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REVIEW

Reuse and valorization practices of mine tailings: a review of existing perspectives and advances

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Abstract

Mine tailings are considered a negative waste group due to their high volume, environmental risks, potential leakage behavior, and storage problems. However, recent studies show that, considering their physical/chemical properties, these wastes have significant potential as secondary resources that can be utilized in various sectors. This study addresses the fact that mining waste is not only an environmental burden but can also be used as functional materials under appropriate conditions. Literature shows that applications focused on construction and building are prominent in the utilization of mining waste. For example, cemented paste backfill applications are widely used as a technology because they allow for the safe disposal of waste underground. Also, the use of waste as a precursor to bricks, ceramics, additional cementitious binders, or geopolymers shows promise in terms of mechanical performance and environmental gains; however, the success of these approaches largely depends on the mineralogical structure, chemical reactivity, and pretreatment requirements of the waste. Outside the construction sector, other studies also reveal the potential of mining waste for metal recovery, environmental remediation, and the use of functional additive materials. These examples demonstrate that the utilization of mining waste cannot be limited to a single technology and that the application must be determined specifically for the field conditions. Although the environmental risks and technical challenges of mining waste have been widely focused in literature, studies that comprehensively evaluate the potential use of these wastes in different sectors are relatively limited. This study provides a systematic synthesis of the literature, outlining viable application areas and conditions for the utilization of mining wastes.

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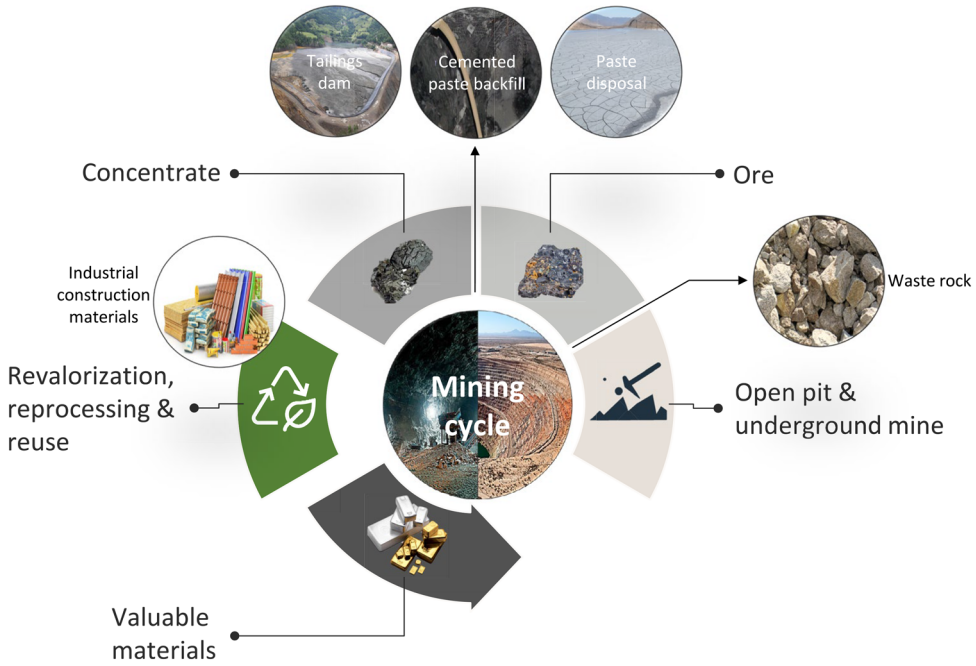
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Graphical abstract



Keywords Tailings · Raw material · Existing and emerging techniques of waste

Introduction

By the creation of concentrates from low-grade ores with different enrichment tech-niques such as flotation, high tonnage wastes are inevitably produced (Adesina 2025). Approximately 20 billion tons of mining waste is produced annually in European mines (Kalisz et al. 2024). It is clear that these wastes, which have different types and components such as metallic, industrial and coal wastes, will pose a menace to survives with weather, water and soil contamination, and degradation of natural resources and greenhouse gas effects if they are not disposed effectively (Yıldız et al. 2024). Therefore, it is essential to re-handle the wastes with sustainable innovative technologies and transform them into raw material products that are harmless to environment and even useful for some sectors (Beniddar et al. 2024). In addition to the waste management systems currently used in mining, there are three basic approaches for more effective use of wastes in socioeconomic/environmental terms: dewatering of wastes, tail recycling/reuse, and integrated waste disposal techniques (Adewuyi et al. 2024).

Within framework of traditional approaches, the generated mining (such as silica, nickel, silver, tungsten, red mud, uranium, lead, zinc, copper, gold and iron) waste is stored in above-ground waste dams and under-ground cavities where the valuable ore is safely mined (Hao et al. 2024). Traditionally, waste is disposed of in above-ground storage areas (waste dams) or as fill in under-ground creation rooms (stopes) where ores are removed (Qiu et al. 2023). The fill practice used for the discarding of dewatered mill tails is recognized by EU Directive as one of the BATs (Garbarino et al. 2020). Disposal of non-dewatered waste in conventional tailings dams carries serious risks such as the dam overcapacity and contamination of the immediate environment (Beylot et al. 2022). Thus, due to all these possible and realized risks, strict legal regulations have emerged in the disposal of mining waste today and mining companies are inspected much more seriously and frequently (Piciullo et al. 2022a). In fact, this situation emerged after the collapse of the waste dam, which has brought a serious economic burden to the enterprises and caused environmental problems that are irreversible or will take many years to be re-habilitated (Araya et al. 2020). In order not to encounter this situation, innovative alternative techniques have been developed for effective waste disposal (Keskin et al. 2024). Besides, some latest works have publicized that dam tailings might be reprocessed with today's technologies and reused as a raw material source in many sectors, especially in construction. (Wang et al. 2025). Figure 1 discusses the re-evaluation of mining waste produced within the framework of a classic mine task with pioneering techniques. By recycling and reusing waste, mining firms can make a

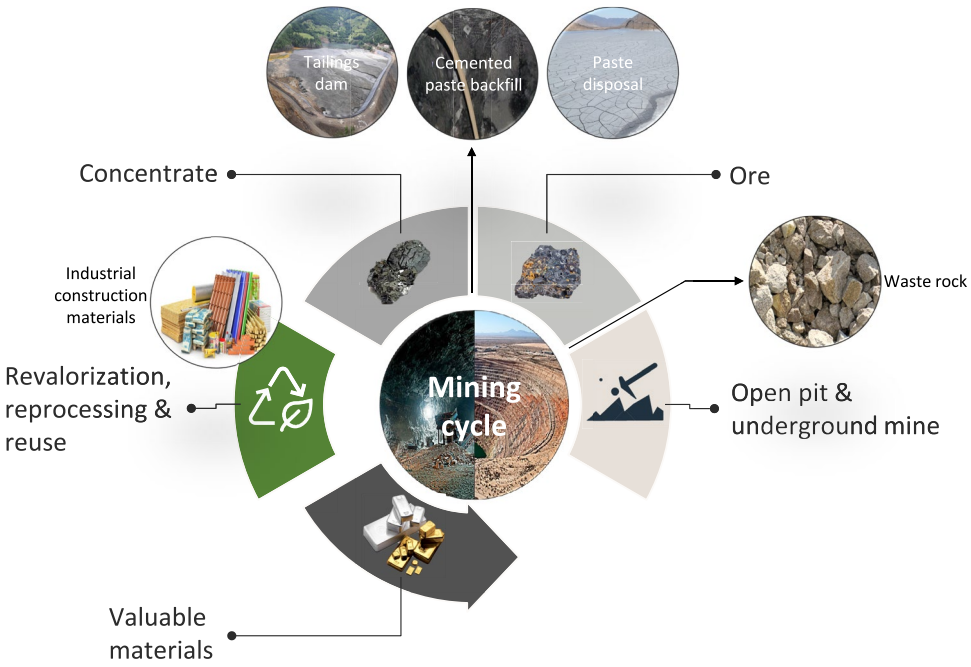


Fig. 1 The creation, disposal and valorization of waste, considering sustainable mining cycle

major contribution to UNs sustainable development goals, namely SDG 11 "sustainable cities and communities" and SDG 12 "responsible consumption and production" (Tsani et al. 2020).

This review examines the existing conventional techniques and several innovative approaches for the disposal of mining waste. The article first commences with a concept that presents the currently used approaches, the difficulties encountered, and using tails as a raw material within different sectors. Then, applications of waste with the emerging innovative techniques are discussed thoroughly. Finally, it presents new products and technological developments that emerge by changing the physico-chemical properties of waste with some treatment techniques. Moreover, the potential of using waste as useful products without causing any harmful effect with a holistic view is emphasized in the current review.

Methodology

This study adopts a mixed-methods approach, combining both quantitative and qualitative analyses to conduct a bibliometric analysis and a systematic literature review on the reuse and valorization of mine waste/tailings. This approach enables the investigation of the theoretical evolution and empirical validation of waste utilization across various contexts from past to present. The research is evaluated based on the steps of "Identification, Screening, Eligibility, and Inclusion/Exclusion" as well as "Data Analysis."

The search string was specifically designed to focus on the reuse/valorization of mine waste and management methods in the mining industry, guiding the selection of relevant keywords. The search was initiated using the following keywords: "mine waste / mine tailings / tailings" & "reuse / valorization", "flotation", and "metal recovery." Additionally, terms commonly associated with the flotation process of mine waste in the mining context were included, such as "mine waste / mine tailings / tailings" & "management / sustainability / disposal / impact / regulations. " Further, searches were expanded to include "mine waste / mine tailings / tailings" & "cemented paste backfill, cemented mine fill, backfill" and "mine waste / mine tailings / tailings" & "geopolymer / reuse / valorization" OR "ceramic reuse / valorization" OR "brick reuse / valorization" OR "supplementary cementitious materials / SCM reuse / valorization" OR "chemical / thermal / mechanical treatment reuse / valorization."

The search was conducted across five bibliographic databases—ScienceDirect, Taylor & Francis, Springer, Wiley, and ACS Publications—focusing on the title, abstract, introduction, and Sects. "Environmental and Socioeconomic Impacts of Mining Waste Mismanagement"–"Legal Regulations and Future Trends of Mine Tailings" of the documents. A summary of the methodological approach followed in this study is detailed in Fig. 2.

