minerals

Review

Towards a Circular Economy in the Mining Industry: Possible Solutions for Water Recovery through Advanced Mineral Tailings Dewatering

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Abstract: The mining industry is confronted with substantial challenges in achieving environmental sustainability, particularly regarding water usage, waste management, and dam safety. The increasing global demand for minerals has led to increased mining activities, resulting in significant environmental consequences. By 2025, an estimated 19 billion tons of solid tailings are projected to accumulate worldwide, exacerbating concerns over their management. Tailings storage facilities represent the largest water sinks within mining operations. The mismanagement of water content in tailings can compromise their stability, leading to potential dam failures and environmental catastrophes. In response to these pressing challenges, the mining industry is increasingly turning to innovative solutions such as tailings dewatering and water reuse/recycling strategies to promote sustainable development. This review paper aims to (I) redefine the role of mine tailings and explore their physical, chemical, and mineralogical characteristics; (II) discuss environmental concerns associated with conventional disposal methods; (III) explore recent advancements in dewatering techniques, assessing their potential for water recovery, technical and economic constraints, and sustainability considerations; (IV) and present challenges encountered in water treatment and recycling within the mining industry, highlighting areas for future research and potential obstacles in maximizing the value of mine tailings while minimizing their environmental impact.

Keywords: climate change; water consumption; water recycling; mine tailings; dewatering; flocculation; electro-dewatering; filtration; decanter centrifuge; mine water treatment
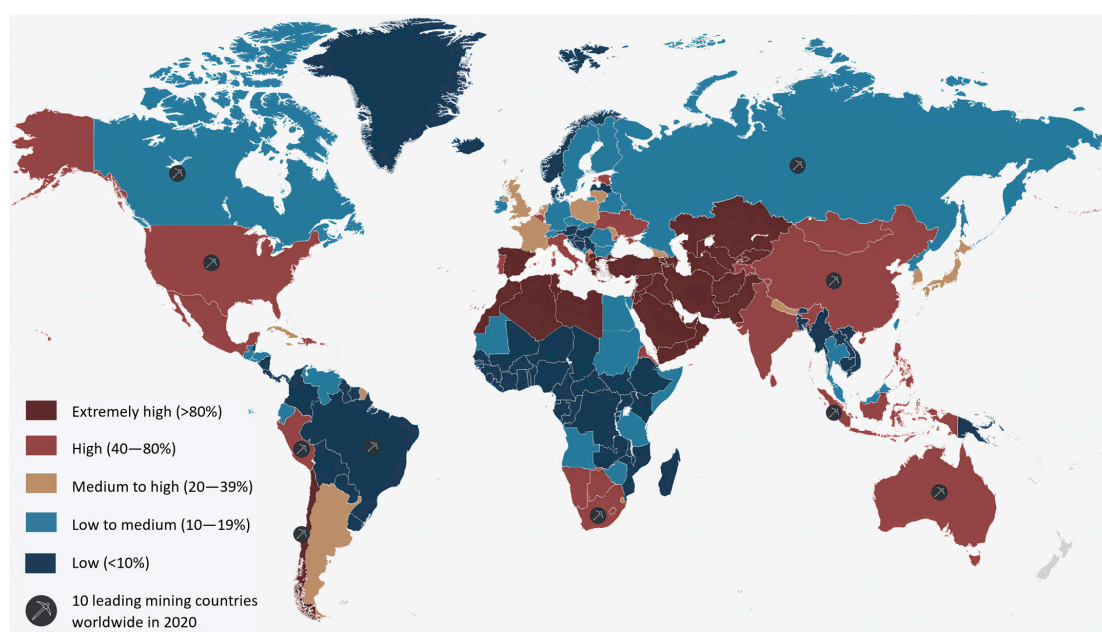
1. Introduction

Since ancient times, the mining industry has contributed significantly to the economic development of countries around the world through the extraction and exploitation of mineral resources [1]. The demand for mineral resources is still growing nowadays. The mining industry plays a crucial role in economic growth through the gross domestic product of many countries, such as Brazil, Canada, China, Morocco, and Tunisia [2]. This industry contributes to employment, export revenues, infrastructure development, and overall economic diversification.

In addition to its participation in the economic development of countries around the world, the mining industry also contributes regionally through the creation of direct and indirect jobs and local sub-enterprises [3]. Despite benefits, this industry faces challenges in

terms of water resource management. Ore beneficiation processes, including wet transport, consume significant volumes of water [4]. The mining industry has, therefore, created environmental impacts through the overexploitation of water resources that are already scarce in many countries around the world. For instance, water consumption for the processing of ore requires 1371 m^3/t for Fe, 327 m^3/t for Co, 1713 m^3/t for Ag, 43 m^3/t for Cu, and 1.5 m^3/t for P_2O_5 [5,6]. Water consumption depends mainly on the climatic conditions of the mining area, the type of ore processed, and the distance of the wet ore transport via conveyor [7]. The volume of water consumed is critical, especially in areas suffering from water deficits. The mining industry is thus one of the main consumers of water (compared to agricultural, industrial, and domestic uses) that can aggravate the overexploitation of water resources [8].

