Cleaner Engineering and Technology 8 (2022) 100499

Contents lists available at ScienceDirect

Cleaner Engineering and Technology

journal homepage: www.sciencedirect.com/journal/cleaner-engineering-and-technology

A review of circular economy strategies for mine tailings

Päivi Kinnunen[a,*], Marjaana Karhu[a], Elina Yli-Rantala[a,b], Päivi Kivikytö-Reponen[a], Jarno Mäkinen[a]

[a] VTT Technical Research Centre of Finland Ltd, Visiokatu 4, 33101, Tampere, Finland
[b] Tampere University, Faculty of Engineering and Natural Sciences, PO Box 589, FI-33014, Tampere University, Finland

ARTICLE INFO

Keywords:
Mining
Circular economy
Tailings
Waste
Valorisation
Institution
Digitalisation

ABSTRACT

There are various existing practices and future potential for turning mining waste into valuable products. The inventory of the tailings in the metal mines in Finland showed that considerable concentrations of many critical metals are contained in the waste. However, the amounts of generated waste are so significant that the full implementation of circular economy is challenging. A combination of several different circular economy approaches (reduce, reprocess, upcycle, downcycle and dispose for future) is needed to manage the waste streams in mining in a holistic way. Various technologies are already in use for the recovery of metals from the tailings and for the use of the mineral residues in high and low-value products. The institutional framework has an impact on the economics of the valorisation of mine waste. Digitalisation can support in identifying where the biggest potential for valorisation exists. The rising concepts of digital material and product passports would support the circularity and the traceability of waste-based materials.

1. Introduction

Metals are essential in the transition to the green technologies e.g. in low emission electric vehicles and in energy storage systems (Upadhyay et al., 2021). At the same time with the positive contribution to the society, mining also produces significant amounts of solid waste (Edraki et al., 2014) belonging with millions of tons annually (Wang et al., 2014) to the largest waste streams in the world (Hudson-Edwards et al., 2011), along with waste waters (Kinnunen et al., 2021). The circular economy preserves the value of materials (Antikainen and Valkokari, 2016) keeping them available instead of disposal (Ritzén and Sandström, 2017). The use of the circular economy principle for mine waste is a mean to reduce liabilities and to increase the value from the mining waste (Tayebi-Khorami et al., 2019) to recover both metals and mineral fraction (Bodénan et al., 2021). It is possible to create value from mining waste by adopting the circular economy principles to keep the resources in the use and to limit the final waste (Lèbre et al., 2017a).

The institutional framework includes regulations, norms and cognitive elements provided by various institutions. The circular economy emerges via regulations, norms and cognitive processes and has been identified as an institution (Stål and Corvellec, 2018). The behavior of organisations is affected by institutional conditions (Campbell, 2006). Regulations are formal rule settings with monitoring and possible sanctions. Norms describe appropriate behavior, means and values (Dale, 2002). The circular economy has been reported only very little in the scientific literature and in the mining companies' sustainability reports, but the number of publications is growing (Upadhyay et al., 2021).

The biggest waste streams both in metal value and in volume in mining are tailings, which create long-term environmental liabilities to the companies (Wang et al., 2014) due to the potential for acid rock drainage generation (Simate and Ndlovu, 2014) from sulphidic tailings. Instead of considering the tailings only as an environmental challenge, the tailings could be treated and used as secondary metal sources (Solomons, 2017) including critical raw materials (Araya et al., 2020) by combining environmental management and economic valorisation (Bellenfant et al., 2013). This option still needs research and development on the industrial scale (Araya et al., 2021). In addition to the metals, the main minerals in the tailings are useable as raw materials. Especially, when the metal concentrations are low, the complete mineral matrix needs to be valorised to increase the economics and to decrease the amount of waste (Blengini et al., 2019). The tailings could be reprocessed into a feedstock for new valuable materials and products e.g. in the high value ceramics such as in chemically bonded ceramics (Kinnunen et al., 2018), in the production of geopolymers (Solismaa et al., 2018) or in ceramic coatings for thermal insulation (Karhu, 2020).

* Corresponding author. VTT Technical Research Centre of Finland Ltd, Visiokatu 4, P.O.Box 1300, 33101 Tampere, Finland.
E-mail address: paivi.kinnunen@vtt.fi (P. Kinnunen).

https://doi.org/10.1016/j.clet.2022.100499
Received 14 October 2021; Received in revised form 12 April 2022; Accepted 22 April 2022
Available online 30 April 2022

In the same way, mining water effluents have traditionally been considered valueless, but reducing the water consumption (Gunson et al., 2012) and closing the water loops in mining (Kinnunen et al., 2021) are crucial to achieve the sustainability targets. When water is recycled, the amount of water withdrawals and the release of pollutants to the environment diminish (Lutandula and Mwana, 2014). Water already itself has value, but it is also possible to recover metals (Shadrunova and Orekhova, 2015) and chemicals from the effluents.

The classical economy identifies material resources fixed and finite. From the institutional perspective, resources are created by humans and vary due to the development in technology and science (De Gregori, 1987). The line between valuable ore and waste is not clear, since it may change over time depending on the extractive strategy, the economic context and technological advancements (Kinnunen and Kaksonen, 2019). Metal grades for recovered ores have decreased over the decades with the implementation of new innovations, which have changed previously worthless materials into valuable ores (West, 2011). The tailings of the past operations have nowadays transformed into potential raw material sources, which is expected to happen also to today's materials in the future (Lèbre et al., 2017b). The types of tailings may change when new kinds of metals and minerals are being mined. Since the richest ores have been already used, there is going to be even more tailings production in the future (Hudson-Edwards et al., 2011).

Lottermoser (2010, 2011) determined the concepts of remining, reuse, recycling, reprocessing and treatment in mining. In remining, minerals are recovered from previously mined areas. Reuse is defined as the process that involves the new use of the mining waste in its original form without reprocessing, which supports the waste hierarchy classification. However, reuse is considered only as using the waste again with no consideration on the value. This is typically made in the close vicinity of the mining site covering large-volume applications such as sand-rich tailings mixed with cement to be used as backfill in underground mines (Kinnunen et al., 2018). Recycling is defined as the conversion of mining waste into new valuable products with physical, thermal, biological or chemical methods. Reprocessing aims at using the waste material as a feedstock for producing valuable products when the used treatment reduces the toxicity or volume of the mine waste. Cisternas et al. (2021) use value retention options (ReX) of refuse, reduce, resell/reuse, repair, refurbish, remanufacture, repurpose, recycle materials, recovery of energy and remine for various circular economy strategies in mining and minerals processing. Not all these ReX imperatives can be used for tailings.

Lèbre et al. (2017b) suggest a holistic approach to the mineral waste management with the prioritization order of 1) reduce, 2) reprocess, 3) downcycle and 4) dispose. Typically, the amount of waste output is reduced by reducing the material input. The amount of target elements in the ore is at the maximum some percentages, so a lot of waste is produced. If the amount of mined ore would be reduced, the associated un-extracted minerals would be lost. With mining waste, the target is to minimize mineral losses in all stages. The existing circularity indicators often take into account only the material in the final product and not the material losses (Lèbre et al., 2017a). Various indicators, such as the Total Material Consumption, are developed to cover also extracted resources, which are left unused (Ellen MacArthur Foundation, 2015). In reprocessing, metals are extracted from the material. In downcycling, no mineral or metallurgical processing takes place and the entire bulk material is used in a low-value application (Lèbre et al., 2017b). As mentioned above, Lottermoser (2010, 2011) defines this with the term reuse, referring to the new use of the total waste in its original form without any reprocessing. In this article, we add upcycling as one additional component to the tailings management hierarchy, since some mineral products can have a higher value and do not fit into the description of downcycling. Even though the valorisation of waste has the potential to decrease environmental impacts, some actions can create new environmental problems (Bian et al., 2012). If the material cannot be reused, reprocessed, upcycled or downcycled, it needs to be stockpiled in a way that enables its future use. Additionally, we discuss the potential of digital technologies to support the holistic mineral waste management including industrial symbiosis to recycle materials and to reduce and to avoid material losses.

This paper investigates how the circular economy principles have been taken into use in the mining industry. The key questions driving the research were: 1) What are the strategies to manage tailings in the circular economy context? 2) How much value is contained in the tailings? 3) How do digital technologies support the material management and waste-to-resource matching and valorisation? The institutional framework affects the transformation towards the circular economy and it is reviewed in the context of mining industry. We evaluate the possibilities to preserve the value of solid waste in mining. We identify the existing commercial and research cases under various waste management categories (reduce, reprocess, upcycle, downcycle and dispose for future use) to summarise what can be done to make the material use more efficient across the categories. We highlight the conceptual transformation from considering the wastes as valueless streams to identifying their potential for a value creation. The results support minimisation of the environmental footprint and an adoption of the circular economy principles in the mining industry.

2. Materials and methods

This review is based on a literature search and a review of journal papers. When relevant, conference publications, company web sites and reports were searched. Databases and search engines, such as Google Scholar and eKnowledge Search (Scopus, Science Direct, EbscoHost, Knovel, IEEE, Springer Nature, Taylor&Francis and Wiley) were used. We focused on a narrative review to find the relevant literature, because it focuses on the topic in a broader way compared to a systematic review. Words such as circular economy in mining, mine tailings, utilization, metals recovery from tailings, tailings reprocessing, tailings hydrometallurgy and digitalisation were used in the search. The gathered information was organised to discuss the circular economy practices in the materials management in mining, and examples for the future material use were analysed. The literature was selected based on the title and the abstract in English except for the inventory of the metal content of tailings in Finland, where information was available mainly in Finnish. Complementary information was collected in the workshops organised by the Circular Design Network project funded by the Academy of Finland.

3. Circular economy in the mining industry

In the circular economy, the waste is turned into valuables and prosperity is decoupled from resource utilization (Ellen MacArthur Foundation, 2013). The value is created from existing materials with better design for reuse and recycling, and with replacing non-renewable products with services and renewable products (Ellen MacArthur Foundation, 2015). Besides reducing pollution, the circular economy also enables repairing previous damages with better designed systems (Murray et al., 2017). The circular economy is often considered as closing material loops (Bocken et al., 2016), which clearly decreases the use of primary materials. Bocken et al. (2016) emphasize an extension of the product lifetime, recycling and circular flow of resources, and resource efficiency, to diminish resources utilization for the same production. In the mining industry, these concepts could relate to using recovered metals in the products for an extended period, to recycling waste streams, such as tailings and water, and to reducing the amount of waste material with advanced sorting.

Different industrial sectors should be analysed for the possibilities for the circular economy transition. Only a limited number of efforts have focused on operating the circular economy concept in mining instead of the current linear economy concept (Lèbre et al., 2017a), despite the significant economic potential in turning waste into useful materials.

The use of the circular economy concept in mining has the potential to increase the metals supply to satisfy the increased needs of metals and to decrease waste and environmental pollution (Lottermoser, 2011). However, based on the interviews, value chains to support the use of side streams are lacking in the mining industry (Kinnunen and Kaksonen, 2019). Mining companies have also emphasised that the amounts of generated waste are so significant that they can not be fully used to fulfil the circular economy approach (Kotarska et al., 2018). Even though the technical use would be possible, often the logistics costs and the environmental impacts would be high due to the typically remote location of the mines. Tayebi-Khorami et al. (2019) highlighted that the technical solutions can fail without the understanding of the economic, legislative and regulatory context.

The circular economy concept can be taken to the company and product micro-level, the regional meso-level and the global and national macro-level (de Jesus et al., 2018). These levels were used in the circular economy definition of Kirchherr et al. (2017) based on the analysis of over 100 definitions. There are different ways to implement the circular economy in mining, starting from the company level where materials can be returned to the process or be used in applications, to the mine area level, and up to the value chain and systemic levels where other companies and industries can use the side streams (Zhao et al., 2012; Balanay and Halog, 2016).