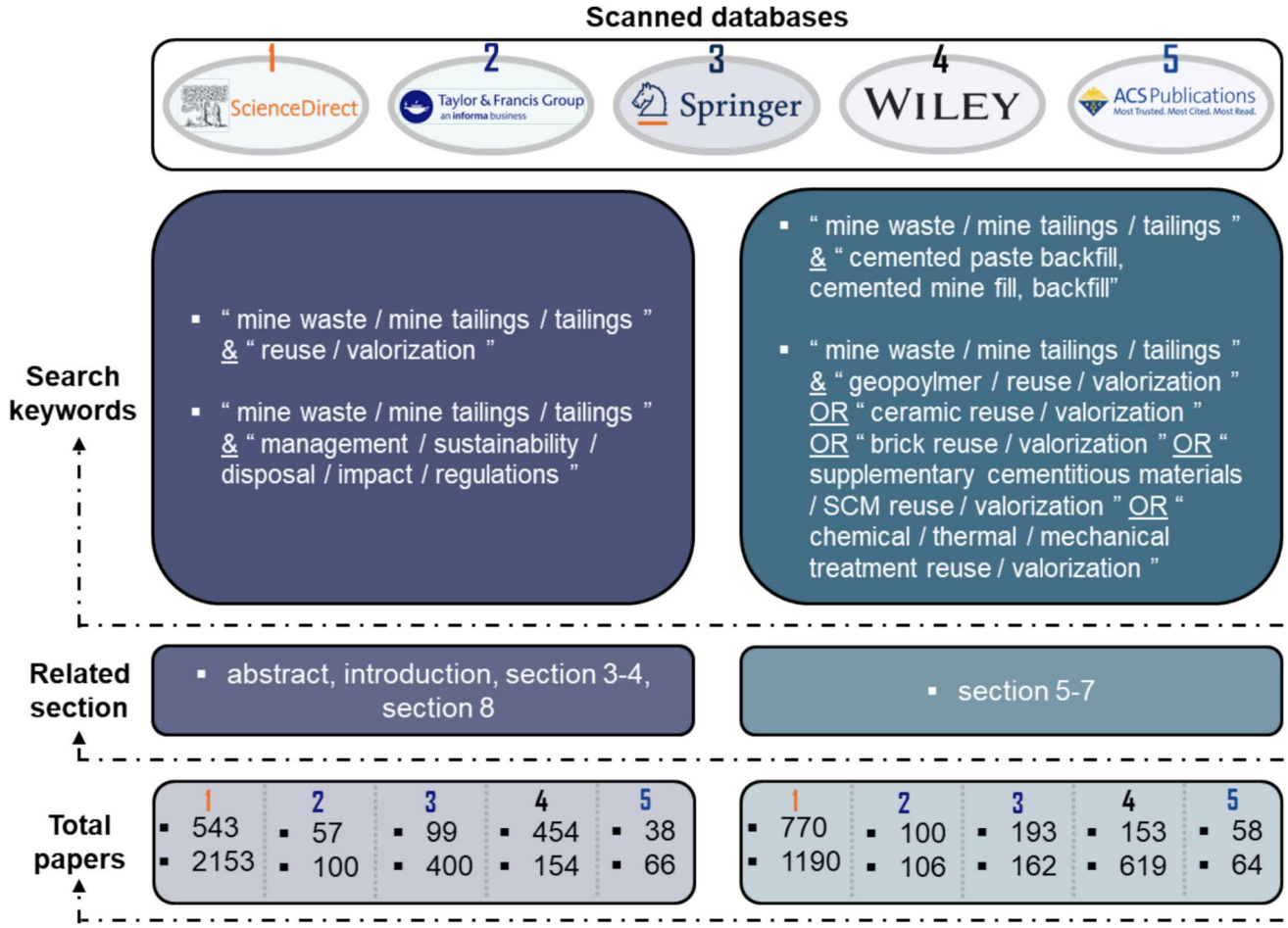


Fig. 2 Global search query for information on mining waste/tailings

Environmental and socioeconomic impacts of mining waste mismanagement

The depletion of rich mineral ores in underground and surface mining and the resulting decrease in grade will cause large amounts of waste to be generated in mining areas. In fact, legal, economic, socio-cultural, geotechnical and environmental restrictions or problems to be encountered during the disposal of these wastes will cause great difficulties (Fig. 3). In addition, improper disposal of wastes can cause many environmental perils like air/water contamination, dust enlistment, stagnant waters, soil pollution, damaged facilities, faunae and society (Fig. 4).

In traditional mining waste disposal methods, irreversible environmental problems such as dam collapse, acidic water formation and soil pollution are often encountered (Phillips 2012). Despite many precautions taken during construction or service life, accidents can still occur. Sulfur-rich wastes are often stored in these dams, and in the event of a dam collapse, these wastes will cause acidic and leaching formation, seriously contaminating the environment (Saedi et al. 2023). In many parts of the world, such accidents have occurred in areas where waste is disposed of by traditional methods, and as a result of these accidents, many lives and property have been lost (Marais et al. 2024). Figure 5 presents dam collapse records that have occurred around the world.

Worldwide, there have been nearly 3000 deaths from tailings dams since 2010 and this number is increasing exponentially. In 2008, a tailings dam collapse in China (Shanxi province—Fig. 6a) caused hundreds of deaths (Wu 2020). The collapse of a tailings dam in Romania (Baia Mare city) released significant quantities of cyanide into the environment, significantly contaminating surface/underground water sources and killing many animals (Bird et al. 2008). In the United States/US (Kingston Fossil Power Plant in Tennessee—Fig. 6b), a coal ash dam failure in 2008 contaminated 300 hectares of fertile land. Cleanup of the pollution caused by these tailings required 6 years and caused 1.2 billion dollars in eco-nomic losses to the government (US Epa and Tennessee Valley Authority 2014). In 2009, a dam storage of gold tailings in Russia (Magadan region) collapsed, damaging about 25 houses in the vicinity. Two people were killed,



Fig. 3 Sustainable management issues of mine tailings

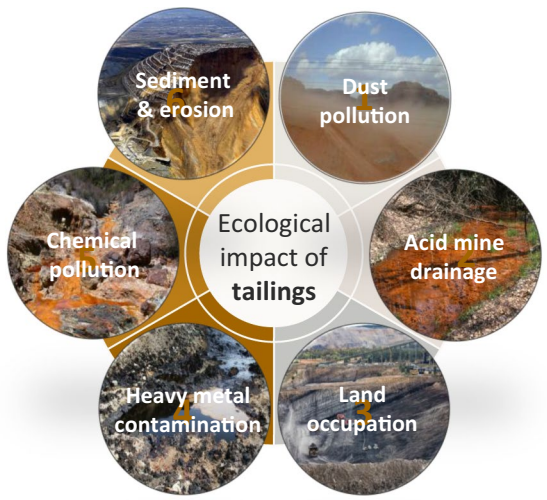


Fig. 4 Ecological impacts resulting from improper management of mine tailings

and the tailings caused significant environmental problems (Glotov et al. 2018). In 2010, an accident at a tailings dam in Hungary (Ajka alumina plant—Fig. 6c) released about 1 million tons of tailings into the environment and killed 2 people. The government spent 103.4 million dollars to address the environmental impact of these wastes (Mayes et al. 2016). A dam accident at Mount Pulley Mine (British Columbia, Canada—Fig. 6d) released 10 million m^3 of water and 4.5 million m^3 of toxic waste into the environment (Adewuyi et al. 2024). In 2012, a dam failure in the Philippines released 13 million m^3 of tailings slurry into the environment (Islam and Murakami 2021).

Apart from the disasters mentioned above, many tailings dam accidents have occurred and continue to occur in different countries around the world. Many sociological, environmental and economic problems are caused by the impact of dam failures where different types of tailings (e.g. silica, nickel, gold-silver, tungsten, red mud, uranium, lead–zinc, copper-zinc, copper, gold and iron) are managed. To eliminate such issues and dispose of waste more sustainably, many entities such as governments, mining companies, regulators and non-governmental organizations have become more interested in waste management by focusing on new technologies and existing practices (Piciullo et al. 2022b). However, today, waste management practices need to be improved, and more sustainable methods need to be adopted for a green environment and the wellbeing of future generations.

Management of mine wastes

Orthodox ways

While the mining sector directly donates to nationals' development, it also roots the formation of huge amounts

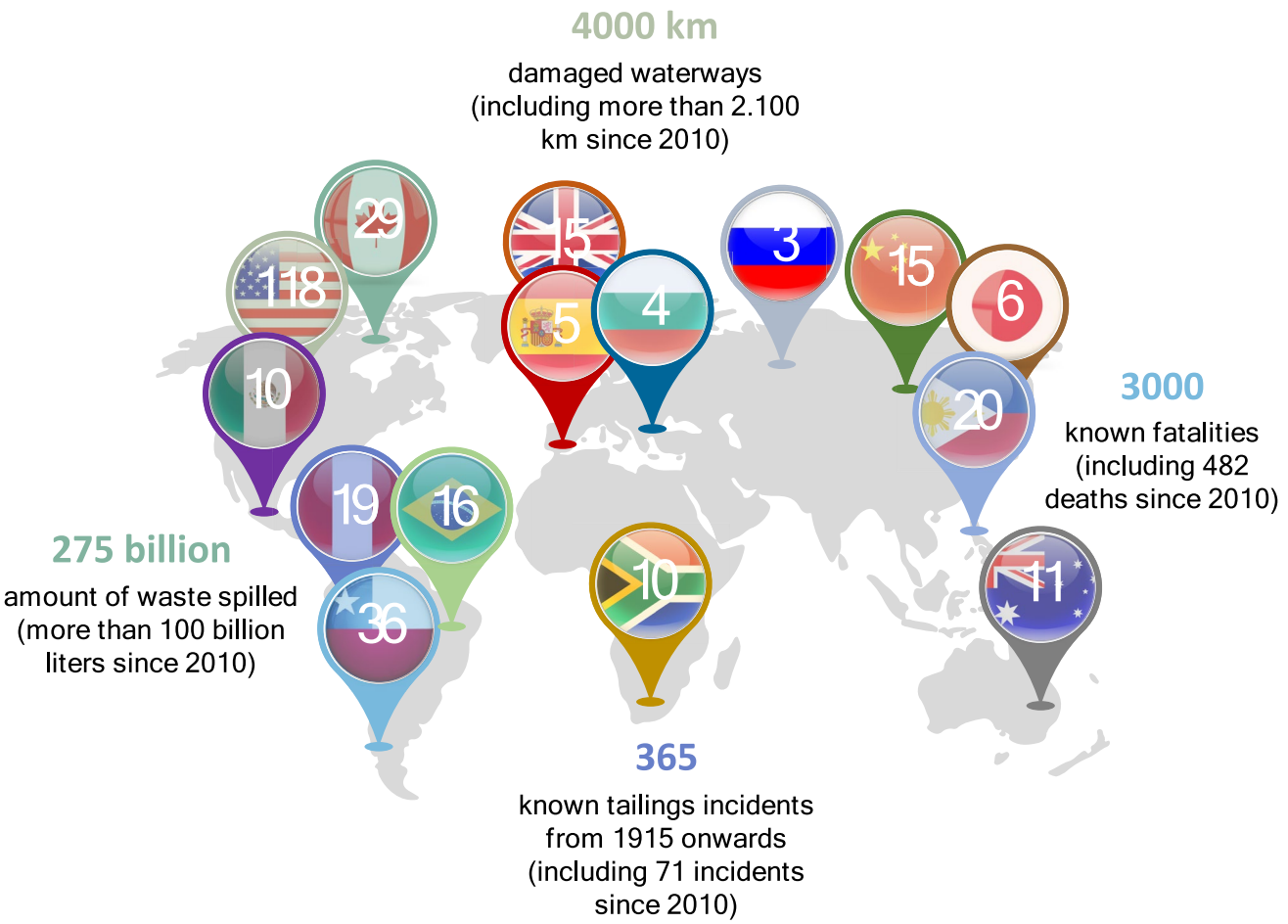


Fig. 5 Amount of waste dam catastrophes worldwide from 1915 to 2020

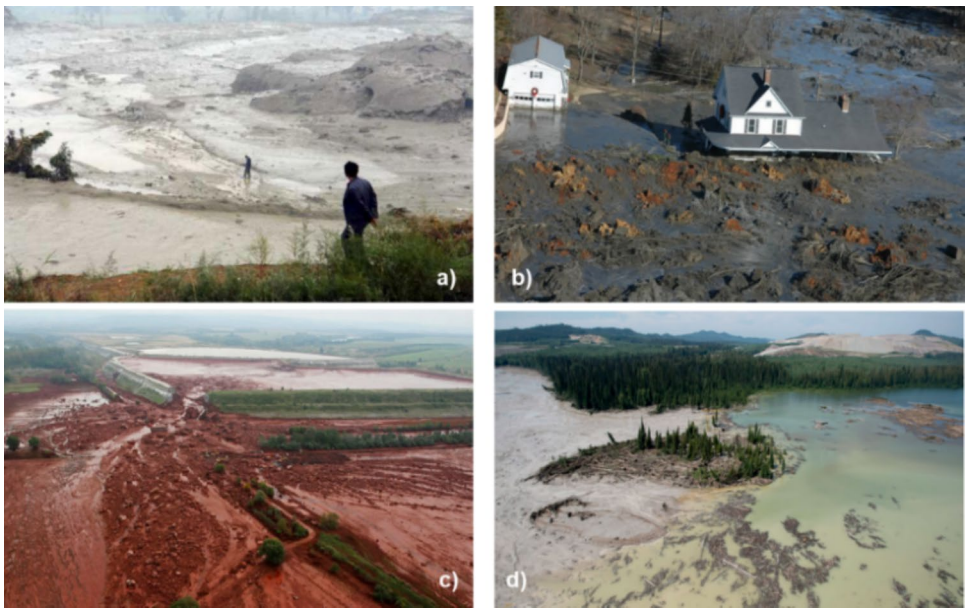


Fig. 6 Tailings dam accidents in China (**a**), the United States (**b**), Hungary (**c**), and Canada (**d**)

of unwelcome waste that is difficult to dispose of. This situation will endure to rise in days to come as the mines go deeper and the ore grade will decrease significantly. These decreases in grade will show their effect on the waste-concentrate ratios and more waste will be formed with less concentration. These wastes, which can cause toxicity due to the minerals they contain, should be disposed of appropriately with reduction, recovery and reprocessing processes at the source (Das et al. 2023). Waste is managed in various ways reliant on their physical–chemical structure, blasting, topography, climatic conditions, environmental restrictions and socio-economic conditions at the mining site (Zou et al. 2024). Tailings are usually disposed of in two ways, either underwater (Yilmaz 2024) or in above-ground tailings dams.