1.1. Challenges of Mine Site Water Availability in the Face of Climate Change

Climate change significantly impacts the availability of global water resources [9], affecting both the quality and quantity of freshwater supplies. Human-induced global warming, driven by greenhouse gas emissions like CO_2 and NO_x, disrupts the hydrological cycle, leading to changes in the global water balance [10–12]. A key consequence of climate change is altered precipitation patterns [13], resulting in more frequent and severe droughts in some areas and increased precipitation in others [12]. This imbalance hinders the natural replenishment of water sources, making it challenging to sustain adequate water supplies for various sectors, including industrial operations, mining, agriculture, and ecosystems. It is apparent that mining production predominantly occurs within regions exhibiting elevated levels of water stress and grappling with a deficit in water resources (Figure 1). The concentration of mining activities in such areas highlights the potential implications for water availability and sustainability.

Figure 1. Water stress by country: 2040 (projected ratio of water withdrawals to water supply (water stress level) in 2040).

The top ten countries in mine production, including China, Australia, the United States, India, the Russian Federation, South Africa, Indonesia, Brazil, Canada, and Chile, play vital roles in the global mining industry due to their rich mineral resources and well-established mining sectors [14]. Seven out of these ten countries are in regions with high or extremely high water stress, emphasizing the overlap between major mining areas and water scarcity challenges. This raises significant concerns about the potential impact of

mining activities on local water resources. This situation underscores the need for enhanced water management practices and sustainable approaches within the mining industry to mitigate the strain on an already limited water supply. By prioritizing responsible water usage and implementing effective conservation measures, these countries can strive towards sustainable mining practices that safeguard water resources and contribute to long-term environmental and social well-being [15].

1.2. Persistent Tailings Challenges

Excessive water consumption in the mining industry results in the production of a substantial amount of waste, including mine tailings that are frequently in the form of a slurry with a high water content. The mining industry currently produces over 10 billion tons of mine tailings annually, and this amount is projected to increase due to the anticipated growth in production. By 2035, it is estimated that the volume of tailings will double [16]. In China, there are over 12,000 tailings ponds, and the total accumulated number of tailings has surpassed 15 billion tons [17]. The mining of lower-grade ores has indeed become more prevalent due to the depletion of high-grade deposits. Lower-grade ores are typically more resource-intensive to process, leading to increased waste generation. For instance, coal preparation plants often discharge significant amounts of tailings, with estimates ranging from 75 to 120 kg of dry tailings per ton of coal processed [18]. The extraction of copper also produces a substantial number of tailings. This underscores the importance of developing more efficient and sustainable tailings management practices.

The management of mineral tailings faced several challenges and was undergoing significant scrutiny and reforms, particularly in the mining industry. Historically, tailings dams have been a common method of storing and managing tailings [19,20]. One of the primary challenges with traditional tailings dams is their susceptibility to failure, which can result in catastrophic consequences for surrounding communities and ecosystems. In Brazil, the Samarco dam failure destroyed villages as it flowed 663 km to the sea, causing human fatalities, leaving hundreds of inhabitants without housing, and ultimately resulting in the deterioration of aquatic life [21]. Another example is the failure of the Aznalcóllar storage ponds (Spain), which underwent a displacement of 55 m over a length of 700 m, causing the generation of huge quantities of acidic water and 5.5 Mm^3 of pyrite and pyroclastic residues, resulting in social, economic and environmental damage [22]. In the event of a failure, the waste in the storage ponds, especially waste rich in acids, can produce acid mine drainage, which can cause uncontrollable damage that is even more dangerous than the failure of the storage ponds [23]. These failures can lead to loss of life, extensive environmental damage, and significant financial liabilities for mining companies. In addition to catastrophic failures, Tailings can contain toxic substances such as heavy metals and sulfides, which can leach into soil and water, contaminating ecosystems and posing risks to human health. In response to these concerns, there has been a push for stricter regulations governing tailings management. This includes implementing new technologies for tailings dewatering and storage, as well as adopting principles such as the Global Industry Standard on Tailings Management, which aims to enhance the safety and environmental performance of tailings facilities.

Some mining companies are exploring alternative approaches to tailings management, such as dry stacking and in-pit disposal, which can reduce the environmental footprint and risks associated with traditional tailings dams. Additionally, dewatering technologies play a crucial role in enabling these alternative approaches by efficiently removing water from tailings. These technologies not only enhance environmental safety and stability but also allow for the recovery of valuable resources from tailings, contributing to resource efficiency and sustainability. However, the adoption of these technologies comes with its own set of challenges. Cost considerations, limited throughput, energy consumption, and the need for technological optimization are key factors that mining companies must address [24]. Nevertheless, given the growing emphasis on sustainable mining practices

and the imperative to minimize environmental risks, these technologies are likely to play an increasingly important role in modern tailings management strategies.