4. Institutional framework concerning mining waste

4.1. Institutions affecting mining

The transformation from the linear economy to the circular one is not only technical, but the institutions have a significant role in it. Companies consider their behavior based on regulations, norms and cognitive elements (Scott, 2008, 2014), which are provided by institutions (Dale, 2002). Despite the facts that institutional conditions determine how responsibly organisations behave (Campbell, 2006) and can simultaneously improve the competitive position and environmental performance of the company (Nikolaou and Evangelinos, 2010), these dimensions have not been sufficiently included into the circular economy discussions (Moreau et al., 2017). The circular economy has been considered as an institution (Stål and Corvellec, 2018), because it is taken into the use by regulative, normative and cognitive processes. Based on the institutional theory, successful companies are mimicked, which results in similar rules between companies in the mature industrial environment (de Villiers et al., 2014). When the existing institutional systems follow the linear economy model of operations, the transition to the circular economy is more challenging (Fischer and Pascucci, 2017). So far, the institutional environment in various areas has supported mainly recycling and not any other types of circular economy approaches (Ranta et al., 2018).

Various institutions have focused on improving the implementation of the circular economy in mining. Society, international networks, and European Union regulations and collaboration were identified as institutions, which drive the circular economy transition in the mining industry (Kinnunen and Kaksonen, 2019). In the global setting, social, regulatory and institutional factors including R&D support were identified as important factors for moving to the circular economy (de Jesus and Mendonça, 2018). Typically, corporate social responsibility has been the widely studied institution in mining (e.g. Gifford et al., 2010). International Council on Mining and Metals has established ten principles for sustainable development, which support the circular economy and in addition address various sustainability issues in the mining sector (ICMM, 2016). Globally, United Nations have established Sustainable Development Goals (SDGs), where the mining industry can contribute, for example, to minimizing the waste and recycling the water (World Economic Forum, 2016). Other efforts include World Business Council for Sustainable Development Vision 2050 work and the World Economic Forum's Mining and Metals in a Sustainable World 2050, which include circular economy compatible strategies (ICMM, 2016). When trying to reach the SDGs and to implement the Paris Agreement, society needs more metals and mining to enable the electrification of transport in the battle against the climate change (Ali et al., 2017).

A number of government initiatives (e.g. Netherlands, Germany, UK, EU, Japan, China) have focused on improving the application and recovery of materials, product design and minimizing waste generation (ICMM, 2016). In the U.S., National Environmental Policy Act, Clean Air Act, Clean Water Act, Toxic Substances Control Act, Resource Conservation and Recovery Act, and Comprehensive Environmental Response, Compensation, and Liability Act affect mining industry activities (Mulvaney et al., 2021). The circular economy has been selected as the main framework also in China (Murray et al., 2017). In Europe, the European Commission has adopted the circular economy package in 2015 in order to use materials more efficiently and to drive a more sustainable economy (European Commission, 2015, 2017a). Directive 2006/21/EC on the management of waste from extractive industries supports the minimisation and prevention of environmental effects of extractive waste (European Commission, 2017b). The European mine waste management is governed by the Extractive Waste Directive (2006/21/EC) (European Commission, 2006). The European Union (European Union, 2016) considers that mining waste could be used for an improved raw materials supply with a subsequent reduction in environmental effects. However, the policies and practices related to the reprocessing of extractive waste have been rather limited in the EU member states and the applied permits have mainly been associated with construction-related purposes with a low number of secondary extraction from tailings and waste (European Commission, 2017b).

4.2. Regulations and taxation

Institutional incentives including regulations can make the transition towards the circular economy easier (Fischer and Pascucci, 2017). The use of waste materials (e.g. gypsum) in materials and products is dependent on regulations and economic instruments (Jiménez-Rivero and Garcia-Navarro, 2017). There are currently no common regulation limits for pollutants in secondary materials, such as mining waste, to be used in construction applications in the EU (Pličanič et al., 2020). A strict global standard setting is considered better than any uncertainties in regulations (Dashwood, 2014). In the future, several economic areas are expected to require specific labels and production standards for the materials that are used within their borders. For example, the European Union is launching the Battery Directive, where the aim is to develop methods to prove the sustainability and track the metals that are used in the battery value chain in Europe.

Even though the institutions have tried to encourage the use of circular economy solutions, sometimes uncertain or complex regulations and policies create barriers instead (Gregson et al., 2015). The possibilities for a reuse of materials depend on local policies and environmental conditions. As an example, mine waste can be reused in roadways in China, but not in the United States (Bian et al., 2012).

Despite regulations being an important factor in applying the circular economy principles, they may not necessarily result in the actual implementation of the circular economy (Ranta et al., 2018). Since there may be some other barriers to the adoption of the circular economy in addition to the restrictive regulation, a holistic approach is needed to create an enabling environment for the circular economy (van Barnefeld et al., 2016).

In addition to regulations, institutions can use sustainable taxation decisions (Stahel, 2013) such as reduced value added tax (Kirchherr et al., 2018) to support the circular products over conventional ones. However, sometimes non-circular product prices are too low because of subsidies on energy and water (Kirchherr et al., 2017). The potential for the circular economy solutions may also relate to the geographical area due to the differences in the taxation of landfilling. Taxation and gate fees of various waste categories vary considerably country-wise and also material-wise. As an example, the landfill taxations in the EU varied from 5 €/ton of municipal solid waste in Lithuania to 268 €/ton for a mix of hazardous and non-hazardous waste in Belgium in 2021 (CEWEP, 2021). The landfill tax is typically higher for the hazardous waste, but in some countries taxation is cheaper for the hazardous waste and the treatment of hazardous material to turn the waste into the non-hazardous waste can actually increase the taxation costs (Fischer et al., 2012). As an example, Finland imposes no taxes on the hazardous waste, but a tax of 70 €/ton is applied on the non-hazardous waste (CEWEP, 2021). In some European countries, waste rock and tailings are exempted from the landfill tax due to the reason that according to the European Commission, an exemption from the landfill tax for these materials is not a subsidy and there are limited possibilities for alternative waste management methods for the large quantities of waste. If the exemption from the landfill taxation was removed, it could result in the use of metal-containing waste material as construction material and in the loss of the possibility to reprocess the old piles in the future (Johansson et al., 2014).

4.3. *Self-implemented initiatives*

In mining, a limited resource is consumed, which makes the use of the sustainability concept in mining challenging. The framework of sustainable mining has focused on reducing the environmental impacts of mine operations, and more recently also taking into account the whole lifecycle of the mined material (Gorman and Dzombak, 2018). When further considering the relationship between the mining industry and the circular economy, the mining sector has been widely lacking from the circular economy discussion (Lèbre et al., 2017a). There has also been criticism about the circular economy in the context of mining due to the unsustainable growth of materials demand (Florin et al., 2015) and a lack of the social dimension (Murray et al., 2017).

Mining companies have various self-implemented sustainability initiatives (Dashwood, 2014). First ones were global, followed by the recommendation to establish local best practices (Gorman and Dzombak, 2018). Global examples are International Council on Mining and Metals' ten principles for sustainable development (ICMM, 2016), UNEP's Mineral Resource Governance in the 21st Century gearing extractive industries towards sustainable development (UNEP, 2020) and International Cyanide Management Code to improve operating practices in order to protect waters (Northey et al., 2016). As a local example, the Finnish Network for Sustainable Mining was established in 2014 and the Mining Standard was developed in Finland by a variety of stakeholders including NGOs (Ruokonen, 2020).

In mining, the institutional environment of the head quarter location largely determines the behavior of the whole company (Dashwood, 2014), and in addition local communities influence decision-making as governance actors (Prno and Slocombe, 2012). Companies and professionals follow the behavior of successful mining companies, which finally results in a shared way of thinking and common norms in the industry (de Villiers et al., 2014). Mining companies have similar environmental management practices due to this mimicking (Nikolaou and Evangelinos, 2010). According to the study of Upadhyay et al. (2021) based on the reporting practices of large and known mining companies, recycling of waste and water has been reported, but the increase of the circular economy practices has not yet taken place on a large scale.

Companies can create partnerships to exchange materials, water and energy (van Beers et al., 2007). The few efforts have focused on recycling and reuse of mining wastes even though there could be also sharing of other resources (Balanay and Halog, 2016). Sharing of resources and the use of by-products from another company can be greatly promoted by establishing external institutions to connect various actors together. One example is Kwinana Industry Council in Australia, which has established relationships between companies in a certain mining area (Chertow and Ehrenfeld, 2012).

5. Tailings management within the circular economy in mining

In this chapter, the possibilities to manage the mine tailings with reduce, reprocessing, upcycle, downcycle and disposal strategies are discussed. In the subchapter 5.2, an inventory of the metal content of mine tailings in Finland is presented.

5.1. *Reduce*

In mining, the needed input flows will even increase in the future, when the ore grades decrease. However, there are some tools that can be used in identifying, which parts of the mined material should go to processing and which parts to the waste. When specialized *in situ* analyses are used to have a better and more detailed understanding of the ore characteristics (Machado et al., 2020), the treatment can be optimized. Ore sorting can be used before further processing steps to remove any materials below the cut-off grade in order to decrease the energy costs and the amount of tailings (Kinnunen et al., 2021). The energy efficiency of comminution is only at the level of 1–2% (Donoso et al., 2013), and with ore sorting significant energy savings can be achieved.

There are examples of 20–30% removal of the ore calculated as final tailings with subsequent production of 70–80% ore mass in flotation due to the successful sorting (Grotowski and Witecki, 2017). With minimized ore losses, also energy, water and reagents use in relation to the outputs are minimized (Lessard et al., 2016). When the processes are designed in a way that takes into account the whole material value and various internal loops are closed, the consumption of chemicals can be reduced.

5.2. *Reprocess*

5.2.1. *Inventory of metal mine tailings in Finland*

Availability of data on secondary materials is needed to advance the recovery practices (Blengini et al., 2019). One of the identified challenges to reprocess tailings is the lack of knowledge on tailings contents (Kinnunen and Kaksonen, 2019). There are some initiatives taken at the European level to gather information on raw material content in tailings, e.g. in Horizon 2020 funded ProSUM (Prospecting Secondary raw materials in the Urban mine and Mining waste project, 2015–2018) and ORAMA (Optimising quality of information in Raw Materials data collection across Europe, 2018–2019). The ProSUM project started gathering the data of mining waste and storing the data as an extension to the Minerals4EU database enabling the link between the primary raw material data to the mining waste data (Huisman et al., 2017). The work continued in the ORAMA project and in May 2019 the mining waste information included Czech Republic, Denmark, Croatia, Ireland, Norway, Sweden, Slovenia, and Ukraine (Wagner et al., 2019). Within these initiatives the work has begun, but is still far from being completed.

Even though there are national mining waste registries, the information is often at a too generic level (e.g. not containing information on concentrations and impurities) in order to evaluate the remining potential, or the information may be available only in a specific language (Žibret et al., 2020). Table 1 shows as a major example the summary of the metal contents of various tailings from some of the existing and historic metal mines in Finland. The tailings contain for example nickel, cobalt and zinc. The value of the metals in one single tailings waste pile reaches hundreds of millions of euros calculated from the concentrations and amounts. However, the business potential needs to be evaluated case-by-case taking into account also impurities and processing costs. In addition, the existing infrastructure is important when considering the valorisation potential.

5.2.2. *Metals recovery from tailings*

Tailings are waste products of mineral processing, where target minerals or metals of an ore are separated from the unwanted gangue. Thus, the mineralogy of the orebody and selections made in mineral processing play a major role in the tailings characteristics and metal

Table 1
Inventory of metals content in some historic and operating metal mines in Finland as a major example.