Underwater storage is the simplest method of waste disposal and is carried out by transporting and discharging waste into a river, lake or sea with a pipe. It is a system that is considered mandatory for mining sites where topography is not suitable, where there are climatic restrictions and where storage is close to a wet area, and it is a certain fact that it causes irreversible damage in terms of environment. It is an undeniable fact that underwater waste storage presents a unique alternative when appropriate techniques are followed. Waste is disposed of in surface tailings dams using a pipeline with a solids content of 25–30%. This system, which is suitable for regions where precipitation is low compared to evaporation, is still widely used in many countries. Figure 7 shows the settlement and tailings dam of a mining company operating in Türkiye.

Modernist ways

Considering the legal/environmental requirements faced to reach primary resources and the incentives for the source of industrial raw resources from secondary sources, alternative innovative waste utilization techniques have become a necessity (Adrianto and Pfister 2022). Moreover, by rising in environmental perception and situational consciousness of societies, a more effective management of waste has emerged, and wastes that were previously considered worthless are being evaluated as a prospective raw substantial source through emerging techniques and methodical works (Cheng et al. 2023). Valuable critical metals in wastes can be re-evaluated and significant contributions are made to the economy of mines. Limited fossil energies and decreases in ore grades root concerns and increase the need for industrial raw materials. This need can be met by the circular economy by supplying waste from secondary sources (Yu et al. 2024). Figure 8 shows various waste disposal strategies within the concept of the circular economy.

Re-evaluating waste as raw material in different sectors will significantly reduce environmental problems. Such a circular economy process can raise resource efficiency and allow for the creation of diverse business sectors (Ma et al. 2024). From now on, processing wastes that are considered worthless with various inventive applications and turning them into valuable products will be a crossroads for the mining sector. It is common for wastes to be considered as a unique basis of raw resources, especially in construction sector as a cement substitute, as well as in sectors such as agriculture, energy, chemistry and the environment, and technological advances are being made for this purpose (Fig. 9).

Reprocessing waste as a raw material source will prevent the opening of new mines, thus paving the way for the allocation of resources to be used in these areas to innovative technologies in different sectors (Adrianto et al. 2023). Application of these advanced waste management techniques will open important doors to the increase in the local economy of the region and the welfare levels of countries and will increase the use of capacity.

The diverse characteristics of metal mine waste allow for a range of applications and uses. For instance, waste from iron, copper, zinc, and gold mining can be used for various products, including bricks, tiles, and lightweight aggregates (Pappu et al. 2007). Copper waste can be successfully used as a substitute for granite in road and highway pavement concretes, as well as in brick production (Oluwasola et al. 2015). Copper slag finds applications in manufacturing roof tiles, mine filling materials, and granular materials (Silva et al. 2014). Iron ore tailings, characterized by their fine granulation and high content of silica, iron oxides, alumina, and other minor minerals, are particularly suited for use in the construction industry (Li et al. 2024a). Tailings can be utilized effectively to produce paving and masonry blocks (Shewalul 2021). Additionally, manganese-rich tailings have applications in agroforestry, building materials, and coatings, while bauxite tailings are valuable as sources of alum (Lottermoser 2011).

Recycling and reuse perspective

Current societal progress relies on mineral resources and on restricted fossil fuels. The energy need that arises with the increasing population causes an increased need for raw materials in every sector. To meet these needs, it is important to re-evaluate waste and use it as a raw material and reintroduce it to the economy (Fig. 10). In recent years, technological advancements and the growing demand for sustainable energy sources have significantly increased the need for raw materials. Industries ranging from electronics to renewable energy systems require further raw materials for their production processes. This surge in demand necessitates more efficient and effective management of raw materials and has heightened interest in recycling and reuse practices. As in other sectors, the increasing need for



Fig. 7 A Turkish copper mine: **a** tailings dam, **b** slope and **c** facilities

raw materials in the mining division has become a weighty problem in production and industrial processes worldwide. To meet this demand, mining activities are being expanded and new resources are being sought. However, these processes cause the accumulation of mining waste and can create environmental impacts. Since mining waste usually contains high amounts of minerals, it can cause environmental pollution if not managed correctly. The storage of mining waste is an important management issue in the mining industry. These wastes can usually be in large quantities and in various components, which requires appropriate storage methods. Waste is usually stored in open-air storage areas or specially designed dams.

During the storage process, precautions such as sealing, and water management are taken to prevent the waste from harming the environment. However, seeing long-standing effects and environmental risks, the effectiveness of these methods should be continuously evaluated. Tail's recycling/

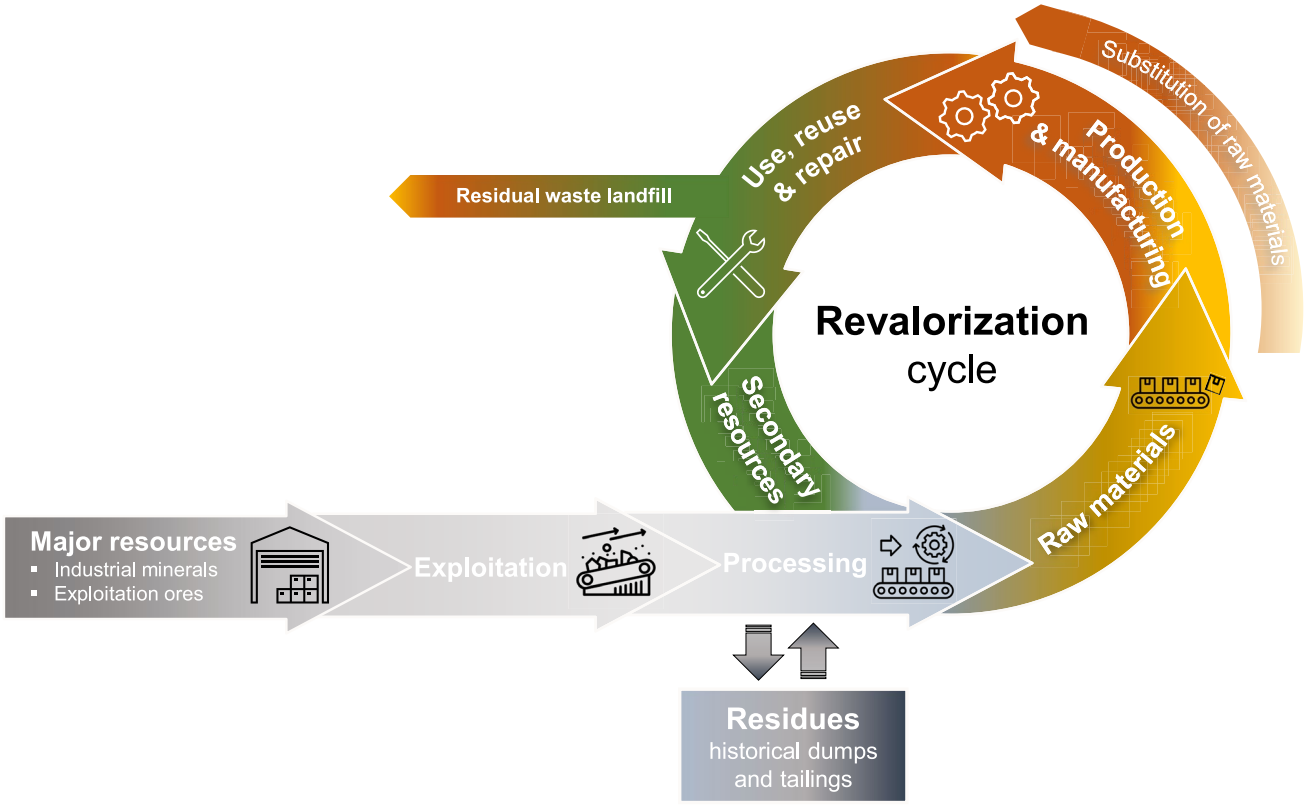


Fig. 8 Sustainable and green management of mine tailings in revalorization cycle framework

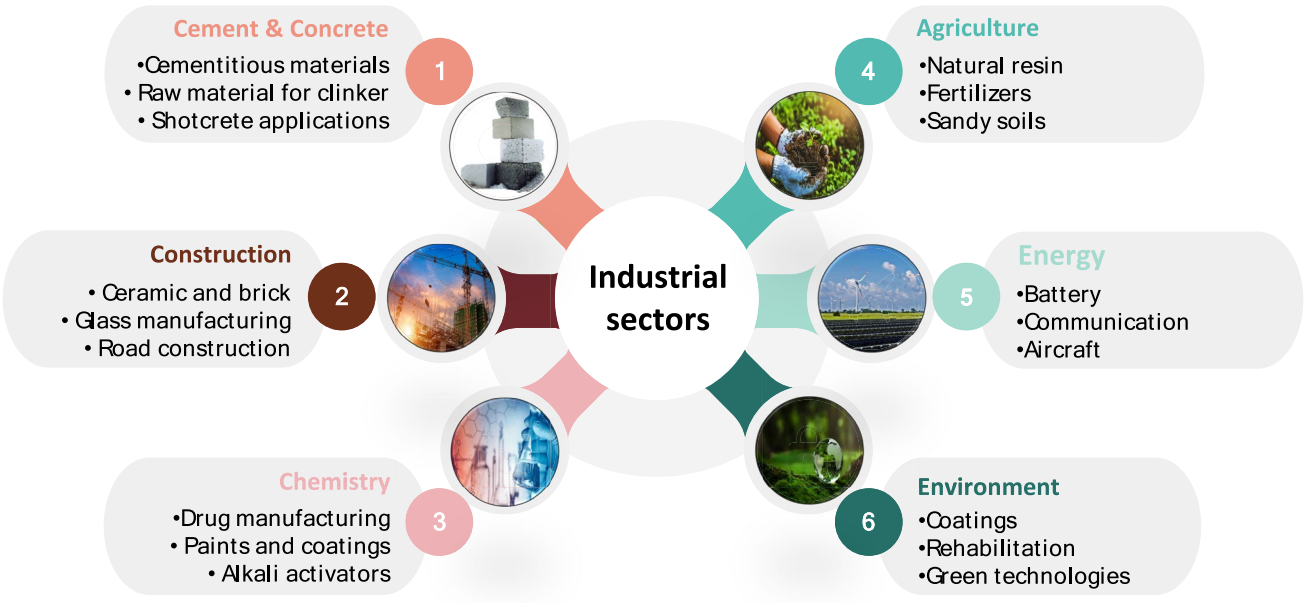


Fig. 9 Usage of waste as raw resources in various divisions

reuse is also of critical importance in terms of sustainable resource management and environmental protection. The waste generated during mining operations contain large amounts of minerals and other substances. Recycling these wastes is pronounced prominence about reducing environmental impacts and protecting natural resources. Raw