1.3. Objectives of This Critical Review

This review paper, which extensively explores tailings dewatering as a critical process within the mining industry, primarily aims to evaluate a wide spectrum of dewatering methods and technologies, ranging from gravitational settlers to advanced filtration and centrifugation processes, while considering the utilization of various energy sources to enhance the dewatering process in terms of their effectiveness and applicability in various mining contexts. Concurrently, this paper evaluates the efficiency of these dewatering processes in reducing water content and mitigating environmental contamination risks, thereby contributing to environmental preservation and risk mitigation. Moreover, this review addresses the challenges associated with water recycling and assesses the suitability of mine water treatment technologies. The ultimate objective is to offer recommendations and insights for future research and development, with a specific focus on enhancing sustainability, minimizing environmental impacts, optimizing dewatering efficiency, and addressing the unique challenges related to water recycling. These efforts contribute to the advancement of environmental and economic sustainability within the mining industry.

2. Water Consumption in the Mining Industry

Water consumption in the mining industry is a critical aspect of operational processes as it plays a pivotal role in various stages of mineral and metal extraction. The sustainable management of water resources within this sector is paramount, considering the environmental and economic impacts associated with high water usage. In this section, the intricate details of water consumption in mining operations are explored, shedding light on the key processes and areas where water resources are particularly vital. A typical flow sheet of mineral and metal treatment processes is presented in Figure 2. Notably, the blue boxes indicate the processes where water resources are highly consumed.
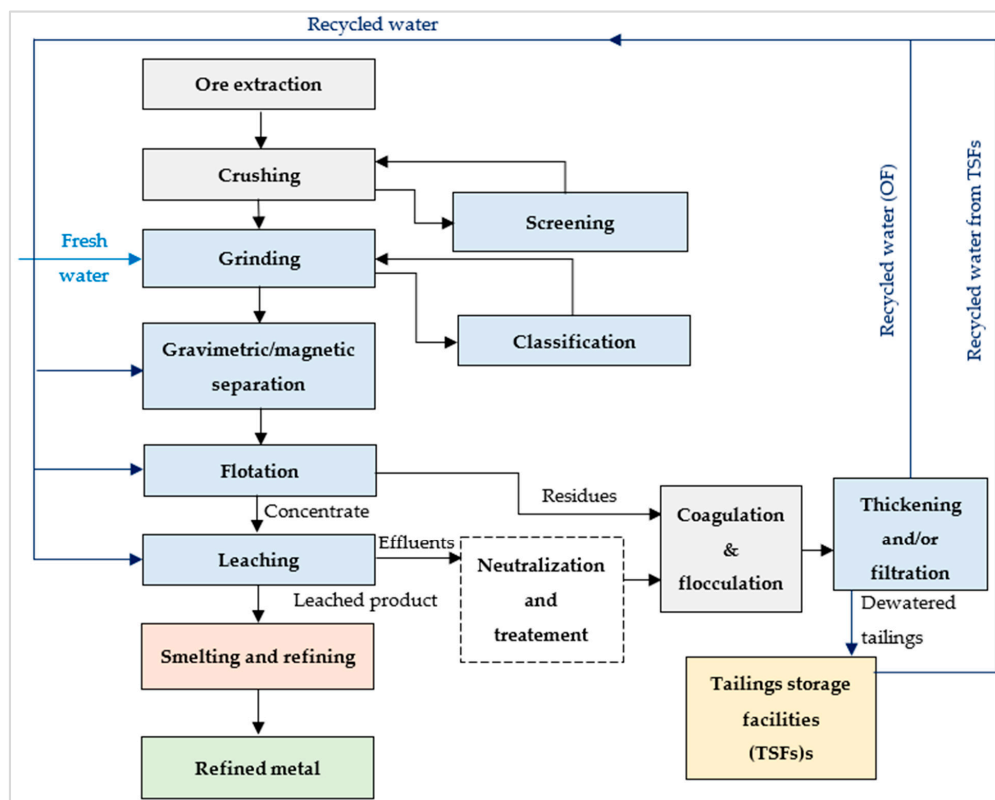

Figure 2. Flow sheet of mineral and metal treatment processes.

Most treatment processes are carried out via wet processes. These treatment processes include classification by screeners and hydrocyclones, gravity-based concentration methods, dense medium separation, froth flotation, and hydrometallurgical leaching [1]. Given that the mining industry consumes a significant volume of water, with averages ranging from 0.37 to 18.25 m^3 per metric ton of processed ore [25–29], some water-intensive processes such as desliming, classification (using screeners and hydrocyclones), and froth flotation face water management challenges [29,30].

The extent of water consumption during ore processing is dependent upon a variety of factors, including the specific type of ore being processed, its grade, the size at which valuable minerals are liberated (referred to as the ore liberation mesh), the geographical location of the ore deposit, and the chosen concentration technology. This diversity in water consumption becomes evident in various scenarios. Different minerals necessitate specific processing methods, which in turn result in variations in water demands and treatment protocols [31]. For example, the water requirements for processing phosphate ores may substantially differ from those for gold or copper ores due to the unique characteristics of each mineral. Second, ore grade, which denotes the concentration of valuable minerals, directly influences the volume of water needed for processing [31,32], with higher-grade ores generally requiring less water than those with a lower grade. Third, the ore liberation mesh, or the size at which valuable minerals are released from the host rock, significantly affects water requirements and treatment processes [33], especially in cases where finely ground ores demand increased water usage for efficient mineral separation and extraction. Finally, the choice of concentration technology, like flotation, leaching, or magnetic separation, introduces specific water demands and associated treatment methods, highlighting the diverse ways in which water consumption is influenced across different processing approaches [31,34].