General info				Content in tailings (g/t)																			Infrastructure		
Mine or plant, tailings piled (years)	Pile size (Mt)	Ag	Al	As	Au	Ba	Cd	Co	Cr	Cu	Fe	Hg	Mg	Mn	Mo	Ni	Pb	S	Sb	Ti	V	Zn	Cover	Road	Reservoir
Aijala[1,2]	2.0	8			0.7					1,200							1,070	71,000				5,070	P	No	No
1949–58;																									
64–74																									
Hammaslahti[2,3]	5.3	2		100	0.1		3	55	30	760	81,000	4,200		305		15	30	37,600				1,230	C	Yes	Yes
1973–86																									
Kemi[4,5] (Elijärvi)	13 (2009)								65,000							1,000						100	P	Yes	Yes
1967-																									
Haveri[2,6]	1.4	3		158	1.6		3	115	43	830	107,000					79	10	29,000			208	140	P	Yes	No
1942–60																									
Hitura[7,8]	13.5 (2006)								2,130	984						2,139						98	O	Yes	Yes
1970-																									
Keretti[2,9]	10.5		1,920	13			100	348	107	781	38,700	0.4	21,000	173	4	375	12	25,800	100			1,380	C	Yes	Yes
1913–89																									
Kevitsa[10,11]	8.9 (2013)		6,880	7.5			0.07	58	615	425	55,500		60,100			978	2	6,500	0.3		42	24	O	Yes	Yes
A: 2012-	1.03 (2013)		6,880	42			0.34	460	490	4,100	205,000		41,000			10,800	5	124,300	0.3		35	80	O		
B: 2012-																									
Korsnäs[2,*] 1961–62;	0.77																3,000	5,000					C	Yes	No
64–73																									
Kotalahti[2]	9.4	0.4		3	<0.1			30	1,100	330	67,000			1,100	7	610	60	1,000				110	C	Yes	No
1959–87																									
Luikonlahti[12,13]	6		9,020	32			5	403	488	947	60,500		44,500	1,470		450		76,300				3,831	O	Yes	Yes
1968–83	2.5		2,400	145			0.5	69	2,276	67	31,780		222,500	1,080		1,295		9,600				175			
1979-	0.5/a							200		500						200		11,900				400			
2006																									
2012-																									
Makola[14]	0.38		16,504					146		898	143,030	0.1		424		2,075		38,800					O	No	No
1941–48;																									
51–54																									
Mustavaara[15]	11.5		27,500	3		58	0.3	56	18	770	54,200		11,900	490	1	83	5	900	4	2,440	520	87	O	Yes	No
1976–85																									
Pahtavaara[16,17]	1.2	0.2	13,200	6		382	0.1	28	860	80	41,500		36,200	990	0.8	390	0.7	2,220	0.2	760	87	9	O	Yes	No
1996–2000;																									
03–14																									
Pyhäsalmi[18,19]	10		28,000	386		111,400		23	26.5	1,030	154,000		23,800	235		29	400	139,000		1,200	71	2,460	C	Yes	No
A: 1962–72; 76-97	3 (2003)									600								203,000				1,800	O		
D: 1997-																									
Stormi[1,2,20,21]	5.8	0.8		8	0.06		0.35	109	410	1,555	115,000	<0.1	146,500			1,530		23,000	<0.1		33	41	O	Yes	No
1974–94	1.59 (2011)			3.9			0.05	1.1	31	11		<0.1				6	5	706	0.25		7	18			
1990-	0.13 (2011)			386			0.25	12	34	33		<0.1				13	5	3,660	0.2		71	60			
1990-																									
Vihanti[2] (Lampinsaari) 1954-92	13.7	5.9			0.14					800	80,000						900	55,000				1,900	C	Yes	Yes
Virtasalmi[2,16] (Hällinmäki) 1966-	4.2	0.3			0.03			50		205	88,000					100	20	2,400					C	Yes	No
83																									
Vuonos[16]	9.1							320		350	69,000					770		33,000				2,900	O	Yes	Yes
1967–86																									
Ylöjärvi[16] (Parosjärvi) 1943-66	2.77	5.7						51		206	98,000						18					192	P	Yes	No

1) Martikainen, 2016.
2) Räisänen et al. (2015).
3) Tenhola and Räisänen (2006).
4) Groundia Ltd, 2009.
5) PSAVI Regional State Administrative Agency for Northern Finland, 2010.
6) Parviainen (2009).

[7] WSP Environmental Ltd, 2007.
[8] Heikkinen and Räisänen (2008).
[9] Tornivaara and Kauppila (2014).
[10] LVT Lapin vesitutkimus Ltd, 2006.
[11] PSAVI Regional State Administrative Agency for Northern Finland, 2014a.
[12] Heikkinen and Räisänen (2009).
[13] Ramboll Finland Ltd, 2014.
[14] Sipilä (1996).
[15] Pöyry (2009).
[16] Toropainen (2006).
[17] PSAVI Regional State Administrative Agency for Northern Finland, 2014b.
[18] PSAVI Regional State Administrative Agency for Northern Finland, 2007.
[19] Toropainen and Heikkinen (2006).
[20] Kuusisto (1991).
[21] LSSAVI Regional State Administrative Agency for Western and Inland Finland, 2014. C) Covered; P) Partly covered; O) Open.
[*]) In addition, 57 g/t of Eu_2O_3 and 7,000 g/t of La_2O_3.

recovery possibilities. From the mineralogy point of view, the tailings may contain silicate-, oxide-, hydroxide-, carbonate- and sulphide minerals, either as main gangue components of an ore, or as minor residues due to the inefficiency of a minerals processing technique (Lottermoser, 2010). As an example of physical properties, flotation tailings generally consist of <100 μm sized particles (Wills et al., 2015) and have 20–40% solids content (Lottermoser, 2010). While the valuable metal concentrations in the tailings are generally lower than in the concentrates or ores, the tailings may still possess recovery potential as the mining and particle size reduction have already been commissioned (Falagán et al., 2017).

Several different technologies have been studied to recover metals from the tailings. Flotation utilizes different surface properties of minerals and is considered effective in separating sulphides from other minerals, or even different sulphide species from each other. However, modern applications include also flotation of non-sulphidic minerals (Wills et al., 2015). Due to its versatility, flotation has been studied as an additional treatment of tailings after primary mineral processing. For example, cobalt (Lutandula and Maloba, 2013), copper (Yin et al., 2018) and tin (Leistner et al., 2016) have been successfully separated from various tailings types. Magnetic separation utilizes different magnetic properties of minerals (Wills et al., 2015). It has shown potential in recovering iron (Bicalho da Rocha et al., 2019), manganese (Zhang et al., 2017), titanium (Zhang et al., 2020) and chromium (Güney et al., 2001) from tailings. The separation technologies based on density and/or size difference have shown potential for recovering chromium (Tripathy et al., 2013), and zinc and lead (Khalil et al., 2019). Pyrometallurgical solutions for tailings treatment are interesting due to the transformation of iron into hematite or magnetite and the transformation of sulphides into sulphuric acid. For example, nickel-containing pyrrhotite may be treated via this route to produce hematite, nickel sulphate and sulphuric acid (Peek et al., 2011). Pyrometallurgy has also been suggested for recovering tin (López et al., 2018) and gold (Fu et al., 2018) from the tailings. Hydrometallurgical technologies are based on the treatment of the solid material in the presence of an aqueous phase. Due to the high diversity of available leaching, oxidizing, reducing and complexing agents, hydrometallurgy can offer very versatile processing options for a wide range of valuable metals (Free, 2013). As an example, sulphuric acid leaching is widely studied for base metals, such as zinc (Espiari et al., 2006) and copper (Antonijevic et al., 2008). Gold can be leached with cyanide and halides (Altinkaya et al., 2018), thiosulphate (Ubaldini et al., 2019) and thiourea (Ahmed et al., 2020). Hydrometallurgical methods can also include leaching of tailings with organic acids (Hernández et al., 2007). Bioleaching, which can be considered as one application of hydrometallurgy, is a potential technology in the tailings treatment, especially when valuable metals are incorporated to sulphide minerals, such as cobaltiferous pyrite (Morin and d'Hugues, 2007), pentlandite (Neale et al., 2017) or mixed sulphides (Mäkinen et al., 2021). With hydrometallurgical processing, the target metal is typically transformed into a dissolved form and must be recovered from the leachate by chemical precipitation, solvent extraction, ion exchange, crystallization and/or electrolysis (Free, 2013).

The majority of the proposed tailings treatment processes rely on technologies that have already been tested and possibly implemented with richer and less complex ores. Thus, these processes can be considered technically feasible for tailings treatment, especially after tailoring the full plant layout to allow more complex elemental composition. However, the economic feasibility is much more challenging, mainly due to the management of high iron and/or sulphur content compared to the low content of valuable metals that cover the costs of the proposed process (Peek et al., 2011). There are cases where tailings have been so rich in the target metal that a treatment plant has been commissioned and it has been successfully operated. For example, Kasese Cobalt Company utilized tank bioleaching with pyrite tailings containing 1.4 wt-% of cobalt. The cobalt value was high enough to pay a rather complex hydrometallurgical process of leaching, iron removal, solution purification and cobalt recovery (Morin and d'Hugues, 2007). Another strategy is to utilize flowsheets that recover also iron and/or sulphur value of the tailings. Historic industrial scale examples can be found from the Sudbury area, rich in nickel-bearing pyrrhotite tailings. Typically, these operations relied on pyrrhotite roasting, then producing different nickel, iron (hematite or magnetite) and sulphur (sulphuric acid or elemental sulphur) products. These processes were eventually shut down due to the increased availability of high-quality iron oxide ores and the low price of sulphuric acid (Peek et al., 2011). As a conclusion, recovering elemental values from tailings is not only a process-related issue, but strongly affected by global markets of ores and chemicals.

The economic benefit of a remining project can be increased, if in addition to the conventional target metals, also the by-products are extracted. The term Enhanced Tailings Mining could be used for the projects, which take into account a higher degree of valorisation (Suppes and Heuss-Aßbichler, 2021).

Due to a high variety in the tailings, including different minerals and metals and/or impurities, aging, particle size, water content and quality, and the presence of process chemicals, each metal recovery process must be tailored according to the site-specific characteristics. According to the literature review, many applications may have to be linked together to result even in a technologically viable processing route. Thus, successful process design requires an understanding of all possible applications and their proper utilization.

5.2.3. Integration of primary and secondary materials processing

There are also possibilities for the integration of primary and secondary metals recovery. Metal production and mineral waste recycling have approached each other in the last decades due to technical, social, legislative and economic factors (Spooren et al., 2020). In the roadmaps for the coming years, the integration of secondary raw materials or intermediates into the primary production has been identified as a means to increase the value of previously unused fractions (Batteries Europe ETIP, 2021). The benefits of the integration include a more efficient use of the existing infrastructure and synergies in materials sourcing and resource recovery. Some examples of the integration of primary and secondary production exist. In Sweden, the mining company Boliden uses both primary and secondary materials in its smelters (Florin et al., 2015).

5.3. Upcycle

In addition to the metals recovery from the tailings, also the mineral fraction in the tailings can be valuable. With reprocessing, the mine tailings can be modified to be utilized in high-value products. E.g. the recent article by Wong-Pinto et al. (2021) reports biosynthesis of copper nanoparticles from copper tailings. In addition, the literature provides several examples of the mine tailings upgrading by reprocessing into secondary raw materials for the construction and ceramic industry. The optimal value creation for the mining residues can be considered as a combination of different circular economy strategies (reduce, reprocess, upcycle, downcycle).

Every mine produces a unique type of tailings because of the compositional differences in the mined ore and the differences in the applied mining and mineral processing methods. The utilization of tailings is dependent on their characteristics: chemical and mineralogical composition, particle size and physical form (Lottermoser, 2010). Thus, efforts need to be put on developing tools and methods to control this variety in characteristics in the material and product design processes (Karhu, 2020).