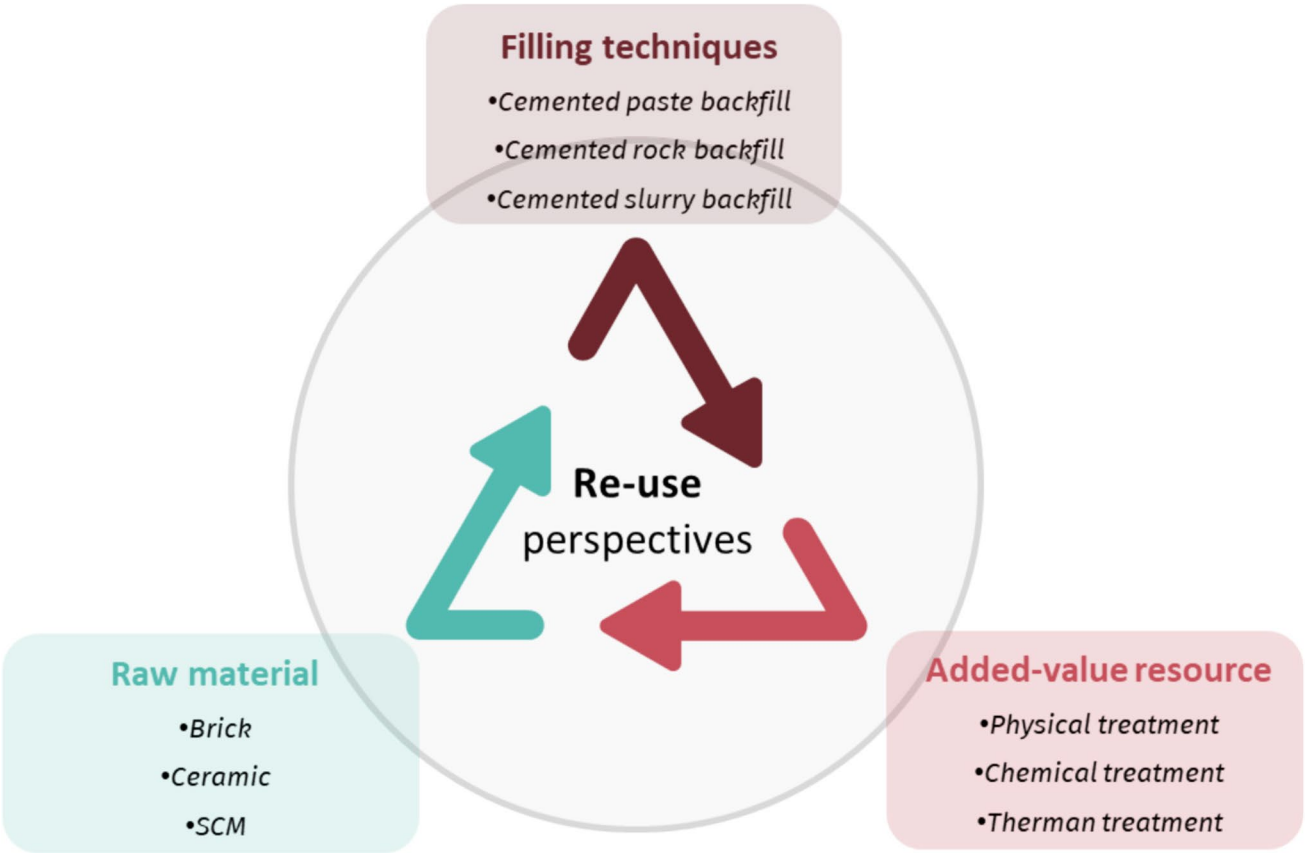


Fig. 10 Innovative and efficient utilization of mine tailings

material recycling enables the processing of waste into reusable materials. For example, mining waste can be used to recover valuable metals and minerals through various processes. These processes both provide economic benefits and minimize environmental pollution.

Cemented paste backfill

CPB, as shown in Fig. 11, is an engineered material employed to stabilize wastes, with a solid content of 70–85%, formed by mixing wastes with cement and water (Jiang et al. 2024). It is usually prepared at surface paste plant and is delivered to underground stopes using pipelines (Creber et al. 2017).

The fluidity of CPB is critical to its transportability; this is necessary for pumpability and the efficiency of the placement processes (Kasap et al. 2022a). The slump test, performed according to ASTM C143 standards, is used to evaluate fill's fluidity properties (Fig. 12). This test determines how fluid the mixture is and helps prevent problems such as pipe blockages. Low fluidity can lead to pipe blockages, high repair costs, and production delays. The fresh fill's rheological features are affected by internal factors like mix density, its components, and pH (Jiang et al. 2025). The exterior issues like heat and time-dependent changes also play a role in fill's rheological performance by affecting the hydration of cementing products. During pipeline transportation, temperature can accelerate cement hydration, which can change the viscosity and fluidity of the paste (Guner et al. 2023). Depth, transportation distance, and environmental temperature changes also play a role in this process. For example, in deep mines or in hot climates, the temperature of the CPB can increase, which can affect trans-portability. Geographic location and seasonal changes can also affect the temperature of the CPB and therefore its fluidity. Understanding heat/time impacts on fill's rheology is critical to ensuring an efficient and cost-effective transportation process. Accurate modeling of rheological properties optimizes the fluidity of the CPB and reduces the risk of pipe blockages. This increases the efficiency of mining operations and reduces costs.

In addition to rheological properties, another factor affecting fluidity is the particle size distribution. Particle size distribution plays an important role in determining the flowability of a mixture. A well-graded particle size distribution generally increases flow-ability. Fine particles

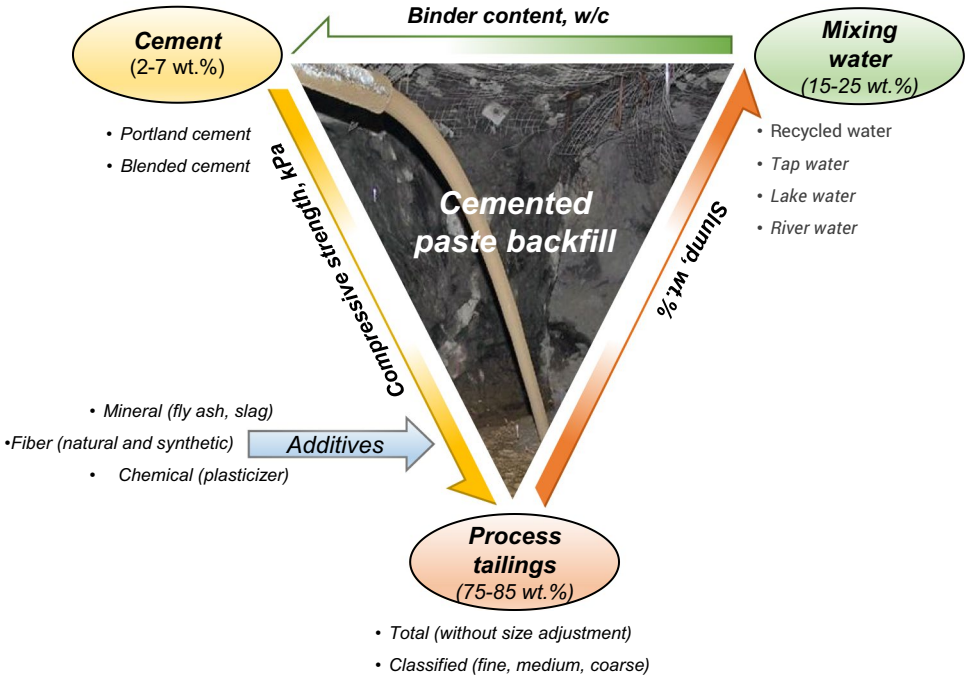


Fig. 11 Main components of CPB enhanced with additives

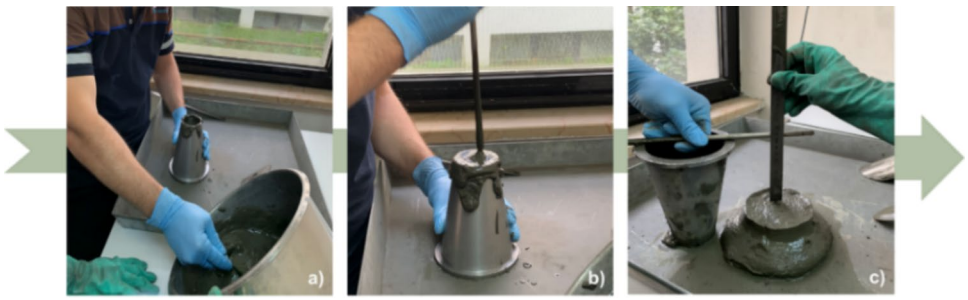


Fig. 12 CPB's mini-slump measurement procedure: **a** filling, **b** tamping and **c** measuring

fill the voids between coarse particles, reducing the overall flow resistance. However, a narrow particle size distribution can cause the material to not compact well or to form bridges during flow, which can lead to poor flow characteristics. To obtain the desired fluidity properties of CPB, the fineness of the waste material in the mixture must be carefully controlled. Optimal waste fineness is necessary both to provide adequate fluidity and to maintain the homogeneity of the mixture (He et al. 2024). Tailings with optimum particle size allow CBP to be easily transported through pipelines and to be placed effectively in underground voids. There are various methods to examine the particle size distribution of CPB wastes. One of these is laser diffraction. In this method, the CPB sample is exposed to laser light and the scattering pattern of light by the particles is analyzed. Data obtained by laser diffraction is processed by computer software to create a grain size distribution curve. As a result, the distribution of grains of different sizes in CPB is shown on a graph with the data obtained from the analyses. Figure 13 displays graduation graphs of mining waste employed within CPB production.

CPB preparation and above ground operations

CPBs are obtained by mixing ore wastes, binders, additives (chemical/mineral) and water. Additional materials such as fiber additives, sand or fiber can be added to the mixtures in appropriate proportions to increase the durability of the waste fill (Li et al. 2024b; Kasap et al. 2023; Yilmaz et al. 2010; Sari et al. 2023a). The mineral structure and grain size of the wastes, which establish a weighty portion of filling, play a critical role in the water retention capacity and final stability of the fill. Addition of sand positively affects the strength of the fill by increasing the density and w/b ratio of the fill. While OPC is generally practiced as an ideal binder in fill composition, products like slag and silica fume might also be preferred to reduce costs (Benzaazoua et al. 2006; Kasap et al. 2022b). The mixing water used in production

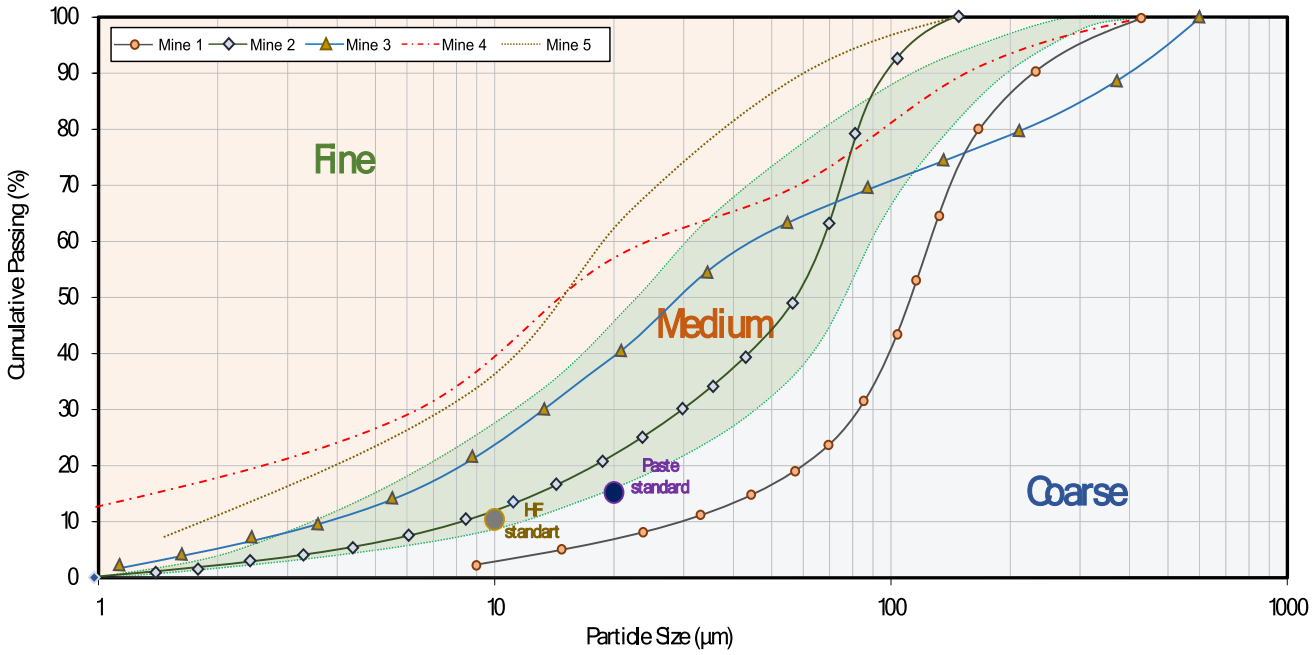


Fig. 13 Usual gradation curves of various mine tailings

can be selected as lake or tap water in different pH ranges so as not to impair the strength properties of the fill. The CPB flow chart showing all aboveground production stages is given in Fig. 14.