According to Figure 3, different types of ores require distinct water volumes for processing. Particularly, phosphate, gold, and polymetallic ores demand the highest levels of specific water consumption for processing (4.77 m^3/t for phosphates, 4.63 m^3/t for gold, and 2.79 m^3/t for polymetallic ores). Unexpectedly, phosphate processing requires significant water usage, surpassing that of gold and silver ore processing. This substantial consumption could be attributed to the specialized treatment of fine and ultrafine phosphate ores, particularly in Saudi Arabia [35,36]. These minerals require considerable volumes of water throughout their processing stages due to several factors, including the characteristics of the ore, the concentration technologies utilized, and the specific treatment processes employed.

Another significant cause of increased water consumption during the beneficiation of mineral ores is the transportation of mineral products from one location to another. The long-distance transport of these products, such as through conveyance pipelines, can have adverse effects on water resources at the point of origin. The extraction of water for transportation purposes can deplete local water sources, further exacerbating water scarcity concerns. Therefore, water consumption in the mining industry requires urgent attention due to its significant environmental impact, competition for resources, inadequate regulation, and long-term sustainability concerns (depletion of aquifers, degradation of water quality, and disruption of local ecosystems). Sustainable water management technologies, interdisciplinary approaches to water resource management, climate change adaptation strategies, and inclusive stakeholder engagement are essential research directions to address these challenges effectively and ensure the responsible use of water in mining operations [37].
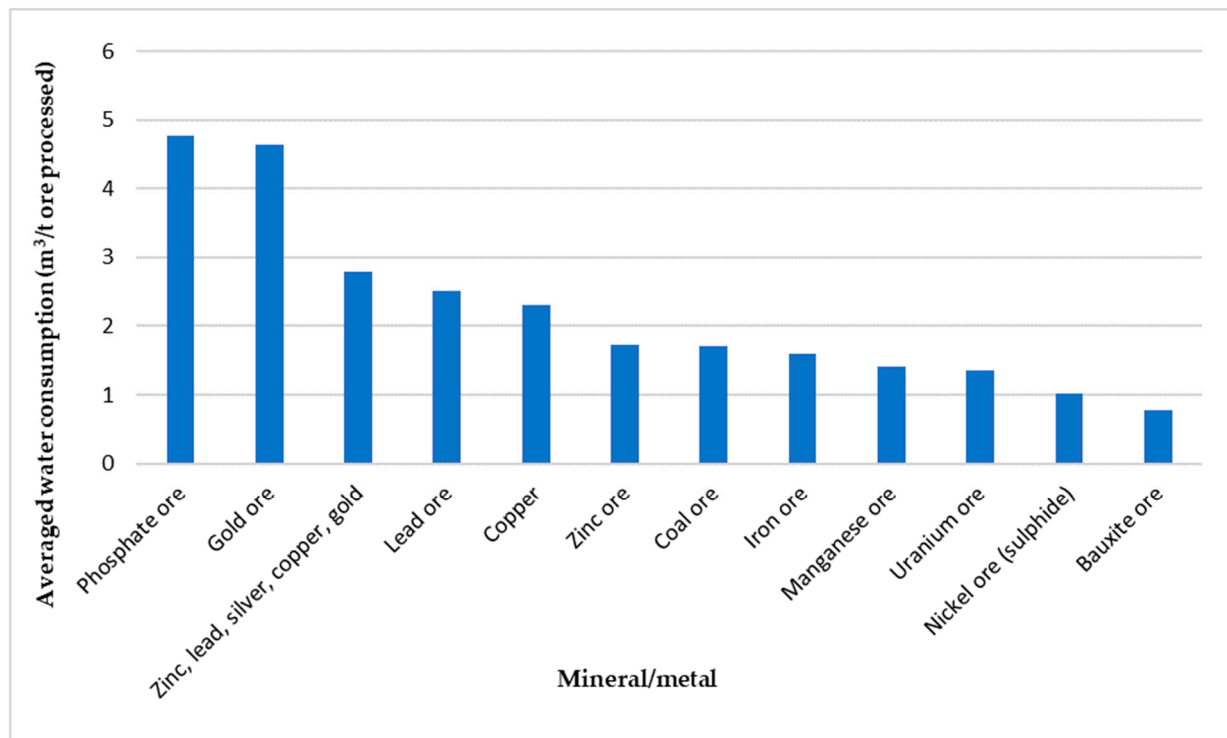
Figure 3. Average water consumption (m³/t) of different metal/mineral ores [4,5,27,31,35,36,38–45].