5.3.1. Upgrading tailings as secondary raw materials for the construction industry

Construction applications, where residues function as active components, such as replace cement in concrete, can be seen as high-value uses (Simonsen et al., 2020). Supplementary cementitious materials (SCMs) are defined as substitute active components which contribute to the properties of concrete. SCMs can be natural or of industrial origin and their chemical and physical properties determine their potential for the cement replacement. The industrial residues typically used as SCMs are blast furnace slag and fly ash (UN Environment et al., 2018). Only a limited number of studies have discussed mine tailings utilization as a means to replace cement in concrete. Kundu et al. (2016) show preliminary experiments of substituting cement with copper mine tailings percentages ranging from 0 to 50%. They concluded that a moderate use of mine tailings can be possible as SCMs but further investigations of the mechanical properties of the concrete will be needed. A study by Simonsen et al. (2020) indicates that depending on their chemical composition and amorphous content, selected mine tailings show potential to be utilized as SCMs but presumably chemical or physical pretreatment can improve their potential. Martins et al. (2021) state in their current review publication that very limited data have been published about mine tailings use as SCMs and specifically for sulphidic tailings because of their chemical composition incompatibility to the common cement standards.

Geopolymerisation is studied in several publications as a technology to reprocess the mine tailings into bricks for the use of the construction and building industry. Publications show e.g. utilization of tungsten mine waste mud for the preparation of geopolymeric binders (Pacheco-Torgal et al., 2008), copper mine tailings use in the production of bricks through geopolymerization (Ahmari and Zhang, 2012, 2013), albite activation for the use in geopolymers (Feng et al., 2012) and sulphidic gold mine tailings use as raw materials in geopolymerization as an option for tailings inertization (Kiventerä et al., 2016, 2018). Generally, geopolymerisation is considered as an effective method to stabilize the mine tailings to be used as construction materials (Ahmari and Zhang, 2013). Ismailov et al. (2020) also show the potential of the mine tailings as a raw material for the magnesium potassium phosphate cements, which are chemically bonded ceramic materials typically used in civil engineering for rapid repair. The mine tailings are also reported to be reused as fine aggregates in concrete to replace natural sand, e.g. by the use of copper tailings (Thomas et al., 2013) and the use of low-sulphide Pb–Zn tailings (Argane et al., 2016).

5.3.2. Upgrading tailings as secondary raw materials for the ceramic industry

An upgrading of the mine tailings into secondary raw materials for the ceramics industry has been studied, e.g. as chemically bonded ceramics (Kinnunen et al., 2018), glass-ceramics utilizing sulphidic gold mine tailings (Shao et al., 2005) and Au–Cu tailings (Ye et al., 2015). The study by Karhu et al. (2019b) shows the potential of the mine tailings as raw materials for mullite-based ceramics. Mullite is a typical ceramic material for high temperatures, such as for refractory bricks and protective coatings. The mine tailings rich in quartz and alkali feldspars show potential to be used as raw materials for the mullite ceramics intended for operating temperatures up to 1,450 °C.

In the high-value ceramic applications, the use of the magnesite-rich mine tailings as a Mg-source for high-temperature electrical insulation ceramic coatings has been recently demonstrated (Karhu et al., 2019a, 2020). The coating deposition resulted in magnesium aluminate spinel ($MgAl_2O_4$) ceramic coatings showing comparable level of electrical insulation capability and considerably lower wear rate, when compared to $MgAl_2O_4$ coatings prepared using virgin, primary raw materials as powder feedstock materials. A considerably lower wear rate of the mine tailings-based coatings indicates a longer lifetime of the coated components, decreasing the input of new raw materials.

5.4. Downcycle

5.4.1. Use without reprocessing at the mining site

In downcycling, the waste bulk is used without reprocessing in large-volume applications. Some examples of tailings use are backfilling, construction materials and carbon capture (Lèbre et al., 2017b). The use of the mine tailings may be defined here as their use as such, in their original form, without any reprocessing. In this case, the mine tailings are typically used at the mining site (Kauppila et al., 2011) or in the close vicinity of the mining site for civil engineering purposes (Kinnunen et al., 2018). A common approach for the inert mine tailings is to use them as construction materials at the mining site as such, e.g. in road construction, as backfill material or as dam support material (Solismaa et al., 2018).

5.4.2. Carbon capture

The capture and storage of atmospheric CO_2 in tailings is a potential CO_2 sequestration technology (Lottermoser, 2010). The capture and storage of CO_2 is based on mineral carbonation, involving the reaction of atmospheric CO_2 with unstable silicates such as olivine, wollastonite, serpentine, anorthite and formation of carbonates. Several studies about mineral carbonation have been published, e.g. for serpentinite rocks and serpentine mineral samples (Lavikko, 2017) and their carbonation rates (Wilson et al., 2006). Additionally, the basis for mineralization in geologically derived minerals and industrial wastes has been discussed (Hills et al., 2021) as well as the feasibility of combining the recovery of valuable components in certain tailing deposits with the ex-situ sequestration of CO_2 (Marin et al., 2021). However, quantifying the amount of CO_2 that can be captured into mine wastes is a complex task because several processes are occurring simultaneously. A great amount of further work and technology development will be required to resolve the full potential of mineral carbonation considering different site and climate conditions (Lechat et al., 2016).

5.4.3. New purpose for the closed mine

When extending the scope from the reuse of waste materials to the reuse of the closed mine site, there are examples of repurposing the mining areas into tourist attractions or science education sites (Zhao et al., 2012). Closed mines have also been used as energy storage systems. In Australia, mining pits have been used in the hydro power storage as the upper and lower reservoirs to generate water power via solar energy (Genex Power, 2021).

5.5. Dispose

The amounts of mine waste residues are so significant that it is challenging to find a suitable usage for all of them. In a case where the material cannot be valorised, it should be safely deposited considering also the possibilities for future use. Long-term planning is needed to consider the waste valorisation already in the planning phase of the mine. The disposal method determines whether the valorisation of waste is possible or whether the material is made unsuitable for future uses (Lèbre et al., 2017a). As can be seen in Table 1, an important factor is also whether the tailings waste pile has already been covered and if there is existing infrastructure at the mine site to allow easier reprocessing.

6. Digital technologies supporting waste prevention and valorisation

The European Commission (2020b) has identified digital technologies as a key factor for reaching the objectives of the European Green Deal and the Sustainable Development Goals. Mining waste prevention pathway includes the reduction of output achieved by decreasing the input for example through targeted excavation or mineral processing optimisation. After minimizing the amount of the residues, the valorisation and utilization of the remaining mine tailings e.g. as concrete will decrease the remaining waste fractions to landfill. Digital mining technologies have a strong link to digital mine and digital twin concepts of the mines and mineral processes. This generated data, if it also includes waste fractions, is potential data source for waste utilization purposes as well.

In this chapter, we summarise the digital core technologies and solutions that currently support or have the potential to support waste management, not concentrating on the incorporated role of business, market, skills or policies related to digitalisation.

6.1. Data flow processes and circular waste strategies

Digital circular economy discussion combines data flow processes and circular economy strategies for minimizing waste. Circular Economy data flow processes start from 1) data acquisition and are followed by 2) data integration and 3) data analysis (Pagoropoulos et al., 2017). Additionally, 4) data sharing (Berg et al., 2020) is identified as an important phase, when structuring and grouping digital technologies for the circular economy solutions. The linkage between data flow processes and circular strategies identified by Berg et al. (2020) includes solutions to cover industrial symbiosis to restore, reduce and avoid material losses. The implementation of these strategies and how smartly data could be presented or generated into knowledge, can vary from descriptive data collection towards predictive and prescriptive data analytics. Digital solutions supporting data flow processes can advance the circular economy approach and reduce the environmental and social footprint. However, data acquisition, data management and data analytics demand considerable amounts of energy, and in addition, digital hardware and electronic devices require numerous natural mineral resources. Therefore, the impacts of the implementation of digital technologies are important to understand.

6.2. Digital solutions to support reduce, reprocess and downcycle strategies

Digitalisation is considered as an enabler for the circular economy through several ways, for example by supporting in the closure of the material loops, by monitoring waste and water streams, by providing accurate data and information about the availability, location, quantity and quality of materials, and by controlling the process more efficiently (Antikainen et al., 2018). Artificial intelligence (AI), machine learning, virtual and augmented reality, automation and autonomous design, the Internet of Things (IoT), digital infrastructure and data security are identified as the main contributors to the digital transformation of the raw materials sector and to the optimisation of processes, resource efficiency and productivity (EITRaw Materials, 2020), also to support waste prevention and data generation for waste valorisation. Furthermore, digital platforms can facilitate the valorisation of mine tailings by new and alternative waste-to-resource matches.

Digital technologies, many of them already supporting waste management, can be divided into three application levels such as processes, products and platforms and their related technologies such as sensor technologies, machine vision, artificial intelligence, the IoT and Distributed Ledger Technologies (DLT) (Berg et al., 2020). The waste material data of the mining processes relates to the hierarchical levels of substances and materials, rather than component, product or product system levels. Data acquisition, data management and data analytics of processes and products are related, for example, to the chemical composition, and physical and chemical properties of substances and materials. The mining waste reduction and reprocessing strategies can be supported by process monitoring and material detection (ore sorting) technologies, such as spectroscopy, machine vision, image analysis or pattern recognition. Digital Twins are commercially available for mining processes, including material flow location, material quantity and quality, and timing data.

Platforms connect consumers and producers, allow development of services and dematerialisation, industrial symbiosis (Berg et al., 2020), and such as Urban Mine Platform may support recovery of secondary raw materials (Hedberg and Šipka, 2020). The digital planning and management tools for mine closure are proposed instead of the traditional written plans, and they should cover aspects related to the management and treatment of tailings, waste rock and water (Kauppila et al., 2019).

6.3. Digital solutions to support upcycle strategies

Waste upcycling strategies target at reprocessing the mine tailings for the raw materials of high-value products. In these development projects and solutions, digital technologies can support both the process and production state, but also the whole 'end' product lifecycle. Therefore, material management relates to the substance and material hierarchical level in the raw material and waste phase, but to the component, product or product system hierarchical level through the final product lifecycle. On the other hand, some digital solutions facilitating the material and product lifecycle management are arising to cover the materials lifecycle starting from mining. Digitalisation of the raw materials data has the potential to support the entire value chain and the circularity of the raw materials. Despite of the need for a database for the properties and prices of secondary materials, there might be barriers to sharing waste related data due to long traditions of data protection by companies, seeing the value of data resources as a competitive business critical advantage and the sensitivity of waste material information, based on our recent workshop for battery value chain actors.

The arising concepts of material and product passports are digital representations of physical substances, materials or products through the value chain. For example, the Global Battery Alliance has presented the concept of battery passport to connect the data from mining and refining stakeholders through the lifecycle of batteries until the recycling phase. The Battery Passport is described as a digital twin of its physical battery enabled by the digital Battery Passport platform (Global Battery Alliance, 2020). However, the potential of data generated through evolving digital technologies is worth of evaluation to support mine tailing valorisation. The concepts of digital passports are evolving as well. To our knowledge, there is no existing passport for waste material.

The concept of circularity is highlighted in raw materials process design and operations e.g. by EIT Raw Materials (2020). Furthermore, satellites, open data and AI are commercially used to support the raw materials value chain, from the geological origin to the final product (EIT Raw Materials, 2021). The other common digital technologies are cloud-based solutions, edge computing and block chain technology to support both (secondary) raw materials trade and raw materials traceability.

7. Conclusions

There are various practices and potential for turning the mining waste into valuable products. As shown in the metal mine tailings inventory from Finland, the tailings deposits contain metals worth of hundreds of millions of euros, and these materials have the potential to be economically valorised but need to take into account the processing costs. In addition, information about existing infrastructure such as roads and covers is needed to determine the possibility for tailings valorisation. Various technologies are already exploited for the recovery of metals from the tailings and for the use of the mineral residues in high- or low-value products. The mine sites can even be used for completely new purposes in tourism and in energy storage. The economics of the valorisation of tailings is dependent on the institutional framework including e.g. taxation and regulations, which may also change over time. The most important parameters affecting the economics are the amount and the price of the targeted metals. The volume must be high enough to support the costs associated with processing.

