.4 Application test facilities

Mine tailings are not standardized products and often constitute inhomogeneous materials with varying characteristics. This applies both for tailings of different origins, as well as for single tailings which may experience variations based on the governing characteristics of the deposit they are extracted from. Making new products from mine tailings is therefore a challenging task, where tailings may have characteristics which sees them fall between two stools, e.g., being too coarse for one application and too fine for another. Not knowing what their tailings are applicable for (B3), the mining stakeholders express a lack of infrastructure to examine potentials for tailings-based products. The R&D stakeholder, in this regard, argues that promising product potentials may be identified by mixing tailings from different sources, and suggests a tailings terminal to collect, store and process tailings into new products. If structured as stand-alone company with its own R&D department, the terminal would have the capabilities needed to develop products based on suitable material mixtures, constituting a joint application test facility for various waste materials. However, all stakeholder groups acknowledge the logistical challenges of transporting tailings over large distances, and a tailings terminal would have to generate sizeable income to compensate for transport expenses.

5.2.5 Legislative measures

Legislative measures can involve different types of incentive measures enforced by the authorities to stimulate increased tailings usage. One option would be to introduce positively oriented incentives for the mining industry, for instance subsidies per ton of tailings put to alternative use. However, this would likely only be effective if the industry is struggling to make money elsewhere. When finances are good, there is not enough incentives to focus on utilisation of side streams with (relatively) minor upside compared to main products; an issue experienced by one of the mining stakeholders.

The EIO's proposed measure of making mine tailings utilisation a prerequisite when granting operation licenses seems unlikely to be adopted before alternative tailings applications have become more available, which is a perception shared by the governmental stakeholder. However, even the mining stakeholders do admit that stricter regulations (e.g., disposal fees) would force them to work more intensively on finding alternative tailings uses. Thus, a combination of positively- and negatively oriented incentives may be the way to go.

Through public procurements, the authorities could involve downstream users, by for instance encouraging contractors to use tailings (and waste materials in general) in infrastructure and construction projects. However, from our stakeholder interviews, we find that potential for use in conventional cement, concrete and road construction is limited. For instance, even if tailings materials have suitable characteristics, the mineral deposits tend to be situated in rural areas, making the transport too expensive to compete with conventional materials. In addition, the marked potential for such applications seems to be limited when compared to the amounts of tailings available.

A greenfield project stakeholder argues a need for legislative measures to liberalize conservative and rigid industry standards, which makes it challenging to introduce tailings-based products into an establish market/industry. In sum, our data material shows that legislative measures are strongly requested, both across stakeholder groups and throughout the value chain for tailings utilisation.

5.3 Towards a business model for mine tailings utilisation

There is a myriad of scientific literature on alternative mine tailings applications, thus the main obstacle for establishing new business models is likely not a lack of knowledge of alternative applications. However, while there may exist many potential uses for mine tailings, of importance is that the tailings are found suitable for a given application. And because mine tailings are not standardized products, this can be quite challenging to achieve. Further treatment (e.g., grinding) and additives can be applied to acquire desired characteristics, but doing so excessively may very well affect the bottom line to an extent where the business case is no longer economically viable. And while mining companies not necessarily expect profitability from tailings utilisation, it must provide sustainable businesses for the companies producing and selling the tailings-based products. Utilizing tailings near their origin, e.g., through a next-door factory, would facilitate CE-business models and synergies through industrial symbiosis.

However, even with tailings materials that show great potential for product development, it could take years of research and development to succeed with commercial products. Related, the greenfield project we interviewed has put behind them a decade of R&D-work, working intensively on product optimalization as well as securing the necessary funding. They are now approaching a successful product development, but (as previously stated) have remaining challenges related to product certification and industry standards. Establishing sustainable business models for mine tailings utilisation is clearly a complex task and may well require significant effort and resources. In other words, one should not expect new solutions to be introduced overnight, nor should one expect the mining industry to succeed on their own. New products from mine tailings can be developed through broad collaboration between mining industry, other industry/manufacturers, and researchers, while introduction of sustainable business models could be accelerated if supported by legislative measures.

In an environmental perspective, new business models should consider a holistic approach and not seek to introduce new solutions at any cost, meaning that, even though deposition has its drawbacks, an alternative solution may in the end prove to be the least environmentally friendly alternative. Furthermore, to limit the environmental concerns related to STD and increase societal acceptance for Norwegian mining activities, new tailings applications should allow for utilisation of significant tailings volume. New applications should also represent continuous and long-term solutions for tailings management, limiting the need for intermediate storage and seizure of land areas. However, as tailings utilisation is clearly in its infancy, any new applications would largely be welcomed by the mining industry.

6. CONCLUDING REMARKS

There is still work to be done to enable the potential of increased utilisation of tailings from Norwegian mining industry. We find that the main barriers towards tailings utilisation are related to lack of circular economy business models and mindset (A1-4), lack of knowledge of alternative applications and use areas (B3), logistics and transportation (D3) and lack of incentive measures (F3). Several measures to mitigate these barriers have been suggested, including i) allocation of mandate and resources in organisations to work with tailings utilisation, ii) information sharing across stakeholders and industries, iii) screening tool for initial assessment of tailings application, iv) application test facilities, and v) legislative measures. Based on our analysis, we find that a combination of measures to increase the utilisation of mine tailings is needed, including both facilitative measures as well as measures targeting the implementation and execution of such practices.

In Norwegian context, tailings utilisation is important not only in a circular economy perspective, but more so related to societal (and political) license to operate. In this regard, the mining industry would largely welcome any utilisation of mine tailings, irrespectively of high or low volume/income applications. However, to obtain increased societal acceptance for future mining activities, new applications should likely contribute to a significant reduction in tailings deposition. In the regard, filling- and covering purposes could represent high-volume uses, but do not comprise continuous or long-term solutions. Ideally, new applications should instead utilize tailings as they are generated, for instance through a next-door factory, reducing the need for intermediate storage. Scaling production towards what a local market could handle would lower transportations costs, but at the same time reduce the amounts of tailings that could potentially be used. However, it is unlikely that a single new application could utilize all generated tailings (at least from bigger mines, generating millions of tons of tailings each year), thus a combination of different uses should be considered. Nevertheless, it is certainly due for mine tailings to be put to alternative use. We observe a willingness in the mining industry to work on this issue, but as of today it seems that an escalation of the drive/clout to follow through these initiatives, stronger incentives, both positive and negative, and cross-industry partnerships are needed to accelerate the circular economy in mining.

This study holds several implications for practitioners; Our findings illustrate a call for action amongst mining industry stakeholders, as well as stakeholders representing the potential use areas along the downstream value chain. Further, the mining industry might also capitalize on the learning of other industries in relation to CE-practices (Upadhyay et al., 2021). That is, there is a need for more focus on CE and utilisation of residual raw material. In this study, we have focused on tailings utilisation in particular, but this call for more focus on sustainable production can serve as a call for increased sustainability in all aspects of handling of waste and residual raw material, stretching beyond the mining industry. Regarding implications for policy makers, we find that there is a strong need for incentive measures aimed at the utilisation of tailings. This includes incentive measures addressing potential end-users, the industry that could make use of such residues. Further, the findings of this study also hold a transfer value to other industry. Measures for handling and utilising tailings from mining industry can also be relevant for other (manufacturing) industries that have big volumes of surplus materials, like building and construction, but also electrometallurgical- and hydrometallurgical industries.

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