Mining operations consume water for tasks such as ore crushing, grinding, washing, mineral separation, dust suppression, conveying tailings and concentrate, and maintaining overall operational efficiency [46]. The specific water sources utilized in these operations can vary depending on the geographical location and the availability of water resources. In the process of mineral ore beneficiation, a variety of water sources are commonly employed. Initially, freshwater sources such as tap water, surface water, and groundwater are typically utilized [31,47–51]. However, in arid and semi-arid regions where water resources are scarce, mining industries located in these areas have progressively embraced alternative water sources, including seawater and recycled water from tailings dams, as a response to the prevailing water scarcity. Numerous studies have emphasized the potential of utilizing seawater as a highly efficient alternative, particularly in coastal regions or areas where freshwater resources are scarce. This approach proves advantageous in mitigating water stress by incorporating seawater into mineral beneficiation processes [48,49,52]. In addition, and as part of their commitment to sustainable development, mining companies have adopted a circular economic approach to recycle the water that they use during ore processing and from tailing storage facilities and thickeners in order to minimize water consumption [25,29,48,53–56].
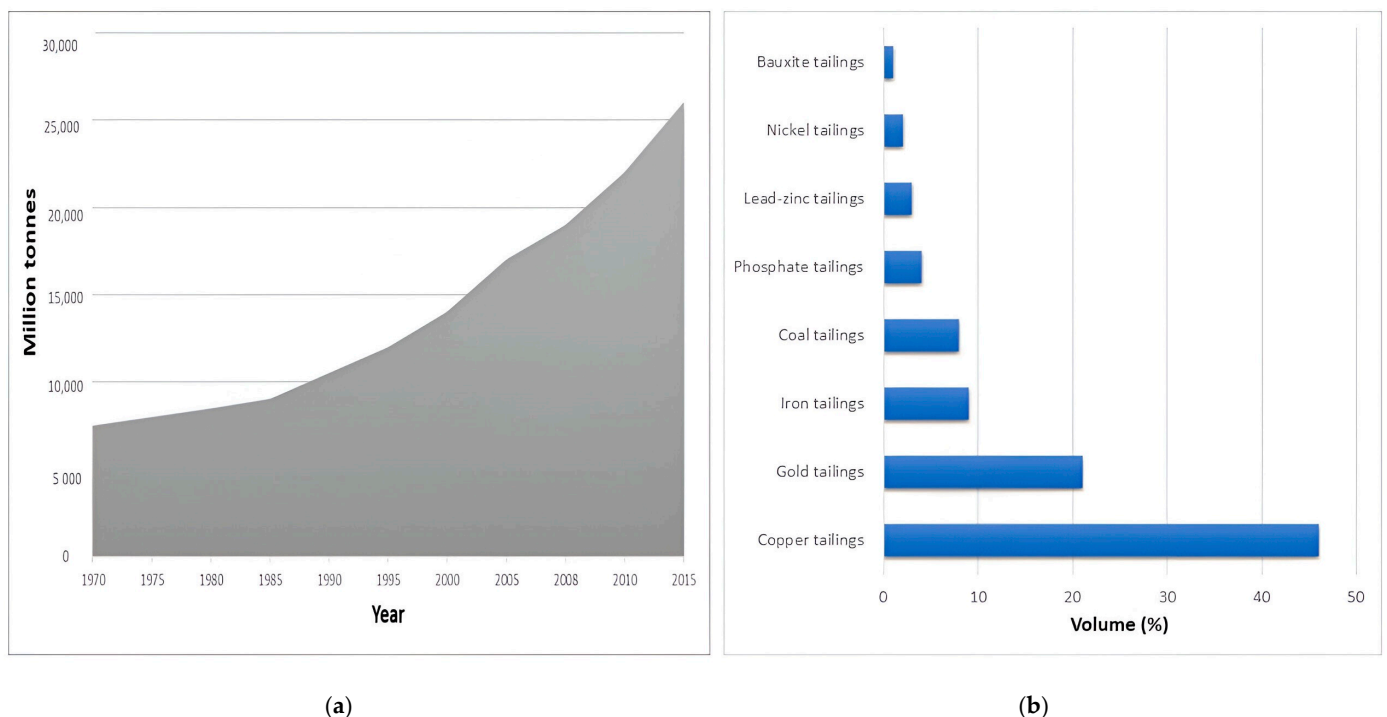
Excessive water consumption in mining leads to environmental degradation, exacerbates water scarcity, faces inadequate regulation, and encounters transparency issues. This necessitates a focus and emphasis on sustainable water technologies specifically designed for mining operations. This involves integrating water resource management principles, conducting comprehensive impact assessments, and enhancing stakeholder engagement and governance to ensure transparent and equitable water management practices [57].

3. Mine Tailings Production: Overview and Industry Trends

The term "mine waste" refers to a wide array of materials produced in mining operations, often having no economic value and considered undesirable by-products. These waste materials can be classified into three main categories: mining waste, processing waste, and metallurgical waste [58]. This review focuses specifically on processing waste, particularly tailings, as an underutilized water resource, exploring their potential in greater depth.

Tailings are residual mixtures of crushed rock and processing fluids left over from mining operations, encompassing various industries such as aluminum, coal, oil sands, uranium, and precious/base metals extraction [59–62]. Typically, tailings are managed in the form of a pulp or slurry with an initial solids content ranging from 25% to 45%. This slurry is transported from the processing plant to tailings storage facilities (TSFs) or tailings dams, where it is deposited and allowed to settle. Over time, the water in the slurry separates and is often recycled back into the mining process, while the solid tailings remain stored in the facility [1,59,63,64].