Since the ore grades are getting lower and the metal demand is known to grow significantly, the amount of tailings is expected to boost in the next decades. At the same time, the demand of new kinds of metals results in the formation of new types of tailings, which also need to be taken into account preferably already in the planning stage. The amounts of generated waste are so significant that their full use in order to fulfil the circular economy approach is challenging. This means that not only one approach is enough, but a combination of several different circular economy approaches (reduce, reprocess, upcycle, downcycle and dispose for future) are needed to manage the waste streams. We emphasize the possibility for upcycling, as according to the waste hierarchy and the Circular Economy framework the value should be kept at the maximum. Typically, the management strategies of tailings have focused on downcycling, but there are possibilities for transforming the tailings into higher value products as described in our examples. We also highlight the need to evaluate the possibilities to valorise the tailings in a holistic way. It is possible that investigating only metals recovery or minerals use in the applications separately, the separate approaches are both economically inviable, but in the holistic view taking into account all approaches, the investment decision can be positive. Various valorisation technologies have already been developed and tested, but many of them are still in the non-commercial stage. In addition to technological advancements, which were in the focus of this article, we acknowledge the need to develop suitable ecosystems and partnerships for tailings valorisation.

Digitalisation can support the material and waste management, for example through the information of the material and waste flow location, quantity, quality and timing. Digital technologies currently enhance process and materials efficiency, as well as business intelligence, through advanced monitoring technologies and data analytics which yield information about waste streams and predict value chain dynamics. Furthermore, digitalisation can facilitate discovering the biggest potential for waste valorisation by identifying and exploring the new and alternative waste-to-resource matches within digital platforms for secondary raw materials. Barriers for data sharing were identified, due to both the business criticality of data and on the other hand the data may be sensitive, especially waste material data. Therefore, the digital tools for mine closure, for example, should especially cover these aspects. Additionally, the rising concepts of digital material and product passports have a potential to increase the circularity and the traceability of the waste-based materials and to support their safe utilization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The work was funded by the Academy of Finland [EcoTail, Decision no. 306079] and VTT Technical Research Centre. Complementary information was derived from a workshop organised in a project funded by the Academy of Finland [Circular Design Network, Decision no. 337713].

References

Ahmari, S., Zhang, L., 2012. Production of eco-friendly bricks from copper mine tailings through geopolymerization. Construct. Build. Mater. 29, 323–331. https://doi.org/10.1016/j.conbuildmat.2011.10.048.

Ahmari, S., Zhang, L., 2013. Durability and leaching behavior of mine tailings-based geopolymer bricks. Construct. Build. Mater. 44, 743–750. https://doi.org/10.1016/j.conbuildmat.2013.03.075.

Ahmed, M.R., Mohammed, H.S., El-Feky, M.G., Abdel-Monem, Y.K., 2020. Gold leaching using thiourea from uranium tailing material, Gabal El-Missikat, Central Eastern Desert, Egypt. J. Sustain. Metall. 6, 599–611. https://doi.org/10.1007/s40831-020-00295-2.
Ali, S.H., Giurco, D., Arndt, N., Nickless, E., Brown, G., Demetriades, A., Durrheim, R., Enriquez, M.A., Kinnaird, J., Littleboy, A., Meinert, L.D., Oberhänsli, R., Salem, J., Schodde, R., Schneider, G., Vidal, O., Yakovleva, N., 2017. Mineral supply for sustainable development requires resource governance. Nature 543, 367–372. https://doi.org/10.1038/nature21359.
Altinkaya, P., Mäkinen, J., Kinnunen, P., Kolehmainen, E., Haapalainen, M., Lundström, M., 2018. Effect of biological pretreatment on metal extraction from flotation tailings for chloride leaching. Miner. Eng. 129, 47–53. https://doi.org/10.1016/j.mineng.2018.09.012.
Antikainen, M., Valkokari, K., 2016. A framework for sustainable circular business model innovation. Technol. Innov. Manag. Rev. 6 (7), 5–12. https://timreview.ca/article/1000.
Antikainen, M., Uusitalo, T., Kivikytö-Reponen, P., 2018. Digitalisation as an enabler of circular economy. Procedia CIRP 73, 45–49. https://doi.org/10.1016/j.procir.2018.04.027.
Antonijevic, M.M., Dimitrijevic, M.D., Stevanovic, Z.O., Serbula, S.M., Bogdanovic, S.M., 2008. Investigation of the possibility of copper recovery from the flotation tailings by acid leaching. J. Hazard Mater. 158, 23–34. https://doi.org/10.1016/j.jhazmat.2008.01.063.
Araya, N., Kraslawski, A., Cisternas, L.A., 2020. Towards mine tailings valorization: recovery of critical materials from Chilean mine tailings. J. Clean. Prod. 263, 121555 https://doi.org/10.1016/j.jclepro.2020.121555.
Araya, N., Ramírez, Y., Kraslawski, A., Cisternas, L.A., 2021. Feasibility of re-processing mine tailings to obtain critical raw materials using real options analysis. J. Environ. Manag. 284, 112060 https://doi.org/10.1016/j.jenvman.2021.112060.
Argane, R., Benzaazoua, M., Hakkou, R., Bouamrane, A., 2016. A comparative study on the practical use of low sulfide base-metal tailings as aggregates for rendering and masonry mortars. J. Clean. Prod. 112, 914–925. https://doi.org/10.1016/j.jclepro.2015.06.004.
Balanay, R., Halog, A., 2016. Charting policy directions for mining's sustainability with circular economy. Recycling 1, 219–231. https://doi.org/10.3390/recycling1020219.
van Barnefeld, J., van der Veen, G., Enenkel, K., Mooren, C., Talman-Gross, L., Eckartz, K., Ostertag, K., Duque-Ciceri, N., Fischer, T., Gama, M., Scheidt, L., Wilts, H., Schäfer, L., Fischer, S., 2016. Regulatory Barriers for the Circular Economy. In: Lessons from Ten Case Studies, p. 169. Final report, 13 July 2016.
Batteries Europe ETIP, 2021. WG2: Raw Materials and Recycling Roadmap. https://ec.europa.eu/energy/sites/default/files/documents/raw_materials_and_recycling_roadmap_2.pdf.
van Beers, D., Corder, G., Bossilkov, A., van Berkel, R., 2007. Industrial symbiosis in the Australian minerals industry. The cases of Kwinana and Gladstone. J. Ind. Ecol. 11 (1), 55–72. https://doi.org/10.1162/jiec.2007.1161.
Bellenfant, G., Guezennec, A.G., Bodénan, F., D'Hugues, P., Cassard, D., 2013. Re-processing of Mining Waste: Combining Environmental Management and Metal Recovery? Mine Closure 2013, pp. 571–582. Sep 2013, Cornwall, United Kingdom.
Berg, H., Le Blévennec, K., Kristoffersen, E., Strée, B., Witomski, A., Stein, N., Bastein, T., Ramesohl, S., Vrancken, K., 2020. Digital Circular Economy: a Cornerstone of a Sustainable European Industry Transformation (White Paper). ECERA European Circular Economy Research Alliance, p. 28.
Bian, Z., Miao, X., Lei, S., Chen, S., Wang, W., Struthers, S., 2012. The challenges of reusing mining and mineral-processing wastes. Science 337 (6095), 702–703. https://doi.org/10.1126/science.1224757.
Bicalho da Rocha, R., Linhares Reis, E., Pancrácio Ribeiro, J., 2019. Wet high-intensity magnetic separators (WHIMS) for recovering iron from tailings deposited in dams. Miner. Process. Extr. Metall. (IMM Trans. Sect. C) 42 (1), 17–23. https://doi.org/10.1080/08827508.2019.1672061.
Blengini, G.A., Mathieux, F., Mancini, L., Nyberg, M., Viegas, H.M., 2019. In: Salminen, J., Garbarino, E., Orveillon, G., Saveyn, H., Mateos Aquilino, V., Llorens González, T., García Polonio, F., Horckmans, L., D'Hugues, P., Balomenos, E., Dino, G., de la Feld, M., Mádai, F., Földessy, J., Mucsi, G., Gombkötő, I., Calleja, I. (Eds.), Recovery of Critical and Other Raw Materials from Mining Waste and Landfills: State of Play on Existing Practices. EUR 29744 EN, Publications Office of the European Union, Luxembourg, ISBN 978-92-76-03391-2. https://doi.org/10.2760/494020,JRC116131.
Bocken, N.M.P., de Pauw, I., Bakker, C., van der Grinten, B., 2016. Product design and business model strategies for a circular economy. J. Ind. Prod. Eng. 33 (5), 308–320. https://doi.org/10.1080/21681015.2016.1172124.
Bodénan, F., Ménard, Y., d'Hugues, P., 2021. Mine waste reuse and reprocessing: an important step for the implementation of the circular economy in Europe. online, 19–30 Apr 2021, EGU21-7764 EGU General Assembly 2021. https://doi.org/10.5194/egusphere-egu21-7764, 2021.
Campbell, J.L., 2006. Institutional analysis and the paradox of corporate social responsibility. Am. Behav. Sci. 49 (7), 925–938. https://doi.org/10.1177/0002764205285172.
Cewep, 2021. Confederation of European Waste-To-Energy Plants. Landfill Taxes and Bans. Last update 20. https://www.cewep.eu/wp-content/uploads/2021/08/Landfill-taxes-and-bans-overview.pdf. (Accessed August 2021).
Chertow, M., Ehrenfeld, J., 2012. Organizing self-organizing systems. Toward a theory of industrial symbiosis. J. Ind. Ecol. 16 (1), 13–27. https://doi.org/10.1111/j.1530-9290.2011.00450.x.
Cisternas, L.A., Ordóñez, J.I., Jeldres, R.I., Serna-Guerrero, R., 2021. Toward the implementation of circular economy strategies: an overview of the current situation in mineral processing. Miner. Process. Extr. Metall. Rev. https://doi.org/10.1080/08827508.2021.1946690.
Dale, B., 2002. An institutionalist approach to local restructuring. The case of four Norwegian mining towns. Eur. Urban Reg. Stud. 9 (1), 5–20. https://doi.org/10.1177/096977640200900101.
Dashwood, H.S., 2014. Sustainable development and industry self-regulation: developments in the global mining sector. Bus. Soc. 53 (4), 551–582. https://doi.org/10.1177/0007650313475997.
Donoso, M., Robles, P.A., Gálvez, E.D., Cisternas, L.A., 2013. Particle size effect on the efficient use of water and energy in mineral concentration processes. Ind. Eng. Chem. Res. 52, 17686–17690. https://doi.org/10.1021/ie402099n.
Edraki, M., Baumgartl, T., Manlapig, E., Bradshaw, D., Franks, D.M., Moran, C.J., 2014. Designing mine tailings for better environmental, social and economic outcomes: a review of alternative approaches. J. Clean. Prod. 84, 411–420. https://doi.org/10.1016/j.jclepro.2014.04.079.
EIT Raw Materials, 17 March 2020. Position Paper on Digitalisation in the Raw Materials Sector. https://eitrawmaterials.eu/wp-content/uploads/2020/03/2020-03-12_EIT-RawMaterials_Digitalisation-RM-Sector.pdf.
EIT Raw Materials, 23 June 2021. EIT Raw Materials Success Stories. https://eitrawmaterials.eu/rovjok-digitalises-your-value-chain/.
Ellen MacArthur Foundation, 2013. Towards the Circular Economy. Economic and Business Rationale for an Accelerated Transition.
Ellen MacArthur Foundation, 2015. Delivering the Circular Economy. A Toolkit for Policymakers.
Espiari, S., Rashchi, F., Sadrnezhaad, S.K., 2006. Hydrometallurgical treatment of tailings with high zinc content. Hydrometallurgy 82, 54–62. https://doi.org/10.1016/j.hydromet.2006.01.005.
European Commission, 2006. Directive 2006/21/EC of the European Parliament and of the Council of 15 March 2006 on the Management of Waste from Extractive Industries and Amending Directive 2004/35/EC.
European Commission, 2015. Communication from the commission to the European parliament, the Council, the European economic and social committee and the committee of the regions, 2015. In: Closing the Loop - an EU Action Plan for the Circular Economy, 2.12. COM, Brussels, 2015) 614 final.
European Commission, 2017a. Report from the commission to the European parliament, the Council. In: The European Economic and Social Committee and the Committee of the Regions on the Implementation of the Circular Economy Action Plan, 26.1. COM, Brussels, 2017, 2017) 33 final.
European Commission, 2017b. Assessment of Member States' Performance Regarding the Implementation of the Extractive Waste Directive; Appraisal of Implementation Gaps and Their Root Causes; Identification of Proposals to Improve the Implementation of the Directive. Brussels.
European Commission, 2020b. Shaping Europe's Digital Future. https://ec.europa.eu/info/sites/default/files/communication-shaping-europes-digital-future-feb2020_en_3.pdf.
European Union, 2016. European Innovation Partnership on Raw Materials. Raw Materials Scoreboard. Publications Office of the European Union, Luxembourg.
Falagán, C., Grail, B.M., Johnson, D.B., 2017. New approaches for extracting and recovering metals from tailings. Miner. Eng. 106, 71–78. https://doi.org/10.1016/j.mineng.2016.10.008.
Feng, D., Provis, J.L., van Deventer, J.S.J., 2012. Thermal activation of albite for the synthesis of one-part mix geopolymers. J. Am. Ceram. Soc. 95 (2), 565–572. https://doi.org/10.1111/j.1551-2916.2011.04925.x.
Fischer, A., Pascucci, S., 2017. Institutional incentives in circular economy transition: the case of material use in the Dutch textile industry. J. Clean. Prod. 155, 17–32. https://doi.org/10.1016/j.jclepro.2016.12.038.
Fischer, C., Junker, H., Mazzanti, M., Paleari, S., Wuttke, J., Zoboli, R., 2012. Transboundary Shipments of Waste in the European Union. Reflections on Data, Environmental Impacts and Drivers. European Topic Centre on Sustainable Consumption and Production. ETC/SCP Working Paper 2/2012.
Florin, N., Madden, B., Sharpe, S., Benn, S., Agarwal, R., Perey, R., Giurco, D., 2015. Shifting Business Models for a Circular Economy: Metals Management for Multi-Product-Use Cycles. UTS, Sydney.
Free, M.L., 2013. Hydrometallurgy: Fundamentals and Applications. John Wiley & Sons, Incorporated, Somerset.
Fu, P., Li, Z., Feng, J., Bian, Z., 2018. Recovery of gold and iron from cyanide tailings with a combined direct reduction roasting and leaching process. Metals 8, 561. https://doi.org/10.3390/met8070561.
Genex Power, 2021. The Kidston Hydro Pumped Storage Project. Genex Power Limited, Sydney, Australia. https://www.genexpower.com.au/project-details.html. (Accessed 8 June 2021). accessed.
Gifford, B., Kestler, A., Anand, S., 2010. Building local legitimacy into corporate social responsibility: gold mining firms in developing nations. J. World Bus. 45, 304–311. https://doi.org/10.1016/j.jwb.2009.09.007.
Global Battery Alliance, November 2020. Briefing Paper. http://www3.weforum.org/docs/WEF_GBA_Battery_Passport_Overview_2021.pdf.
Gorman, M.R., Dzombak, D.A., 2018. A review of sustainable mining and resource management: transitioning from the life cycle of the mine to the life cycle of the mineral. Resour. Conserv. Recycl. 137, 281–291. https://doi.org/10.1016/j.resconrec.2018.06.001.
De Gregori, T.R., 1987. Resources are not; they become: an institutional theory. J. Econ. Issues 21 (3), 1241–1263. https://doi.org/10.1080/00213624.1987.11504702.
Gregson, N., Crang, M., Fuller, S., Holmes, H., 2015. Interrogating the circular economy: the moral economy of resource recovery in the EU. Econ. Soc. 44 (2), 218–243. https://doi.org/10.1080/03085147.2015.1013353.