In the production of CPB, dewatering of waste is vital. Various dewatering methods such as deep cone thickeners, cyclones and disc filters are used. Among them, the use of deep cone thickeners allows to avoid increased operating costs. Dewatering process is carried out using selected equipment. This process reduces the water content of waste and provides a denser fill material. This is necessary to increase the solid content of fill and to provide higher efficiency during transportation (Deng et al. 2024). The mixing process for CBPs is a critical step in fill production. Waste, binders and water are brought together for pre-mixing. Mixing process is usually carried out using nonstop screw mixers or other suitable mixing equipment. With the help of nonstop screw mixers, all components are thoroughly mixed to form a homogeneous mixture before being transported to underground cavities. Here, the consistency, fluidity and solid content of cement paste are adjusted until they reach the required properties. The amount of water used during mixing affects the cement's w/c rate and the fill's fluidity. This enables the fill to be transferred to underground stopes efficiently. Fill is transported underground using gravity-driven systems or positive dis-placement pumps. The transport systems cover pipelines and other delivery equipment. Considerations during transport include pressure and friction losses in the pipeline. The transported cement paste is placed in underground voids or stops (Fig. 14). This stage ensures that fill is evenly distributed and compacted. At the end of the production shift, the pipeline is cleaned using compressed air and water. If the cleaning process is not carried out, paste accumulates in the pipelines and productivity decreases. This can lead to pipeline blockages and production delays.

CPB stope placement and underground operations

After the ore is extracted, steel reinforced concrete barricades are constructed along the lower section to prepare the stopes, limit the areas where fill will be placed and ensure that the fill remains in the right places. These barricades, consisting of a plywood wooden frame, embedded reinforcement ribs and sprayed concrete, prevent the cement paste from overflowing and spreading into unnecessary voids. It is placed in empty stopes by the top accumulation method with the help of a CPB pipeline. Fill applications are usually carried out in two layers in stopes. Initially, the first layer of fill, 7-m high and usually with a cement content of 5–7%, is poured into the stope. This fill is left to cure to prevent excessive loads on the barricades (Sari et al. 2023b). After the curing process of the first fill is completed, the cement ratio is reduced to 2–5% and the remaining fill is added up to a height of approximately 30 m. This layered placement method ensures that the fill forms a more solid and stable structure. The placement speed of the fill, pump pressure and fill flow are continuously monitored, and adjustments are made when necessary. CPB hardens over time, filling the mine voids and supporting the nearby rock mass. This

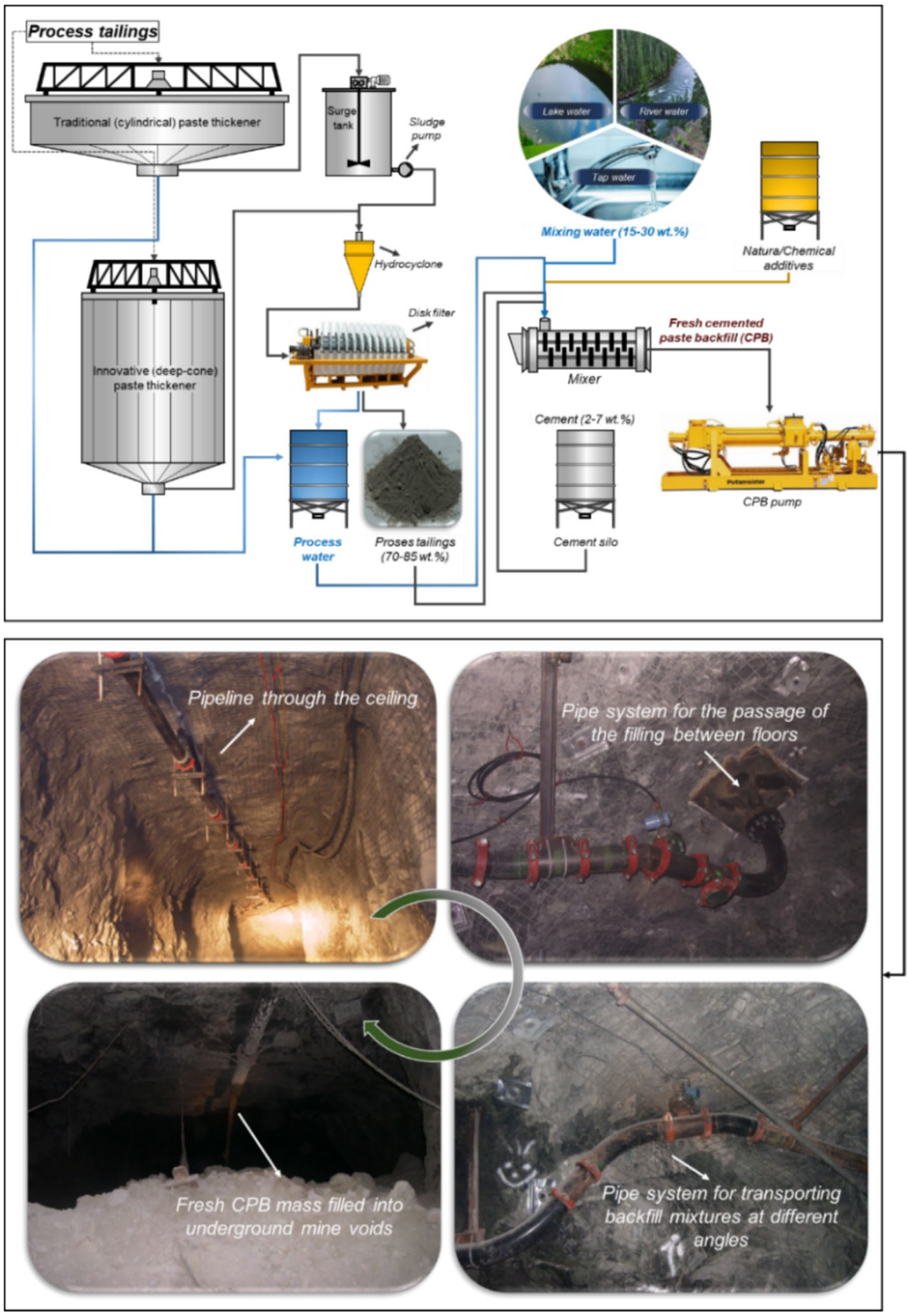


Fig. 14 Flowsheet of a typical paste plant and underground pipeline transmission of CPBs

is where the cement hydration process comes into play, which gives the backfill strength. The hardening process can vary depending on the temperature, humidity and other environmental conditions underground. Once hardened, fill increases the structural integrity of the mine and provides a safe working environment. Fill operations require coordination and collaboration between mining professionals and other stakeholders, and a fill management plan should be developed for this purpose. This plan helps develop a common understanding of all aspects of the fill operation and ensures the smooth running of the operation.

Potential for reuse of mine tailings

In general, reuse of tailings can be defined as their reuse for a precise drive with no treatment. It agrees mining tailings to be evaluated as potential secondary metal resources, especially thanks to the various elements they contain, and at the same time, they provide an input in production by meeting the raw material needs of various sectors. With this process, tailings are added to the economy, while environmental risks are reduced. Tailings have various oxides and play an effective role in widely used applications like bind-er, aggregate, geo-polymer, ceramics and complementary cement material thanks to these oxidized compounds they contain. Therefore, tailings are considered a potential resource, especially for the construction industry, and this has made the reuse of mine tailings attractive in recent years.

Geo-polymer production

Mine wastes are among the potential materials that can be evaluated in the production of geopolymers through alkali activation. Activation conditions are a determining factor on the mechanical and chemical performance of geopolymers. The type of alkali activator used in the activation process (Kucharczyková et al. 2024; Zhao et al. 2023; Sasui et al. 2023; Shi et al. 2024; Liu et al. 2024a; Król et al. 2018) and its concentration (Khaled and Soliman 2025; Turkoglu et al. 2023; Chen et al. 2021; Singh et al. 2022; Chi 2012) are important factors affecting the properties of the geopolymer. In addition, the modulus ratio (Ling et al. 2024; Luo et al. 2023; Chi 2015; Sun et al. 2025; Liu et al. 2024b), pozzolan composition (Arachchige et al. 2024; Ibrahim et al. 2017; Najimi et al. 2018; Bondar et al. 2011; Najimi and Ghafoori 2019), initial pH of the activator solution (Yang et al. 2024; Zhang et al. 2022; Xing and Wang 2024; Shen et al. 2022) and curing conditions (Zhang et al. 2025, 2023; Liu et al. 2024c; Correia et al. 2019; Athira et al. 2021) are also factors affecting the material and hydration properties. The basic structure of geopolymers consists of 3D Si-O-Si and Al-O-Si structures similar to polymers. These complex structures are generally formed by the response of aluminosilicate-based minerals like silica fume and slag by intense alkali hydroxide/silicate salt solutions (Zhang et al. 2020). If material is rich enough in terms of alkaline solution, Al and Si, geo-polymerization begins as a result of making of $Si(OH)_4$ or $Al(OH)_4$ oligomers. This process continues until metal–oxygen links (Si-O-Si, Al-O-Si), which form basic structure of geopolymer, condense. In addition, because of the reactions (alkali activation), cementation gels like C-S-H or C-A-S-H may form (Asadizadeh et al. 2024). Geopolymerization hinges on many bounds, most important of which are type/amount of activator, cure regimes and mineralogical structure of aluminosilicates. In addition, the silicon dioxide-aluminum oxide ratio, ambient temperature, pH value and solid–liquid ratio also affect the geopolymerization process (Castillo et al. 2021). These variables pave the way for the use of the materials produced after the geopolymerization processes in different areas (e.g. concrete, fire-resistant materials and hazardous waste containment).

Since they contain silica and aluminosilicate-based minerals, mining waste is measured as a potential material for geopolymer. Yet, unlike resources by pozzolanic features such as slag/silica fume, waste mineralogy has a more crystalline structure. This limits the tendency of tailings to enter chemical reactions. In addition, the reason for the low chemical reactivity of mining tailings is that they are generally produced by chemical procedures, unlike by-products produced at high temperatures. An example of this is the fact that silica mineral, an inert material with a regular crystal structure contained in mine tailings, has less reactivity with alkaline solutions. Therefore, for these tailings to be easily used in geopolymers, different pretreatments (heat treatment) or combinations by other aluminosilicates need to be evaluated. Some geopolymer applications using mine tailings are shown in Table 1.

The mechanical behavior of geopolymers derived from mine tailings is significantly influenced by the type of tailing material, the choice of activator, and the synthesis conditions employed during production. Due to these variables, the compressive strength, a key parameter for evaluating mechanical properties, can fluctuate widely, reaching values as high as several hundred MPa. This variability underscores the importance of optimizing each factor to achieve the desired strength and performance characteristics for specific applications (Mabroum et al. 2020). Many studies have been conducted on various mine tailings from past to present. Research has demonstrated that copper mine tailings, particularly when activated with sodium hydroxide (NaOH) and sodium silicate, are effective primary materials for geopolymer production (Ahmari et al. 2012). Studies reveal that compressive strength significantly increases with a 15MNaOH concentration at a curing temperature of 90 °C, producing a denser and more robust microstructure.