The expansion of the global economy and the growth in the world's population have led to a substantial increase in the utilization of mineral resources. This heightened demand has correspondingly boosted the extraction of metals and minerals, as illustrated in Figure 4a. Consequently, there has been a significant rise in mine residues, commonly known as tailings. In 2016, it was estimated that over 8 billion tons of tailings were generated from metal and mineral extraction activities [65], and 19 billion solid tailings will be accumulated by 2025 [66]. The highest proportion of these tailings, accounting for 46 percent, originated from copper mining (Figure 4b).

(**a**)   (**b**)

Figure 4. (**a**) The global extraction of metal ores from 1970 to 2015, (**b**) Percentage of global tailings volume per commodity in 2016 [65].

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Mining waste, especially tailings from metal mines, poses challenges and opportunities for resource utilization and environmental management. By embracing circular economy approaches, mining companies can develop comprehensive waste management strategies that minimize waste generation, maximize resource recovery, and reduce environmental impact. This comprehensive approach involves several key elements, including reduce, reprocess, upcycle, downcycle, and dispose for the future [19]. In recent years, there has been notable attention towards resource management strategies for recycling mine waste, driven by the potential economic and environmental advantages they offer. This includes the recovery of valuable minerals and metals, the production of cost-effective building materials, and the preparation of soil modifiers and agricultural fertilizers [66].

Recycling, the process of reusing waste after undergoing transformations to adapt its properties for a specific production chain, provides raw material for the manufacture of other products. Often, tailings contain trace amounts of valuable minerals that can be recovered using various methods, such as advanced separation technologies or chemical processes [67,68]. Older tailings storage facilities may still contain concentrations between 0.2 and 0.6 wt.% Cu. With advancements in mining technology, science, and economics, tailings materials with 0.3% Cu by weight can now be regarded as georesources, enabling the application of a circular economy [69]. Advanced extraction methods like flotation [70,71], leaching, bioleaching [72], solvent extraction [73], and ion exchange [74] facilitate the efficient recovery of critical minerals from materials with lower concentrations. The recovery of valuable minerals like copper, cobalt, and zinc using the flotation method has shown promising results in various studies [75]. Montenegro et al. [76] developed a superstructure comprising various flotation circuits for evaluation. They investigated parameters such as flotation efficiency, capacity, product quality, economics, and environmental impact to generate concentrates with specific arsenic (As) and copper (Cu) grades. Their approach facilitated an analysis of the interplay between circuit structures and key indicators, enabling the selection of the optimal flotation circuit based on multiple objectives. On the other hand, leaching represents a relatively less expensive alternative. Considering the low metal grades and small grain size of tailings material, it is likely the most cost-effective method for final recovery from tailings. Companies like PAN African Resources, Codelco, and Sibanye Stillwater are already reprocessing their tailings to extract residual metals, including copper and platinum. However, there are several criticisms and challenges associated with this practice. These include the fact that (1) historical tailings often lack detailed information about their composition, making it difficult to predict their metallurgical performance and recovery potential.; (2) the reprocessing of mine tailings may lead to increased water consumption and the release of potentially toxic substances, which can have negative environmental consequences; and (3) the reprocessing of mine tailings often requires advanced technologies and techniques, which can be costly and energy-intensive. Researchers should continue to develop and improve technologies for the reprocessing of mine tailings, focusing on methods that are more efficient, cost-effective, and environmentally friendly.

One significant aspect of resource recovery from mine tailings is the extraction of water. This water can be laden with various contaminants, including heavy metals and other pollutants, making it unsuitable for immediate discharge into the environment. Water recovery from tailings involves the extraction and treatment of this water for reuse in various mining processes or for other purposes such as irrigation or dust suppression. By recovering water from tailings, mining operations can reduce their reliance on freshwater sources, mitigate the environmental impact of water discharges, and potentially lower operational costs associated with water procurement and treatment. An overview of current dewatering technologies is provided in the following sections [60].

By adopting a holistic approach that combines different circular economy principles and leveraging advanced technologies, the mining industry can effectively manage waste streams while maximizing resource utilization and minimizing environmental harm. This integrated approach is essential for sustainable mining practices and the transition towards a more circular economy.

4. Mine Tailings Characteristics

Dewatering plays a crucial role in removing excess water from these materials and improving their handling, transportation, and storage. However, the efficiency of dewatering can be influenced by various factors, including the specific characteristics of the mine tailings or sludge. This section aims to provide a comprehensive characterization of mine tailings or mine sludge and explore how their properties affect the dewatering process. By understanding the composition, physical properties, and chemical behavior of these materials, efficient dewatering strategies can be developed while also mitigating potential environmental impacts [77].

4.1. Physical Properties

Tailings particles are classified into three grain size fractions: coarse sand particles (>63 μm), fine silt particles (2–63 μm) and fine clay particles (<2 μm) [18], but the majority of particles fall within the silt range [58].