Grotowski, A., Witecki, K., 2017. Research on the possibility of sorting application for separation of shale and/or gangue from the feed of Rudna concentrator. E3S Web Conf. 18 https://doi.org/10.1051/e3sconf/20171801004. MEC2017.
Groundia Ltd, 2009. Outokumpu Chrome Ltd. Kemin Kaivoksen Laajennus – Ympäristövaikutusten Arviointiselostus (Extension of Kemi Mine – Report on the Environmental Impact Assessment).
Güney, A., Önal, G., Atmaca, T., 2001. New aspect of chromite gravity tailings reprocessing. Miner. Eng. 14 (11), 1527–1530. https://doi.org/10.1016/S0892-6875(01)00165-0.
Gunson, A.J., Klein, B., Veiga, M., Dunbar, S., 2012. Reducing mine water requirements. J. Clean. Prod. 21, 71–82. https://doi.org/10.1016/j.jclepro.2011.08.020.
Hedberg, A., Šipka, S., 2020. The circular economy: going digital. In: European Policy Centre. https://doi.org/10.1038/531435a. March. 1–120.
Heikkinen, P.M., Räisänen, M.L., 2008. Mineralogical and geochemical alteration of Hitura sulphide mine tailings with emphasis on nickel mobility and retention. J. Geochem. Explor. 97 (1), 1–20. https://doi.org/10.1016/j.gexplo.2007.09.001.
Heikkinen, P.M., Räisänen, M.L., 2009. Trace metal and as solid-phase speciation in sulphide mine tailings – indicators of spatial distribution of sulphide oxidation in active tailings impoundments. Appl. Geochem. 24 (7), 1224–1237. https://doi.org/10.1016/j.apgeochem.2009.03.007.
Hernández, C.M.F., Banza, A.N., Gock, E., 2007. Recovery of metals from Cuban nickel tailings by leaching with organic acids followed by precipitation and magnetic separation. J. Hazard Mater. B139, 25–30. https://doi.org/10.1016/j.jhazmat.2006.03.074.
Hills, C.D., Tripathi, N., Carey, P.J., 2021. Mineralization technology for carbon capture, utilization, and storage. Front. Energy Res. 14 https://doi.org/10.3389/fenrg.2020.00142.
Hudson-Edwards, K.A., Jamieson, H.E., Lottermoser, B.G., 2011. Mine wastes: past, present, future. Elements 7 (6), 375–380. https://doi.org/10.2113/gselements.7.6.375.
Huisman, J., Leroy, P., Tertre, F., Ljunggren Söderman, M., Chancerel, P., Cassard, D., Løvik, A.N., Wäger, P., Kushnir, D., Rotter, V.S., Mählitz, P., Herreras, L., Emmerich, J., Hallberg, A., Habib, H., Wagner, M., Downes, S., December21, 2017. Prospecting Secondary Raw Materials in the Urban Mine and Mining Wastes. Final Report. ProSUM), Brussels, Belgium, ISBN 978-92-808-9060-0, 978-92-808-9061-7 (electronic).
ICMM, 2016. Mining and metals and the circular economy. International Council on Mining and Metals, London, ISBN 978-1-909434-22-6.
Ismailov, A., Merilaita, N., Solismaa, S., Karhu, M., Levänen, E., 2020. Utilizing mixed-mineralogy ferroan magnesite tailings as the source of magnesium oxide in magnesium potassium phosphate cement. Construct. Build. Mater. 231, 117098 https://doi.org/10.1016/j.conbuildmat.2019.117098.
de Jesus, A., Mendonça, S., 2018. Lost in transition? Drivers and barriers in the eco-innovation road to the circular economy. Ecol. Econ. 145, 75–89. https://doi.org/10.1016/j.ecolecon.2017.08.001.
de Jesus, A., Antunes, P., Santos, R., Mendonça, S., 2018. Eco-innovation in the transition to a circular economy: an analytical literature review. J. Clean. Prod. 172, 2999–3018. https://doi.org/10.1016/j.jclepro.2017.11.111.
Jiménez-Rivero, A., García-Navarro, J., 2017. Exploring factors influencing post-consumer gypsum recycling and landfilling in the European Union. Resour. Conserv. Recycl. 116, 116–123. https://doi.org/10.1016/j.resconrec.2016.09.014.
Johansson, N., Krook, J., Eklund, M., 2014. Institutional conditions for Swedish metal production: a comparison of subsidies to metal mining and metal recycling. Resour. Pol. 41, 72–82. https://doi.org/10.1016/j.resourpol.2014.04.001.
Karhu, M., 2020. Utilization of Mineral Side Streams in High Temperature Ceramic Materials. Dissertation University of Tampere, ISBN 978-952-03-1737-9. http://urn.fi/URN.
Karhu, M., Lagerbom, J., Solismaa, S., Huttunen-Saarivirta, E., 2019a. Magnesite-rich mining tailings as a raw material for refractory ceramics – microstructural and thermal analysis. Proc. Est. Acad. Sci. 68 (2), 145–149. https://doi.org/10.3176/proc.2019.2.05.
Karhu, M., Lagerbom, J., Solismaa, S., Honkanen, M., Ismailov, A., Räisänen, M.-L., Huttunen-Saarivirta, E., Levänen, E., Kivikytö-Reponen, P., 2019b. Mining tailings as raw materials for reaction-sintered aluminosilicate ceramics: effect of mineralogical composition on microstructure and properties. Ceram. Int. 45, 4840–4848. https://doi.org/10.1016/j.ceramint.2018.11.180.
Karhu, M., Lagerbom, J., Honkanen, M., Huttunen-Saarivirta, E., Kiilakoski, J., Vuoristo, P., Solismaa, S., Kivikytö-Reponen, P., 2020. Mining tailings as a raw material for glass-bonded thermally sprayed ceramic coatings: microstructure and properties. J. Eur. Ceram. Soc. 40, 4111–4121. https://doi.org/10.1016/j.jeurceramsoc.2020.04.038.
Kauppila, P.M., Räisänen, M.L., Myllyoja, S., 2011. Best Environmental Practices in Metal Ore Mining. Finnish Environment en29/2011. Helsinki. ISSN 1796-1637.
Kauppila, T., Bellenfant, G., Solismaa, L., Mittelstädt, P., 2019. In: Digitalisation of Continuous Mine Closure Planning and Management: an EIT RawMaterials Initiative, Mine Closure 2019 - AB Fourie & M Tibbett. © 2019 Australian Centre for Geomechanics, Perth, ISBN 978-0-9876389-3-9. https://doi.org/10.36487/ACG_rep/1915_81_Kauppila.
Khalil, A., Argane, R., Benzaazoua, M., Bouzahzah, H., Taha, Y., Hakkou, R., 2019. Pb–Zn mine tailings reprocessing using centrifugal dense media separation. Miner. Eng. 131, 28–37. https://doi.org/10.1016/j.mineng.2018.10.023.
Kinnunen, P., Kaksonen, A., 2019. Towards circular economy in mining: opportunities and bottlenecks for tailings valorization. J. Clean. Prod. 228, 153–160. https://doi.org/10.1016/j.jclepro.2019.04.171.
Kinnunen, P., Ismailov, A., Solismaa, S., Sreenivasan, H., Räisänen, M.-L., Levänen, E., Illikainen, M., 2018. Recycling mine tailings in chemically bonded ceramics - a review. J. Clean. Prod. 174, 634–649. https://doi.org/10.1016/j.jclepro.2017.10.280.
Kinnunen, P., Emler, R., Raatikainen, J., Guignot, S., Guimerà, J., Heiskanen, K., 2021. Review of closed water loops, ore sorting and tailings valorization for more sustainable raw material supply. J. Clean. Prod. 278, 123237 https://doi.org/10.1016/j.jclepro.2020.123237.
Kirchherr, J., Reike, D., Hekkert, M., 2017. Conceptualizing the circular economy: an analysis of 114 definitions. Resour. Conserv. Recycl. 127, 221–232. https://doi.org/10.1016/j.resconrec.2017.09.005.
Kirchherr, J., Piscicelli, L., Boura, R., Kostense-Smit, E., Muller, J., Huibrechtse-Truijens, A., Hekkert, M., 2018. Barriers to the circular economy: evidence from the European union (EU). Ecol. Econ. 150, 264–272. https://doi.org/10.1016/j.ecolecon.2018.04.028.
Kiventerä, J., Golek, L., Yliniemi, J., Ferreira, V., Deja, J., Illikainen, M., 2016. Utilization of sulphidic tailings from gold mine as a raw material in geopolymerization. Int. J. Miner. Process. 149, 104–110. https://doi.org/10.1016/j.minpro.2016.02.012.
Kiventerä, J., Lancellotti, I., Catauro, M., Dal Poggetto, F., Leonelli, C., Illikainen, M., 2018. Alkali activation as new option for gold mine tailings inertization. J. Clean. Prod. 187, 76–84. https://doi.org/10.1016/j.jclepro.2018.03.182.
Kotarska, I., Mizera, B., Stefanek, P., 2018. Mining waste in the circular economy – idea versus reality. E3S Web Conf. 41, 02013 https://doi.org/10.1051/e3sconf/20184102013.
Kundu, S., Aggarwal, A., Mazumdar, S., Dutt, B., 2016. Stabilization characteristics of copper mine tailings through its utilization as a partial substitute for cement in concrete: preliminary investigations. Environ. Earth Sci. 75, 227. https://doi.org/10.1007/s12665-015-5089-9.
Kuusisto, E., 1991. Metalli- Ja Rikkimalmikaivosten Ja -louhosten Jätealtaiden Ja Jätekasojen Vaikutusta Ympäristöön Tutkivaan Hankkeeseen Liittyvä Esiselvitys. Geological Survey of Finland. Archival Document S/42/0000/1/1991.
Lavikko, S., 2017. Geological and Mineralogical Aspects on Mineral Carbonation. Academic dissertation, ISBN 978-952-12-3485-9. http://urn.fi/URN.
Lèbre, E., Corder, G., Golev, A., 2017a. The role of the mining industry in a circular economy. A framework for resource management at the mine site level. J. Ind. Ecol. 21 (3), 662–672. https://doi.org/10.1111/jiec.12596.
Lèbre, E., Corder, G., Golev, A., 2017b. Sustainable practices in the management of mining waste: a focus on the mineral resource. Miner. Eng. 107, 34–42. https://doi.org/10.1016/j.mineng.2016.12.004.
Lechat, K., Lemieux, J.-M., Molson, J., Beaudoin, G., Hébert, R., 2016. Field evidence of CO2 sequestration by mineral carbonation in ultramafic milling wastes, Thetford Mines, Canada. Int. J. Greenh. Gas Control 47, 110–121. https://doi.org/10.1016/j.ijggc.2016.01.036.
Leistner, T., Embrechts, M., Leissner, T., Chehreh Chelgani, S., Osbahr, I., Möckel, R., Peuker, U.A., 2016. A study of the reprocessing of fine and ultrafine cassiterite from gravity tailing residues by using various flotation techniques. Miner. Eng. 96–97, 94–98. https://doi.org/10.1016/j.mineng.2016.06.020.
Lessard, J., Sweetser, W., Bartram, K., Figueroa, J., McHugh, L., 2016. Bridging the gap: understanding the economic impact of ore sorting on a mineral processing circuit. Miner. Eng. 91, 92–99. https://doi.org/10.1016/j.mineng.2015.08.019.
López, F.A., García-Díaz, I., Rodrígues Largo, O., García Polonio, F., Llorens, T., 2018. Recovery and purification of tin from tailings from the Penouta Sn–ta–Nb deposit. Minerals 8, 20. https://doi.org/10.3390/min8010020.
Lottermoser, B.G., 2010. Mine Wastes. In: Characterization, Treatment and Environmental Impacts, third ed. Springer, pp. 1–393.
Lottermoser, B.G., 2011. Recycling, reuse and rehabilitation of mine wastes. Elements 7, 405–410. https://doi.org/10.2113/gselements.7.6.405.
LSSAVI Regional State Administrative Agency for Western and Inland Finland, 2014. Dragon Mining Oy Vammalan Rikastamon Ympäristölupa, Olennainen Muutos Ja Lupamääräysten Tarkistaminen, Sastamala (Asia 1); Ympäristölupapäätöksen Nro 15/2008/2 Lupamääräyksen 3 Mukainen Selvitys Rikastushiekka-Altaan Aiheuttamasta Sulfaatti- Ja Nikkelikuormituksesta Kovero- Ojaan (Asia 2). License decision Nr, 124/2014/.
Lutandula, M.S., Maloba, B., 2013. Recovery of cobalt and copper through reprocessing of tailings from flotation of oxidised ores. J. Environ. Chem. Eng. 1, 1085–1090. https://doi.org/10.1016/j.jece.2013.08.025.
Lutandula, M.S., Mwana, K.N., 2014. Perturbations from the recycled water chemical components on flotation of oxidized ores of copper—the case of bicarbonate ions. J. Environ. Chem. Eng. 2, 190–198. https://doi.org/10.1016/j.jece.2013.12.012.
LVT Lapin vesitutkimus Ltd, 2006. Scandinavian Minerals Limited, Kevitsan Kaivoshankkeen Ympäristövaikutusten Arviointiselostus (Report on the Environmental Impact Assessment of Kevitsa Mine Project).
Machado, R.C., Andrade, D.F., Babos, D.V., Castro, J.P., Costa, V.C., Sperança, M.A., Garcia, J.A., Gamela, R.R., Pereira-Filho, E.R., 2020. Solid sampling: advantages and challenges for chemical element determination—a critical review. Anal. At. Spectrom. 35, 54. https://doi.org/10.1039/c9ja00306a.
Mäkinen, J., Heikola, T., Salo, M., Kinnunen, P., 2021. The effects of milling and pH on Co, Ni, Zn and Cu bioleaching from polymetallic sulfide concentrate. Minerals 11, 317. https://doi.org/10.3390/min11030317.
Marin, O., Valderrama, J.O., Kraslawski, A., Cisternas, L.U., 2021. Potential of tailing deposits in Chile for the sequestration of carbon dioxide produced by power plants using ex-situ mineral carbonation. Minerals 11 (3), 320. https://doi.org/10.3390/min11030320.
Martikainen, K., 2016. Aijalan Cu-Zn-Pb-Kaivoksen Aiheuttama Metallikuormitus Vesistöön Ja Kuormituksen Mahdollinen Hallinta (The Metal Contamination to Waters at the Aijala Mine and its Management Options). M.Sc. thesis. Department of Geosciences and Geography, University of Helsinki.