Table 1 Different requests of waste reinforced geopolymers

Applications	Geopolymer types
Binder materials	Iron tailings and fly ash based
Binder materials	Iron tailings and fly ash based
Binder materials	Phosphate tailings based
Lightweight aggregates	Slag and metakaolin and gold tailings based
Road base construction materials	Copper tailings based
Binder materials	Copper tailings and fly ash based
Fire-resistant materials	Silica-rich vanadium tails and fly ash based
Bricks	Copper tailings based
Bricks	Copper tails and cement kiln dust based
Bricks	Copper and gold tailings based

The addition of fly ash further enhances mechanical properties by forming a more compact structure and optimizing the Si/Al ratio, which is critical for stability and durability (Zhang et al. 2011). Other studies explored the effects of adding aluminum sludge, which allows for precise Si/Al ratio adjustments, achieving compressive strengths as high (Ren et al. 2015). Similar investigations with gold mine tailings have shown that NaOH and potassium-based activators yield good results, with optimal com-pressive strengths under specific curing and activator conditions (Caballero et al. 2014). Though some samples experienced reduced durability in acidic environments, those activated with NaOH at 170 °C displayed excellent performance, reaching up to 40 MPa in compressive strength by incorporating calcium hydroxide and aluminum oxide (Huang et al. 2020). These findings highlight the versatility, sustainability and robustness of mine tailings-based geopolymers for construction applications.

To create more sustainable geopolymers, incorporating iron mine tailing is a viable option, as it represents a significant source of solid tailing that contributes to environ-mental degradation. These untreated tailings not only occupy vast areas of land but also lead to the contamination of water resources and air quality. For this reason, the reuse of iron ore tailing for cement production has been investigated, offering a potential strategy to mitigate environmental impacts while increasing sustainability (Sharath et al. 2018). One promising method involves reusing iron mine tailing as a secondary resource, acting as precursors in the production of geopolymers (Nadia et al. 2023).

Using metal mine tailings in geopolymer production offers notable advantages, including effective waste management, resource efficiency, and reduced energy consumption. It helps mitigate environmental issues related to mine waste disposal and conserves natural resources. Additionally, some metal mine tailings can enhance the properties of geopolymers, such as strength and durability (He et al. 2022). However, there are limitations to this approach. The variability in tailings composition can affect the consistency of geopolymer quality, and contaminants in mine tailings pose health and environmental risks. In the evaluation of mine tailings as geopolymers, the high variability in chemical and mineralogical composition significantly affects the reaction kinetics, setting time and mechanical properties. Inappropriately formulated geopolymers may pose a risk of soil and water pollution through leachates containing heavy metals (lead, arsenic, mercury, etc.) and high pH alkaline solutions (NaOH, KOH) (Lazorenko et al. 2021; Ahmari and Zhang 2013a). In addition, the high demand for alkaline activators (sodium hydroxide, sodium silicate) in some types of wastes increases both production costs and reduces the environmental advantages of the geopolymer technology. Dust emissions generated during the process may lead to air pollution, and high energy requirements may increase the carbon footprint (Davidovits 2008). From a chemical perspective, the irritating effect of alkaline substances, the release of flammable gases such as hydrogen, the release of toxic components as a result of insufficient polymerization and the long-term risks of radioactive elements are other hazards that require attention. Variability in waste composition may affect the consistency of geopolymer quality, and pollutants in mining wastes pose health and environmental risks. Economic factors, including initial processing costs, and technical challenges related to mix design and performance optimization also need to be addressed (Qaidi et al. 2022). Overall, while utilizing tailings in geopolymers presents a promising opportunity, careful management and ongoing research are essential to overcoming these challenges.

Ceramic production

Ceramics (functional-polycrystalline) produced using powder raw materials with traditional methods require high temperature processes such as sintering and hot isostatic pressing to both require diffusion from the solid and be sufficient in terms of strength (Lange 1989). In addition, ceramics attract attention with their ability to withstand difficult conditions such as extreme temperatures and pH values common

in industrial processes (Adam et al. 2020). This resistance is due to the natural properties of covalent/ionic bonds in ceramic materials; these bonds reduce the interaction of the material with its environment by keeping electrons in their low-energy positions. Chemically attached tiles refer to a set of inorganic products which have common features by cement and traditional ceramics. Such ceramics deal a possible substitute ceramic process method that can be formed at ambient heat and in the incidence of mineral layers without the need for high-temperature processes (Marabini et al. 1998). Ceramics produced in this way have a complex mineralogical structure and the strength of the product is partly due to the presence of insoluble minerals. In short, while soluble phases form the binding agent, unsolvable minerals serve as fill in the complex edifice.

Compared to traditional methods, nowadays the utilization of different types of wastes in the ceramic industry is becoming increasingly prevalent. Especially the utilization of (non-toxic) mining wastes in ceramic production has recently become a popular topic due to its benefits (Romero et al. 2021). Sustainable management of mine tailings requires the use of innovative technologies to minimize the environmental and sociological impacts of tailings disposal. The minerals, metals and metalloids contained in mine tailings, which are considered as inert, allow them to be used as a source of raw materials for products such as ceramics. This allows the production volume of tailings to be controlled, and environmental problems caused by landfill to be reduced. Clays, the traditional base material for ceramics, have a high content of hydrated components based on SiO_2 and Al_2O_3, making it easy to replace other materials in ceramic production due to its favorable particle size and shape (Baowei et al. 2013; Shao et al. 2005). The grain size of the materials used in ceramic production has an impact on many properties (such as sintering, density, porosity and plasticity) (Saif et al. 2024). Therefore, preferring relatively smaller grain size tailings and materials with similar chemical properties to clay offers a viable alternative in ceramic production. Products such as ceramic floor/wall tiles are among the examples where industrial waste can be used in ceramic production. Moreover, tailings can significantly increase the strength and durability of materials such as ceramics due to the valuable minerals they contain (Kinnunen et al. 2018). However, challenges include variability in waste composition, which can affect product consistency, and the need to manage hazardous contaminants (Drif et al. 2021). Technical adjustments and eco-nomic considerations are also necessary to effectively integrate waste into ceramic pro-duction.

Several studies in literature have made significant progress in revealing the potential of using mine tailings as secondary raw materials in the ceramic industry (Lemougna et al. 2019; Liu et al. 2017; Wei et al. 2024). Especially the use of chemically bonded ceramics containing mineral tailings and sulfate-containing tailings such as gold (Au) and copper (Cu) in the production of glass ceramics is widely spread (Jiang et al. 2023; Ye et al. 2015). Besides, the potential of using mine tailings as a raw material source for mullite-containing ceramics has attracted attention in certain researches. Mullite is widely used in the production of ceramic materials such as high temperature resistant protective coating and refractory bricks. Particularly quartz and feldspar-containing mine tailings have high potential for use in the production of high-temperature resistant mullite ceramics. Also, mineral-rich mine tailings like magnesite have been used as a source of magnesium in ceramic applications for different purposes (e.g., high-temperature electrical insulation) (Karhu et al. 2019, 2020).

Brick production

Brick, which has been an indispensable material in the construction/building sector for thousands of years, is constantly being used more and more with the increasing population and construction. This causes the raw materials used in brick production to de-crease continuously and rapidly. To attain viable progress goals, studies conducted by researchers have focused on finding alternatives to brick raw materials (Sarani et al. 2023). As a result of this search, it has been revealed that mining tails might be employed as a potential raw product within brick production in addition to examples such as cement-based composites and geopolymers thanks to the various compounds it contains (Zhang et al. 2017). Among the natural binders used to bind materials together and achieve sufficient strength in brick production, clay and schist stand out because they have strong binding properties in meeting the strength requirements. These materials form the brick raw material and should be processed by baking at high temperatures between 800 and 1000 °C. Mine tailings containing aluminum and silicon oxide can replace clay in brick production with geopolymerization method (Ahmari and Zhang 2013b).

Although many researchers propose different approaches in brick production, this production from tailings generally follows certain stages. First, mine tailings is ground or crushed into powder, then subjected to sieving. After this process, the tailings are blended by water and various activators to make it homogeneous, thus obtaining brick mud. After shaping, drying (at 100 °C) for one day and baking (at < 1000 °C), the brick reaches its final form. Various examinations such as compressive strength are applied to appraise produced brick's quality. Figure 15 demonstrates the detailed production process of geopolymer bricks. Research shows that bricks produced from mine tailings are more advantageous in economic/environmental terms than baked clay bricks manufactured by traditional methods

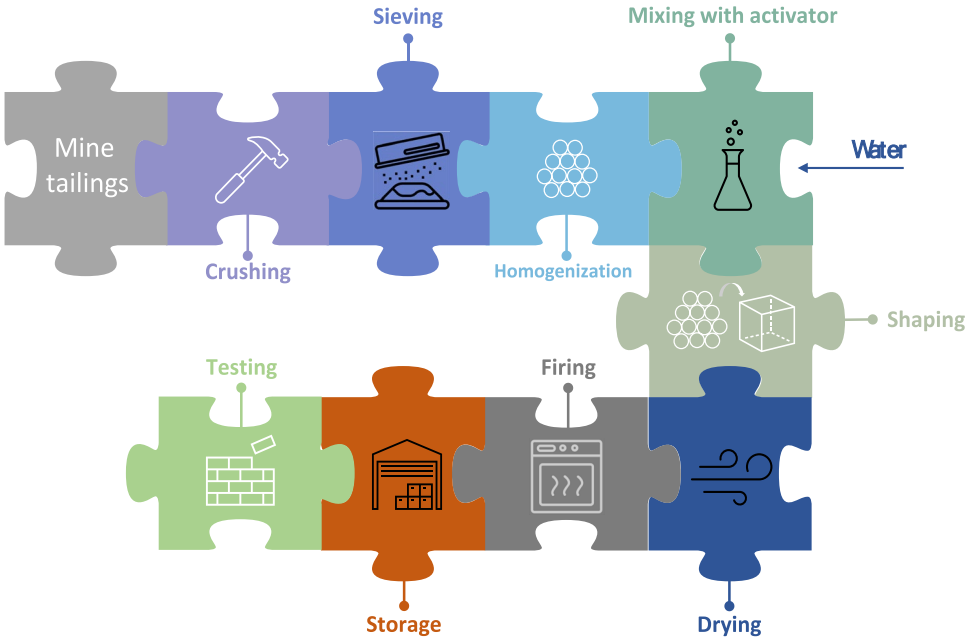


Fig. 15 Flow chart of brick making with mine tailings

(Nikvar-Hassani et al. 2022). Many researchers have conducted numerous studies on the use of different types of mining waste in brick production. Although the idea of using mining tailings in brick production is not new, this practice has evolved significantly as environmental concerns and sustainability issues have become prominent in industrial processes (Simão et al. 2022).