The morphology of tailings particles is generally described as angular to very angular, contributing to a notably high friction angle when the tailings are dry. Additionally, the density of tailings varies depending on the parent rock type, typically falling within a broad range of 1.8 to 1.9 t/m^3. This density variation is accompanied by a specific gravity ranging from 2.6 to 2.8, as reported by [78].

4.2. Chemical and Mineralogical Properties

The chemical characteristics of mine tailings can vary depending on the type of mineral being mined, the processing techniques employed, and the composition of the ore body. A study conducted on the chemical characteristics of different types of tailings, including Au, Cu, Fe, Mo, Pb, and Zn, found that regardless of the type of tailings, the main elements present were Si, Al, Fe, Mg, Mn, Ca, Na, and K [17]. However, the specific contents of these elements varied significantly among the different types of tailings.

The minerals present in tailings can be categorized into three main groups: the gangue fraction, the residual uneconomic sulfide oxide fraction, and the secondary mineral fraction. Typically, tailings consist of a combination of these groups, often comprising various types of minerals or a mixture of common and associated useful elements. In the case of sulfide tailings resulting from the extraction of base and precious metals, the gangue fraction is predominantly composed of quartz, possibly with inclusions of K-feldspar, Na-feldspar, Ca-feldspar, sericite, chlorite, calcite, and dolomite. The sulfide oxide fraction in these tailings commonly contains pyrite and may also include pyrrhotite, arsenopyrite, marcasite, magnetite, sphalerite, chalcopyrite, and galena [62].

Clay is a crucial mineral component found in mine tailings, characterized as fine-grained hydrous aluminum phyllosilicates composed of tetrahedral and octahedral sheets [79]. These sheets form unit layers through diverse forces and atomic bonding, categorizing clays into predominant groups found in ore deposits: kaolinites, smectites, and illites, each distinguished by their layer structures and bonding forces [80]. Mineral tailings from the alumina, phosphate, and copper industries exhibit variations in composition, with lower levels of clay minerals and higher concentrations of metal oxides. The specific composition depends largely on the mineralogy of the ore deposit. However, it is evident that phyllosilicate minerals, predominantly clay minerals, are universally present in these tailings. These phyllosilicate minerals are found in the finer fractions [18,81].

The specific properties of clays pose challenges to the dewatering process within tailings: (1) a layered structure with a physical dimension in the nanometer range; (2) the anisotropic nature of layers or particles; (3) the presence of various surface types (external basal (planar) and edge surfaces, alongside internal (interlayer) surfaces); (4) the susceptibility of surfaces to alteration through adsorption, ion exchange, or grafting; and (5) plasticity and solidification upon drying or firing, a characteristic shared by most clay minerals [82]. Clay properties, especially the charge characteristics, greatly impact interactions between clay and minerals, affecting surface reactivity with reagents (e.g., polymer flocculants) and the formation of aggregate structures in suspensions. The presence of clay can impede dewatering processes. For instance, even a small amount of smectite in tailings can notably elevate viscosity and yield stress and result in gel formation. This complicates dewatering and consolidation, impacting the transportation of tailings and the long-term stability of storage facilities [83].

4.3. Geochemical Characteristics Environmental Issues from Accumulated Mine Tailings

Mine tailings often contain deleterious substances, including metal(loid)s (e.g., As, Cd, Hg, Pb), sulfides, and other chemicals used in the extraction and processing of minerals. For example, the utilization of mercury in gold mining operations has resulted in its common presence as a mobile contaminant in gold extraction residuals [84]. The primary environmental concern associated with mine tailings lies in the potential concentration of metal(loid)s in water, which contacts the solid material, rather than the overall metal(loid) concentrations present in the tailings. The expected level of metal(loid)s in water is influenced by various physicochemical characteristics of the solid material, such as pH, grain size, mineralogy, chemical composition, and speciation. These factors play a crucial role in determining the bioavailability of these metal(loid)s and assessing the potential risks that mine wastes pose to the soil, water, and wildlife in the surrounding area [85,86]. Table 1 presents the general characteristics of mineral tailings or sludge from various sources.

Detailed analyses have revealed that radionuclides, metals, and metalloids are present in various forms within tailings. These forms include ion-exchangeable forms, carbonate, and readily acidic soluble forms, as well as iron and manganese hydrous oxides, fluorides, alkaline earth sulfates (e.g., $BaSO_4$, $SrSO_4$), organic matter, sulfides, and arsenates. The stability of these solid phases plays a critical role in determining whether radionuclides, metals, and metalloids can be mobilized into the pore water of tailings [61]. Different types of tailings exhibit variable levels of radioactive elements. Among the tailings tested by [17], Mo tailings exhibited the highest specific activity of Ra-226, while gold mine tailings had the highest specific activity of Th-232 and K-40.

Mine tailings have a smaller grain size and larger surface area compared to the surrounding undisturbed geological materials. This characteristic makes them more susceptible to water-related contamination known as acid mine drainage (AMD) [87]. The chemistry of the drainage water is primarily influenced by the process of oxidation, which occurs when certain minerals containing iron sulfide, such as pyrite and pyrrhotite, are exposed to oxygen and water. This oxidation process leads to the release of sulfuric acid, which contributes to the acidity of the drainage. Then, dissolved metals present in the tailings, such as Cu, Fe, and Zn, can also be released into the drainage, further contributing to its composition [88]. The environmental impacts of AMD can occur throughout the entire mining lifecycle, and numerous examples have been documented in the scientific literature [89,90].