Martins, N.P., Srivastava, S., Simão, F.V., Niu, H., Perumal, P., Snellings, R., Illikainen, M., Chambart, H., Habert, G., 2021. Exploring the potential for utilization of medium and highly sulfidic mine tailings in construction materials: a review. Sustainability 13, 12150. https://doi.org/10.3390/su132112150.

Moreau, V., Sahakian, M., van Griethuysen, P., Vuille, F., 2017. Coming full circle. Why social and institutional dimensions matter for the circular economy. J. Ind. Ecol. 21 (3), 497–506. https://doi.org/10.1111/jiec.12598.

Morin, D.H.R., d'Hugues, P., 2007. In: Biomining, Rawlings, D.E., Johnson, D.B. (Eds.), Bioleaching of a Cobalt-Containing Pyrite in Stirred Reactors. Springer: Berlin/Heidelberg, Germany, pp. 35–54, 2007.

Mulvaney, D., Richards, R.M., Bazilian, M.D., Hensley, E., Clough, G., Sridhar, S., 2021. Progress towards a circular economy in materials to decarbonize electricity and mobility. Renew. Sustain. Energy Rev. 137, 110604 https://doi.org/10.1016/j.rser.2020.110604.

Murray, A., Skene, K., Haynes, K., 2017. The circular economy: an interdisciplinary exploration of the concept and application in a global context. J. Bus. Ethics 140, 369–380. https://doi.org/10.1007/s10551-015-2693-2.

Neale, J., Seppälä, J., Laukka, A., Van Aswegen, P., Barnett, S., Gericke, M., 2017. The MONDO Minerals nickel sulfide bioleach project: from test work to early plant operation. Solid State Phenom. 262, 28–32. https://doi.org/10.4028/www.scientific.net/SSP.262.28.

Nikolaou, I.E., Evangelinos, K.I., 2010. A SWOT analysis of environmental management practices in Greek Mining and Mineral Industry. Resour. Pol. 35, 226–234. https://doi.org/10.1016/j.resourpol.2010.02.002.

Northey, S.A., Mudd, G.M., Saarivuori, E., Wessman-Jääskeläinen, H., Haque, N., 2016. Water footprinting and mining: where are the limitations and opportunities? J. Clean. Prod. 135, 1098–1116. https://doi.org/10.1016/j.jclepro.2016.07.024.

Pacheco-Torgal, F., Castro-Gomes, J., Jalali, S., 2008. Properties of tungsten mine waste geopolymeric binder. Construct. Build. Mater. 22, 1201–1211. https://doi.org/10.1016/j.conbuildmat.2007.01.022.

Pagoropoulos, A., Pigosso, D.C.A., Mcaloone, T.C., 2017. The emergent role of digital technologies in the Circular Economy : a review, 64, pp. 19–24. https://doi.org/10.1016/j.procir.2017.02.047.

Parviainen, A., 2009. Tailings mineralogy and geochemistry at the abandoned Haveri Au–Cu mine, SW Finland. Mine Water Environ. 28, 291. https://doi.org/10.1007/s10230-009-0088-2.

Peek, E., Barnes, A., Tuzun, A., 2011. Nickeliferous pyrrhotite-waste or a resource? Miner. Eng. 24, 625–637. https://doi.org/10.1016/j.mineng.2010.10.004.

Pličanič, S., Mladenović, A., Pranjić, A.M., Vrhovnik, P., 2020. Mining waste in circular economy - legislative aspect. Geol. Maced. 34 (21), 149–156.

Pöyry, 2009. Report for Adriana Resources Inc., Appendix 6.3. Mustavaaran Rikastushiekan Ja Sivukiven Ympäristökelpoisuustestit (Environmental Acceptability Tests of Tailings and Gangue from Mustavaara). SLU. Working number 9M707012.BOR01.

Prno, J., Slocombe, D.S., 2012. Exploring the origins of 'social license to operate' in the mining sector: perspectives from governance and sustainability theories. Res. Pol. 37, 346–357. https://doi.org/10.1016/j.resourpol.2012.04.002.

PSAVI Regional State Administrative Agency for Northern Finland, 2007. Pyhäsalmen Kaivoksen Ympäristö- Ja Vesitalouslupa, Pyhäjärvi (Environmental and Water Management Permit for Pyhäsalmi Mine, Pyhäjärvi). License decision Nr. 85/07/02.

PSAVI Regional State Administrative Agency for Northern Finland, 2010. Kemin Kromiittikaivoksen Ja Rikastamon Ympäristö- Ja Vesitalouslupa Sekä Toiminnan Aloittamislupa, Keminmaa (Environmental and Water Management Permit, and Permission to Start the Operation of the Chromite Mine and Refinery in Kemi, Keminmaa). License decision Nr. 125/10/1.

PSAVI Regional State Administrative Agency for Northern Finland, 2014a. Kevitsan Kaivoksen Tuotannon Laajentamisen Ympäristö- Ja Vesitalouslupa Sekä Töiden Ja Toiminnan Aloittamislupa, Sodankylä (Environmental and Water Management Permit for the Expansion of Production in Kevitsa Mine, and Permission to Start the Works and Operation, Sodankylä). License decision Nr. 79/2014/1.

PSAVI Regional State Administrative Agency for Northern Finland, 2014b. Pahtavaaran kaivoksen Länsimalmion ympäristölupa, Sodankylä (Environmental permit for the western ore body of Pahtavaara mine, Sodankylä). License decision Nr. 32/2014/1.

Räisänen, M.L., Beucher, A., Tornivaara, A., Kauppila, P., 2015. Suljettujen ja hylättyjen metallikaivosalueiden nykytila ja arvio jätealueiden ympäristöriskipotentiaalista. Geological Survey of Finland. Archival document 46, 2015.