Past studies in this field have provided a basis for more sophisticated and sustainable approaches developed today. Many studies have examined the technical properties of bricks produced using mining tailing. Boron mining tailing has been used instead of both clay, which is the basic raw material for brick production, and boron compounds used as plasticizers. This use has not only alleviated the environmental problems associated with mining by-products but has also increased the overall quality of red bricks. In addition, the use of these tailings has contributed to cost savings by reducing the required temperatures in the firing process (Uslu and Arol 2004; Kavas 2006). Bricks consisting of 45% gold mine tailing and 55% red clay met the standards for compressive strength, linear shrinkage and water absorption and were 15% less costly than traditional bricks (Roy et al. 2007). Bricks made from 75% gold mine tailing and 25% clay reached MU10 compressive strength without problems such as lime burst (Yonggang et al. 2011). Hematite mine tailing, clay and fly ash mixtures were used to produce bricks that comply with Chinese regulations (Chen et al. 2011; Zhao et al. 2012). Gold-silver mine tailings were effectively used in the production of ceramic bricks and showed equivalent or better performance compared to conventional bricks (Li et al. 2022). In addition, bricks containing copper-nickel, apatite-nepheline and iron-enriched quartzite tailings were evaluated in terms of performance (Suvorova et al. 2017). Lightweight sintered bricks were produced by reusing zinc smelting slag for the recovery of metal tailings. This approach provided a viable alternative for recycling tailings and provided economic advantages (Hu et al. 2014). The use of tailings in brick production can offer the gains of low price and comprehensive performance, as well as reducing social and environmental damage (Wei et al. 2021; Liu et al. 2015). The reduction in tailing is the most obvious advantage, as tailing often contains hazardous substances that pollute soil and water resources. By using these tailings in brick production instead of storing them, mining firms can significantly reduce their environmental impact. In addition, the reduction in dependence on natural clay reserves helps preserve topsoil, which is vital for agriculture and biodiversity. The integration of mining tailing into brick production can contribute to the economy by creating a value chain based on tailing reuse. Looking ahead, the use of mining tailing in brick production is expected to increase as sustainability becomes a priority in both the construction and mining sectors.

Supplementary cementitious materials

Cement is a product that is frequently used in the construction/building sector and is a critical component of concrete, which is used in very large quantities worldwide. The production of cement used in different areas is growing gradually and it is predicted that this amount will rise to 4.83B tons m^3 by 2030. In addition, up to 8% of this production causes CO_2 emissions (Dandautiya and Singh 2019). Considering such disadvantages, the use of alternative

materials to cement in the production of different industrial products can offer some benefits both environmentally and economically. In this context, supplementary cementitious materials (SCM) can be partially or completely replaced with cement or can be used as raw materials in cement production. SCMs include mineralogical or chemical combinations other than aggregates, hydraulic binder and fiber reinforcement (Xu et al. 2022). The use of SCMs by mixing with Portland cement can greatly affect the structural, technical and economic properties of the product. Mineral-based SCMs can be physically, physically–chemically and chemically active, and examples of these are quartz sand, powdered quartz sand and silica fume, respectively. Additionally, granulated slag, pulverized fly ash and powder silica fume are good instances of SCM. They are obtained from the metal-based blends, iron/coal industries, and their reusing in the cement industry can cut CO2 emissions and lower product costs (Wang et al. 2024). The amorphous SiO_2, mineral size and pH level of these mate-rials play an important role in cement's hydration. Key function of SCMs is to form nuclei for pozzolanic reactions or growth of hydration products and to react with binders.

In terms of the minerals contained in mine tailings, SiO and Al_2O_3 can be given as examples. They have similarities with cement or derivative materials with pozzolanic features, which increases their usability in the cement industry and in the production of cementitious materials.

In recent years, significant progress has been made in understanding the pozzolanic and cementitious properties of mining wastes. Mining wastes, coal mine wastes, copper and iron mine wastes have been successfully used in cement production and provide significant benefits in terms of mechanical performance and durability (Shreekant et al. 2016). Incorporating copper mine tailings as a cement substitute in cement paste, mortar, and concrete presents a viable solution to address key challenges faced by both the construction and mining sectors. Existing studies have investigated this approach. Notably, substituting 15% of cement with copper mine tailings has been found to achieve optimal compressive and splitting tensile strengths in concrete (Marais et al. 2024; Esmaeili et al. 2020; Yin et al. 2018). Moreover, the addition of copper slag and copper mine tailings to concrete mixtures has been shown to reduce porosity, enhance resistance to chloride ions, improve compressive strength through pozzolanic reactions, and maintain workability (Yin et al. 2018). Several studies have assessed the use of iron tailings as supplementary cementitious materials (SCM) through mechanical and thermal activation. These tests indicate that the substitution of iron tailings for traditional materials only provides partial replacement, with the maximum additive content ranging from 10 to 30% by weight (Cheng et al. 2016; Yi et al. 2009; Han et al. 2017; Yao et al. 2024).

In another study, the impact of micro-active copper tailings on the strength and pore structure of cement mortar was examined, revealing that the compressive strength remained comparable to that of ordinary cement mortar when the tailings content was kept below 30% (Zhang et al. 2019). Regarding gold tailings, prior research has indicated their potential for effective use in the production of cement and concrete materials. One investigation focused on the mechanical activation of gold tailings and its effects on their pozzolanic activity and hydration properties when used as an additive in cement. The findings showed that the pozzolanic activity of these mechanically activated tailings increased progressively with longer milling times. Remarkably, the strength activity index (SAI) of mortars made with tailings cured for 28 days reached as high as 78.99% (Yao et al. 2019). Thanks to these studies, ecological anxieties linked to waste management are partially eliminated. However, the presence of sulfide minerals such as pyrite, especially in tailings, causes oxidation, which can cause unwanted reactions with cement's hydration and calcium hydroxide by-product released during this process (Kasap et al. 2022c). As a result of these negative reactions (sulfate attack), expanding secondary minerals such as gypsum and ettringite can be formed, and thus, defects in the structure of the material can occur.

The use of mining waste as SCM might cause the cement's hydraulic features to change during hydration or offer pozzolanic reactivity by hydrated binding agents such as portlandite. These materials can improve the performance of cement mixtures when they have both hydraulic and pozzolanic properties. In addition, some wastes (such as sodium silicate) may have activating properties and can be used directly as a cement replacement. The physical features of wastes are thoroughly associated to void ratio and grain size of the material. However, different crystal structures of the minerals may sometimes prevent the tailings from having direct cement properties. In this case, some pretreatment might be required to increase relevant hydraulic/pozzolanic features. Diverse treatment means (chemical/mechanical/thermal and/or hybrid of them) might be implemented to increase tails' functionality in reactions and thus the pozzolanic properties. Some methods and procedures used in the treatment of mine tailings are shown in Fig. 16. Among these methods, mechanical and thermal treatments are the most used. In fact, calcination of these tailings (1000 °C) or reduction of grain size by grinding processes are effective in increasing the cement properties of tailings (Perumal et al. 2019).

In addition, the mineral crystallography of mining tailings can be affected by thermal treatment processes and can transform into reactive complementary products and become amorphous. Examinations have revealed that strength performance of mining tailings is improved by up to 40% with

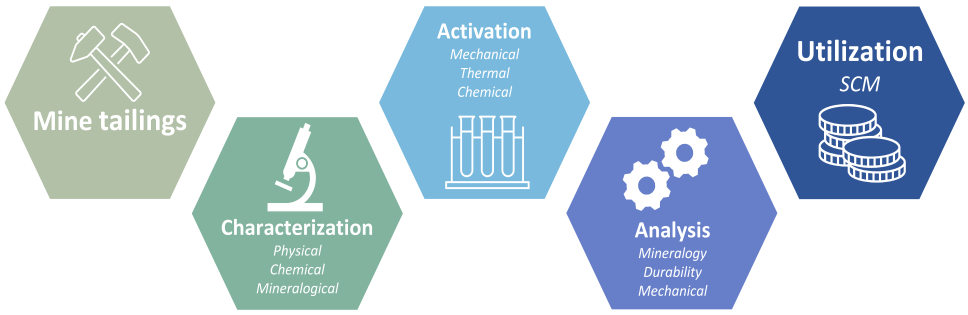


Fig. 16 Summary of the treatment steps followed by SCM

thermal/mechanical treatments (Saedi et al. 2023). The grinding treatment method causes high energy consumption for both mining tailings and other SCMs. To reduce this energy consumption and to implement a more economical/sustainable application, it can be suggested that tail grinding process be shared by cement clinker in plants. The high CaO, SiO_2 and Fe_2O_3 contents of mining tailings should not be ignored in replacing natural calcium, silicate and iron sources. The use of tailings as supplementary cementitious material contributes to the environment and economy by reducing current cement consumption and the huge carbon dioxide emissions caused by this consumption (Magalhaes et al. 2020). However, the changing chemical components of the tailings and the amount of these components limit the quality and performance of the produced SCMs (Simonsen et al. 2020).

Techniques for turning tailings into value added products

There are various strategies for the utilization (remediation) of mining tailings that can be used in different branches of industry. The processing of these tailings is often of critical importance and, as mentioned before, is usually chemical, mechanical, thermal or hybrid. Depending on the type of process applied, the properties of tailings (physico-chemical and mineralogical composition) can be changed. In rare cases, the separation of precious metal fragments may be the main purpose of the process. In the next section, detailed information on the treatment techniques used for mine tailings is given.

Chemical treatment

Chemical treatments are approaches that involve changing the chemical conditions of mining tailings that could not be used as a building material before to be evaluated in this field. One of these methods or approaches is undoubtedly geopolymers. The crystal structure of the minerals in mine tailings generally does not interact directly with silicon from silicate solutions by sharing ions during the geopolymerization process. However, the formation of silica chains around these tailings because of the ion sharing between them and the tailings allows them to be used as aggregates. This process works in a way similar to the development of cement products around aggregates such as sand. However, mineral changes in mining tailings (for example, resulting from the oxidation of pyrite) do not affect the silica chains, unlike hydrated cement products. However, ions from mining tailings may contribute to the geopolymerization process and the formation of subordinate minerals to a small extent.

Various chemical methods can be used to alter chemical/mineralogical properties of tail particles. One of these methods is leaching processes which are usually carried out using acids or bacteria and can be applied for different targets. With this treatment method, new mineral species can be formed by converting the sulfides in the tailings into sulfates during the leaching procedure, or certain ions such as copper and lead can be separated from the tailings optionally (Ristović et al. 2022).

It is possible to change the surface properties and therefore the chemical structure of the minerals in the mine tailings. Surfactants can be used for this purpose and thanks to this method, the mineralogical structure/properties of the tailings remain constant while the parts with changed surface properties can be evaluated as inert materials for various applications. In addition, organo-functional silanes constitute an example of surfactants by coating the surface of the minerals in the tailings (Fig. 17). Silane molecules (R) are equipped with organic groups connected to silicon ions and these groups might be polar or apolar. Non-polar organic sets allow the material to repel water. During sol–gel practice, the hydrolyzed parts of the silane molecules turn into silanols (SiOH) that can make hydrogen bonds with the OH groups of the minerals. At this stage, reduction of H + ties into siloxanes and their progress in minerals' surface constitute the future stage of surface handling process (Fig. 18).