Ramboll Finland Ltd, 2014. Luikonlahden Rikastamon Sivutuotteiden Ja Kaivannaisjätteiden Elinkaarisuunnittelu – Ympäristövaikutusten Arviointiohjelma (Life Cycle Planning of By-Products and Extractive Wastes from Luikonlahti Refinery – Environmental Impact Assessment Program). Kylylahti Copper Ltd.

Ranta, V., Aarikka-Stenroos, L., Ritala, P., Mäkinen, S.J., 2018. Exploring institutional drivers and barriers of the circular economy: a crossregional comparison of China, the US, and Europe. Resour. Conserv. Recycl. 135, 70–82. https://doi.org/10.1016/j.resconrec.2017.08.017.

Ritzén, S., Sandström, G.Ö., 2017. Barriers to the circular economy – integration of perspectives and domains. The 9th CIRP IPSS conference: circular perspectives on product/service-systems. Procedia CIRP 7–12.

Ruokonen, E., 2020. Preconditions for successful implementation of the Finnish standard for sustainable mining. Extr. Ind. Soc. 7, 611–620. https://doi.org/10.1016/j.exis.2020.03.008.

Scott, W.R., 2008. Approaching adulthood: the maturing of institutional theory. Theor. Soc. 37, 427–442. https://doi.org/10.1007/s11186-008-9067-z.

Scott, W.R., 2014. Institutions and Organizations: Ideas and Interests. SAGE Publications, Inc.

Shadrunova, I.V., Orekhova, N.N., 2015. A process for advanced recycling of water originating from mining operations, with metal recovery. Mine Water Environ. 34, 478–484. https://doi.org/10.1007/s10230-015-0338-4.

Shao, H., Liang, K., Peng, F., Zhou, F., Hu, A., 2005. Production and properties of cordierite-based glass-ceramics from gold tailings. Miner. Eng. 18, 635–637. https://doi.org/10.1016/j.mineng.2004.09.007.

Simate, G.S., Ndlovu, S., 2014. Acid mine drainage: challenges and opportunities. Int. J. Eng. Res. Afr. 2, 1785–1803. https://doi.org/10.1016/j.jece.2014.07.021.

Simonsen, A.M.T., Solismaa, S., Hansen, H.K., Jensen, P.E., 2020. Evaluation of mine tailings' potential as supplementary cementitious materials based on chemical, mineralogical and physical characteristics. Waste Manag. 102, 710–721. https://doi.org/10.1016/j.wasman.2019.11.037.

Sipilä, P., 1996. Makolan Kaivoksen Rikastamon Jätealueen Kunnostussuunnitelma (Restoration Plan for the Waste Area of Makola Mine Refinery). Geological Survey of Finland. KA 61/97/3.

Solismaa, S., Ismailov, A., Karhu, M., Sreenivasan, H., Lehtonen, M., Kinnunen, P., Illikainen, M., Räisänen, M.-L., 2018. Valorization of Finnish mining tailings for use in the ceramics industry. Bull. Geol. Soc. Finland 90, 33–54. https://doi.org/10.17741/bgsf/90.1.002.

Solomons, I., 2017. Mine tailings recovery can be value generator, says Council for Geoscience. Mining Weekly 9 (6), 2017. http://www.miningweekly.com/article/mine-tailings-recovery-can-be-value-generator-reduces-enviro-impact-2017-06-09.

Spooren, J., Binnemans, K., Björkmalm, J., Breemersch, K., Dams, Y., Folens, K., González-Moya, M., Horckmans, L., Komnitsas, K., Kurylak, W., Lopez, M., Mäkinen, J., Onisei, S., Peys, A., Pietek, G., Pontikes, Y., Snellings, R., Tripiana, M., Varia, J., Willquist, K., Yurramendi, L., Kinnunen, P., 2020. Near-zero-waste processing of low-grade, complex primary and secondary ores: challenges and opportunities. Resour. Conserv. Recycl. 160, 104919 https://doi.org/10.1016/j.resconrec.2020.104919.

Stahel, W.R., 2013. Policy for material efficiency — sustainable taxation as a departure from the throwaway society. *Philos. Trans. Royal Soc.* A 371, 20110567. https://doi.org/10.1098/rsta.2011.0567.

Stål, H.I., Corvellec, H., 2018. A decoupling perspective on circular business model implementation: illustrations from Swedish apparel. J. Clean. Prod. 171, 630–643. https://doi.org/10.1016/j.jclepro.2017.09.249.

Suppes, R., Heuss-Aßbichler, S., 2021. Resource potential of mine wastes: a conventional and sustainable perspective on a case study tailings mining project. J. Clean. Prod. 297, 126446 https://doi.org/10.1016/j.jclepro.2021.126446.

Tayebi-Khorami, M., Edraki, M., Corder, G., Golev, A., 2019. Re-thinking mining waste through an integrative approach led by circular economy aspirations. Minerals 9, 286. https://doi.org/10.3390/min9050286.

Tenhola, M., Räisänen, M.L., 2006. Rikastushiekan Läjitysalueen Suotovesien Vaikutus Ympäröivän Turpeen Kemialliseen Koostumukseen, Vanha Hammaslahden Cu-Zn -kaivos, Pyhäselkä (Effect of Seepage Water from the Tailings Deposits on the Chemical Composition of Surrounding Peat, Old Cu-Zn Mine of Hammaslahti, Pyhäselkä) Geological Survey of Finland. Archival document S44/0000/1/2006.

Thomas, B.S., Damare, A., Gupta, R.C., 2013. Strength and durability characteristics of copper tailing concrete. Constr.Build. Mater. 48, 894–900. https://doi.org/10.1016/j.conbuildmat.2013.07.075.

Tornivaara, A., Kauppila, P.M., 2014. Kaivoksen Sulkeminen Ja Jälkihoito; Ekskursio Luikonlahden Ja Keretin Kaivosalueille (Mine Closure and Rehabilitation; Excursion to the Luikonlahti and Keretti Mine Sites), vol. 60. Geological Survey of Finland, Guide.

Toropainen, V., 2006. Yhteenveto Sulfidimalmikaivostoiminnasta Suomessa Ja Toiminnassa Muodostuvista Sivutuotteista Sekä Niiden Ympäristövaikutuksista (Summary of Metal Sulfide Ore Mining in Finland, its Byproducts and Their Environmental Effects). Geological Survey of Finland. Archival Document S 49/0000/2006/2.

Toropainen, V., Heikkinen, P., 2006. Mineralogical and Chemical Composition of the Tailings and Waste Rock Samples of Pyhäsalmi, Hitura, Talvivaara and Ihalainen Ore Deposits. Geological Survey of Finland. Archival Document S49/0000/2006/3.

Tripathy, S.L., Murthy, Y.R., Singh, V., 2013. Characterisation and separation studies of Indian chromite beneficiation plant tailing. Int. J. Miner. Process. 122, 47–53. https://doi.org/10.1016/j.minpro.2013.04.008.

Ubaldini, S., Guglietta, D., Vegliò, F., Giuliano, V., 2019. Valorization of mining waste by application of innovative thiosulphate leaching for gold recovery. Metals 9 (3), 274. https://doi.org/10.3390/met9030274.

Un Environment, Scrivener, K.L., Vanderley, M.J., Gartner, E.M., 2018. Eco-efficient cements: potential economically viable solutions for a low-CO2 cement-based materials industry. Cement Concr. Res. 114, 2–26.

UNEP, 2020. Mineral resource governance in the 21st century: Gearing extractive industries towards sustainable development. A Report by the International Resource Panel. United Nations Environment Programme, Nairobi, Kenya.

Upadhyay, A., Laing, T., Kumar, V., Dora, M., 2021. Exploring barriers and drivers to the implementation of circular economy practices in the mining industry. Resour. Pol. 72, 102037 https://doi.org/10.1016/j.resourpol.2021.102037.

de Villiers, C., Low, M., Samkin, G., 2014. The institutionalization of mining company sustainability disclosures. J. Clean. Prod. 84, 51–58. https://doi.org/10.1016/j.jclepro.2014.01.089.

Wagner, M., Bide, T., Cassard, D., Huisman, J., Leroy, P., Bavec, Š., Ljunggren Söderman, M., Løvik, A.N., Wäger, P., Emmerich, J., Sperlich, K., Baldé, C.P., Schjøth, F., Tivander, J., Brown, T., Petavratzi, E., Whitehead, D., Tertre, F., Mählitz, P.M., Nikolova, V., Horváth, Z., 2019. Optimising Quality of Informationin RAw MAterials Data Collection across Europe (ORAMA), Technical Final Report & Recommendations. November 15, 2019, Brussels, Belgium.

Wang, C., Harbottle, D., Liu, Q., Xu, Z., 2014. Current state of fine mineral tailings treatment: a critical review on theory and practice. Miner. Eng. 58, 113–131. https://doi.org/10.1016/j.mineng.2014.01.018.
West, J., 2011. Decreasing metal ore grades. Are they really being driven by the depletion of high-grade deposits? J. Ind. Ecol. 15 (2), 165–168.
Wills, B.A., et al., 2015. Wills' Mineral Processing Technology: an Introduction to the Practical Aspects of Ore Treatment and Mineral Recovery. Elsevier Science & Technology.
Wilson, S.A., Raudsepp, M., Dipple, G.M., 2006. Verifying and quantifying carbon fixation in minerals from serpentine-rich mine tailings using the Rietveld method with X-ray powder diffraction data. Mineralogist 91 (8–9), 1331–1341. https://doi.org/10.2138/am.2006.2058.
Wong-Pinto, L.-S., Mercado, A., Chong, G., Salazar, P., Ordóñez, J.I., 2021. Biosynthesis of copper nanoparticles from copper tailings ore-An approach to the 'Bionanomining. J. Clean. Prod. 315, 12810 https://doi.org/10.1016/j.jclepro.2021.128107.
World Economic Forum, 2016. Mapping mining to the sustainable development Goals: an atlas. Available at: http://unsdsn.org/wp-content/uploads/2016/11/Mapping_Mining_SDGs_An_Atlas.pdf.
WSP Environmental Ltd, 2007. Hitura Mining Oy, Hituran Kaivoksen Rikastushiekka-Alueiden YVA–arviointiohjelma (Environmental impact assessment program of tailing areas of Hitura mine). WSP.
Ye, C., He, F., Shu, H., Qi, H., Zhang, Q., Song, P., Xie, J., 2015. Preparation and properties of sintered glass–ceramics containing Au–Cu tailing waste. Mater. Des. 86, 782–787. https://doi.org/10.1016/j.matdes.2015.07.173.
Yin, Z., Sun, W., Hu, Y., Zhang, C., Guan, Q., Wu, K., 2018. Evaluation of the possibility of copper recovery from tailings by flotation through bench-scale, commissioning, and industrial tests. J. Clean. Prod. 171, 1039–1048. https://doi.org/10.1016/j.jclepro.2017.10.020.
Zhang, X., Tan, X., Yi, Y., Liu, W., Li, C., 2017. Recovery of manganese ore tailings by high-gradient magnetic separation and hydrometallurgical method. J. Occup. Med. 69, 2352–2357. https://doi.org/10.1007/s11837-017-2521-5.
Zhang, H., Zeng, J., Xie, H., Guan, C., Chen, L., 2020. Enhanced separation for ilmenite tailings with a novel HGMS-flotation process. Separ. Sci. Technol. 55, 752–760. https://doi.org/10.1080/01496395.2019.1567546.
Zhao, Y., Zang, L., Li, Z., Qin, J., 2012. Discussion on the model of mining circular economy. Energy Proc. 16, 438–443. https://doi.org/10.1016/j.egypro.2012.01.071.
Žibret, G., Lemiere, B., Mendez, A.-M., Cormio, C., Sinnett, D., Cleall, P., Szabó, K., Carvalho, M.T., 2020. National mineral waste databases as an information source for assessing material recovery potential from mine waste, tailings and metallurgical waste. Minerals 10, 446. https://doi.org/10.3390/min10050446.