Thermal treatment

Thermal treatments are widely used for purposes such as transforming minerals in materials into new forms,

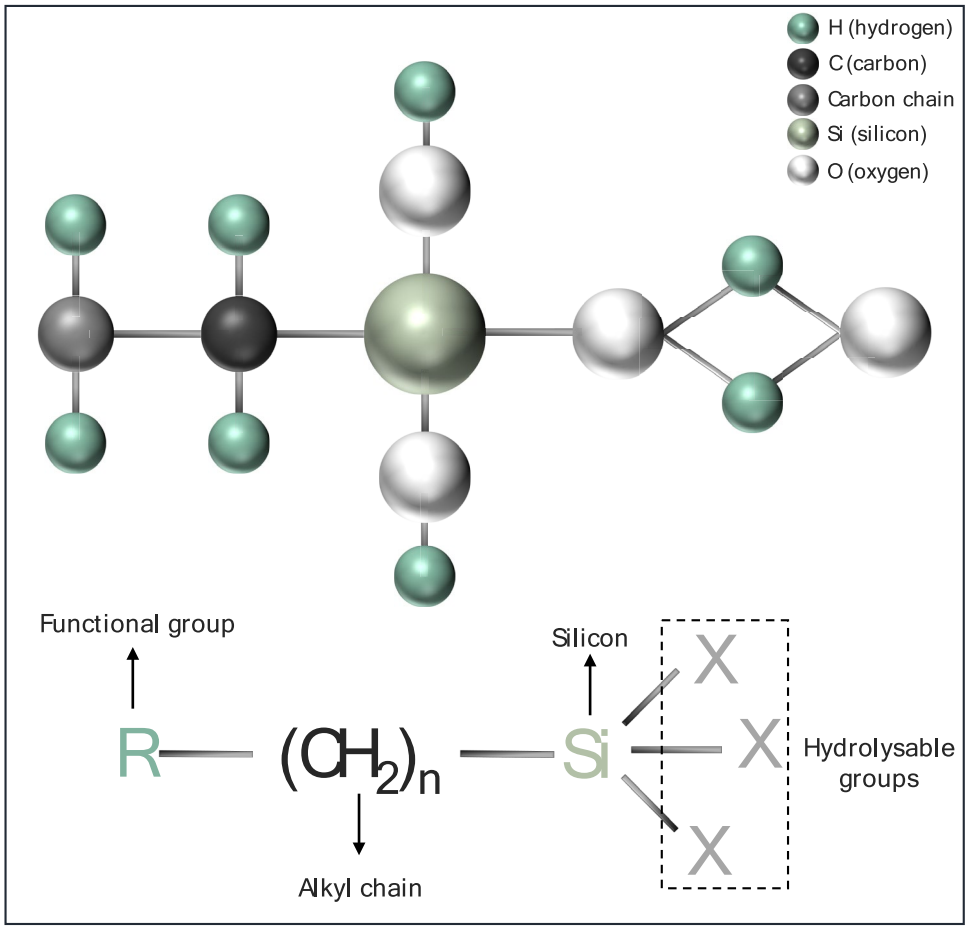


Fig. 17 Typical structure of organosilanes

recovering valuable elements, removing toxic substances and increasing chemical reactivity (Huang et al. 2022). These treatments, which are usually carried out in traditional furnaces, cause excessive energy consumption and therefore lose their eco-nomic sustainability in terms of waste recycling. When energy and cost are considered, microwave thermal treatment stands out as a more efficient alternative (Zheng et al. 2024). The use of microwave heat treatment technologies can provide many advantages (such as rapid heating, on-site application and effective cost). In addition, the interaction of microwaves with minerals and metals makes an important contribution to the separation of desired minerals from mine tailings (Everaert et al. 2020). For example, in a microwave (5000 watts), it may take only 10 s to convert pyrite into iron oxides. In addition, at high temperatures, the crystal structures of minerals can be made amorphous, as in other industrial wastes (such as blast furnace slag). However, due to the mineral imbalance contained in the mine tailings, unwanted mineral phases and gases such as CO_2 may be released during thermal processes.

As another application example, higher temperatures ($\geq$ 1000 °C) are needed to change the existing silicates of calcite, which can decompose above 800 °C. However, high temperatures cause sintering of the particles and therefore additional processes such as grinding may be required to increase the smoothness of the particles. It is possible to obtain new products from mine tailings through thermal treatment, and the use of sulfur dioxide during the thermal processing of pyrite-rich sulfurous metal mine tailings to produce sulfuric acid can be given as an example. It should not be overlooked that the amount of oxygen given to the environment must be precisely controlled to obtain sulfur dioxide during this process (Elsadek et al. 2023). In addition, depending on the amount of oxygen given to the environment, different iron oxides (such as hematite: (Fe_2O_3) or magnetite: (Fe_3O_4)) may be formed during the oxidation of pyrite (above 600 °C), and these oxides can be used as additives in different areas (Bhattacharya et al. 2024). Thermal treatments applied to mine tailings enable the production of magnetic minerals such as magnetite and thus the removal of iron oxides from the environment through magnetic separation can be facilitated. It should also be noted that the pyrite contained in the tailings is used as a valuable mineral in the cathodes of lithium-ion batteries (Su et al. 2023).

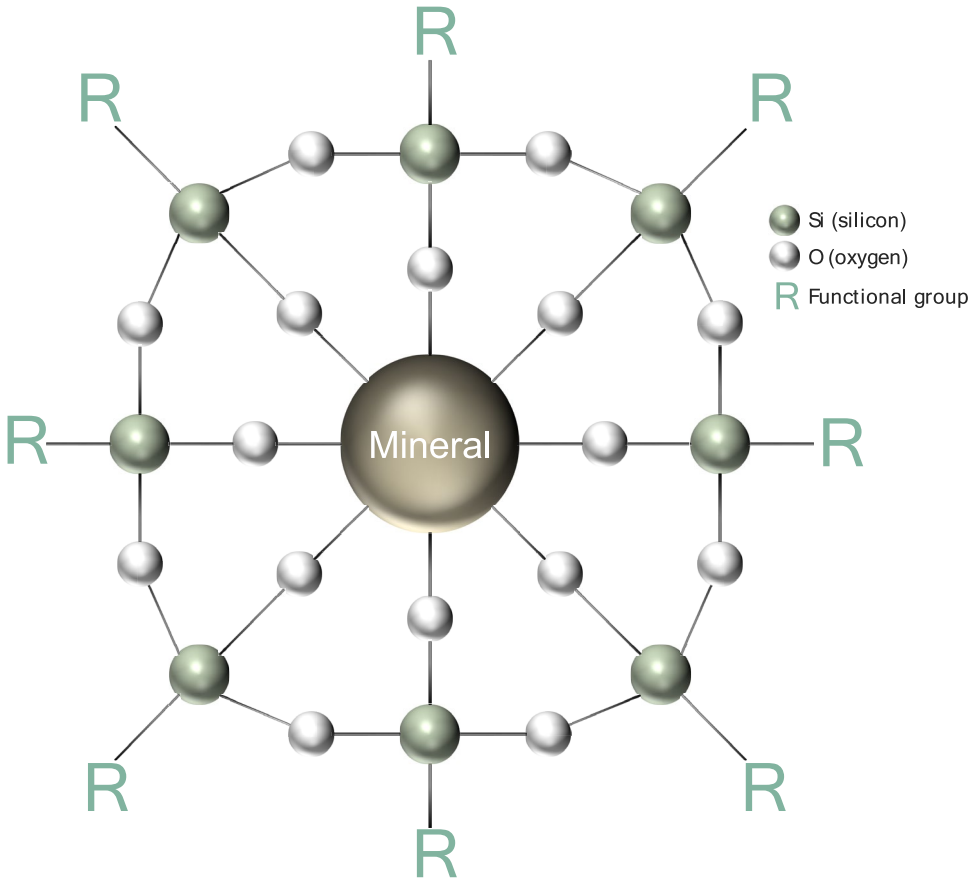


Fig. 18 Shortened system of a usual organosilane around mineral's grain

Mechanical treatment

Mechanical treatment is a method of remediation applied to mine tailings by using mechanical energy to change their physical, chemical or a combination of these, and thus to increase their structure and reaction tendencies. Thanks to mechanical processes, not only tails' gradation is condensed, or surface zone is increased, but also the excess energy used can be stored in the crystal structure (lattice) of the material and evaluated as activation energy. Mechanical treatment covers a long process that provides size change of mine tailings using different types of mills (planetary, attrition and vibratory) apart from a short grinding process (Curry et al. 2014). In comparison with chemical/thermal processes, mechanical process is preferred as an ecologically cleaner method because it does not require the use of chemicals and provides a high degree of activation compared to calcination. The effectiveness of mechanical processes hangs on physical properties, chemistry and crystal edifice of minerals. For instance, the crystal structure of serpentine subjected to dry grinding for 120 min becomes amorphous, while forsterite can continue to maintain its crystal structure even with longer grinding times (240 min) (Tunsu et al. 2019).

Legal regulations and future trends of mine tailings

In countries where mining activities are actively carried out, haphazard/inappropriate tailings management causes adverse effects on the environment and health. In order to eliminate these risks, it is important to create comprehensive tailings management plans and comply with these plans (Lin et al. 2023). These tailings management plans should be addressed throughout the entire life cycle of the tailings (covering all processes from production to evaluation in different areas) (Adiansyah et al. 2015). Existing mine tailings management plans focus on almost similar issues (such as tailings recovery and economic re-evaluation; production, treatment and processing; water use and slurry properties, tailings stabilization). Legal regulations and additional policies should be considered to safely store, containment and process tailings, and to determine potential risks and, if necessary, prevent them (Manjengwa et al. 2023). For this purpose, tailings should be monitored regularly, and risk assessments should be carried out. In addition to mine tailings, analyses of underground/surface water and the outputs of the tailings reusing process should also be included in risk assessment processes. With these practices/regulations,

it is of critical importance for local people, environmental organizations and mining companies to adopt effective intervention policies and implement these policies effectively (Zandariya 2022).

The continuous updating of different laws and regulations established by countries facilitates more efficient management of mining tailings and its inclusion in the sustainable production process. Various developed countries (e.g., USA, Canada, Australia, South Africa) started to implement solid mine environmental protection and assessment systems in the 1970s, and thus the importance of tailings management has been understood by the whole world. Each country has brought a different perspective to tailings management practices and has emphasized different practices. For example, while Australia has adopted the necessity of restoration during mining, the USA has adopted the Land Reclamation Act. While South Africa has established regulations for the use of the water sector and mining companies, China has focused on mine environmental protection, and Chile has arranged some regulations on bioremediation and rehabilitation (Kengni and Mostert 2022; Campos-Medina et al. 2023). With these laws and regulations, the standards of the mining sector have been increased as well as the international sharing of knowledge and experience in the management of mine tailings.

Future trends in metal mine tailings management focus on sustainability and innovation. Key developments include advanced recycling technologies for extracting valuable minerals, the use of tailings in construction materials, improved environmental remediation techniques, energy recovery methods, integration into a circular economy, and enhanced monitoring through smart technology. These trends aim to reduce environmental impact, optimize resource use, and promote more sustainable mining practices.

Summary and conclusion

Countries need metallic raw materials to grow economically and increase their level of prosperity, but these metals are generally found in nature in the form of metal components. In the process of metal extraction from ores, billions of tons of fine tailings are generated annually, and these tailings can trigger some environmental problems (such as dust formation, dam collapses, acid mine drainage and heavy metal pollution). The tailings dam disasters experienced in China, Canada and Hungary in recent years have painfully revealed the extent of these dangers. Therefore, instead of just storage in tailing management, solutions aimed at the reuse of these materials in industrial processes have become an important issue.

This article reveals that current approaches to the utilization of mining wastes differ significantly in terms of technical feasibility, environmental benefits, and limiting factors. The studies reviewed demonstrate that it is impossible to address mining wastes with a single application or technology; the mineralogical composition, chemical reactivity, and grain characteristics of the wastes directly determine the chosen application method. Furthermore, chemical, thermal, and mechanical pretreatment techniques play a critical role in the utilization of these wastes; these processes increase the reactivity of the wastes, significantly affecting their usability in building materials or binding systems. However, the energy consumption, cost, and secondary environmental impacts of these processes are factors that need to be carefully considered in terms of feasibility. This highlights the need for a balanced approach between technical performance and sustainability goals.

In conclusion, this study provides a comprehensive review of tailings applications, and its reusability in various areas depending on physical, chemical and mineralogical structures of tailings. The process of utilization of mining tailings plays a critical role in enhancing environmental sustainability and preserving natural resources. In this context, processing mining tailings using environmentally friendly technologies both minimizes the harmful effects of tailings and ensures that economically valuable products are obtained. In addition, calcined clay and other minerals are used in the production of high-performance building materials in the construction sector and thus tailings reusing processes provide economic benefits. The development of such innovative technologies is of great importance in terms of integrating mining tailings into the circular economy and achieving sustainable development goals. Therefore, efficient utilization of mining tailings provides long-term benefits both environmentally and economically. In addition, the role of these tailings in various application areas such as geopolymer, supplementary cement material, brick and ceramic and the different treatment methods applied to provide the desired reactivity of the tailings are also discussed in this study.

While the environmental risks and technical limitations of mining waste are generally discussed in detail in the literature, studies that comparatively and integrally evaluate the potential of these wastes in different application areas are limited. This study addresses different application areas and processing methods within a common framework, revealing clearer conclusions about under what conditions mining wastes can offer functional and sustainable solutions. In this respect, the study provides a reference and guiding ground for future application-oriented research.

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Declarations

Conflict of interest The authors declare no competing interests.

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