Table 1. General characteristics of mineral tailings or sludge from various sources.

Type	Origin	Mineral Composition	Chemical Composition	Physical Propriety	Reference
Iron ore tailings	Sangan iron beneficiation plant	Major phases: hematite, quartz, calcite and, chlorite; minor phases: goethite and dolomite	Fe_2O_3 (31.33%), SiO_2 (16.24%), CaO (14.98%), and MgO (12.33%)	D_{50} (μm) = 31.16	[91]
Plomb tailings	Zaida abandoned mine site, Morocco	Quartz (50%), orthoclase (30%), albite(5.5%), chlorite (4%), barite (8%) and fluorite (2%).	SiO_2 (68%) and Al_2O_3 (9%)	D_{50} (μm) = 230 Fine content (% < 63 μm) = 18.5 Specific gravity (g/cm³) = 2.7 Specific surface area (m²/g) = 1.484	[64]
Zinc tailings	Boubeker abandoned mine site, Morocco	Dolomite content (87%) with a small content in terms of quartz (9%), smithsonite (3%) and albite (1%).	Cao (25%) and MgO (17%)	D50 (μm) = 120 Fine content (% < 63 μm) = 28 Specific gravity (g/cm³) = 2.9 Specific surface area (m²/g) = 1.573	[64]
Nickel Rim tailings	Nickel rim, Sudbury, Canada	Gypsum, goethite, jarosite, and sulfides	Cu = 313 mg/g Ni = 294 mg/g Zn = 95 mg/g	Particle density (g/cm³) = 2.68, Bulk density (g/cm³) = 1.38	[92]
Chromite ore tailing sample	M/s. Tata steel, Sukinda, Odisha, India	Major phases: magnesioferrite, chromite, Goethite, gibbsite, and quartz; Minor phases: hematite and kaolinite	Fe (27.39%), Cr_2O_3 (17.95%) SiO_2 (17.25%) and Al_2O_3 (12.39%).	D_{50} = 10.72 μm Particle density (g/cm³) = 3.02 BET surface area (m²/g) = 23.79	[93]
Calamine processing mine tailings	Calamine hydrometallurgical processing plant, Morocco	Gypsum, quartz, and calcite	SiO_2 (13.4 wt%), CaO (23.5 wt%) Fe_2O_3 (13.3 wt%) and SO_3 (24.6 wt%)	2–63 μm = 68% Specific gravity (g/cm³) = 2.66 Specific surface area (m²/g) = 18.65	[94]
Phosphate Sludge	Gafsa, Tunisia	Fluoroapatite, Calcite, dolomite), and clays (i.e., Heulandite, vermiculite and palygorskite)	SiO_2 (39 wt%), CaO (17 wt%), Al_2O_3 (7.3 wt%) and P_2O_5 (6.5 wt%)	D_{50} = 8.3 μm D_{80} = 17.2 μm	[4]

Ensuring proper management and disposal of mine tailings is crucial to prevent environmental contamination and protect nearby communities. This comprehensive approach involves several key elements, including the establishment of robust tailings storage infrastructure, the implementation of liner systems, the use of effective treatment systems, adherence to a regulatory framework with surveillance, ongoing research and innovation, and, in particular, the adoption of innovative dewatering techniques.

5. Dewatering Methods Classification

Dewatering mine tailings is undeniably one of the most intricate and demanding technical endeavors in the realm of mining operations. The category of mine tailings dewatering encompasses a wide array of challenges that require innovative solutions and rigorous engineering. Dewatering methods include a range of techniques employed to separate water from solids using various processes. Conventional dewatering technologies, such as gravitational settling, mechanical dewatering, and thermal drying, form the foundation of this field. These methods rely on basic principles like gravity and mechanical force to facilitate water removal. However, the field has evolved to include assisted mechanical dewatering devices, which introduce additional force fields such as temperature, shear, acoustic or ultrasonic waves, magnetic fields, microwaves, or electricity. These advanced methods enhance the efficiency of dewatering processes, offering innovative solutions for industries seeking to extract water from solids more effectively [95–97].

The efficiency and effectiveness of dewatering methods depend on factors such as the type of material, its water content, the distribution of water within the material, and the specific dewatering technique used. Water can exist in different forms within materials, including free water, interstitial water, surface (or vicinal) water, and intercellular and chemically bound water. Mechanical dewatering methods are efficient in extracting free water. However, there are three types of water that require more energy or specific methods for extraction. The first type is interstitial water, which becomes trapped within the flocs. The second type is surface water, which remains held on the surface of the solid particles due to adsorption and adhesion. Finally, there is bound water, which is tightly bound to the solid particles [96,98]. A general conceptual visualization of dewatering methods and their relationship to water distribution in materials is provided in Figure 5.

(**a**)   (**b**)
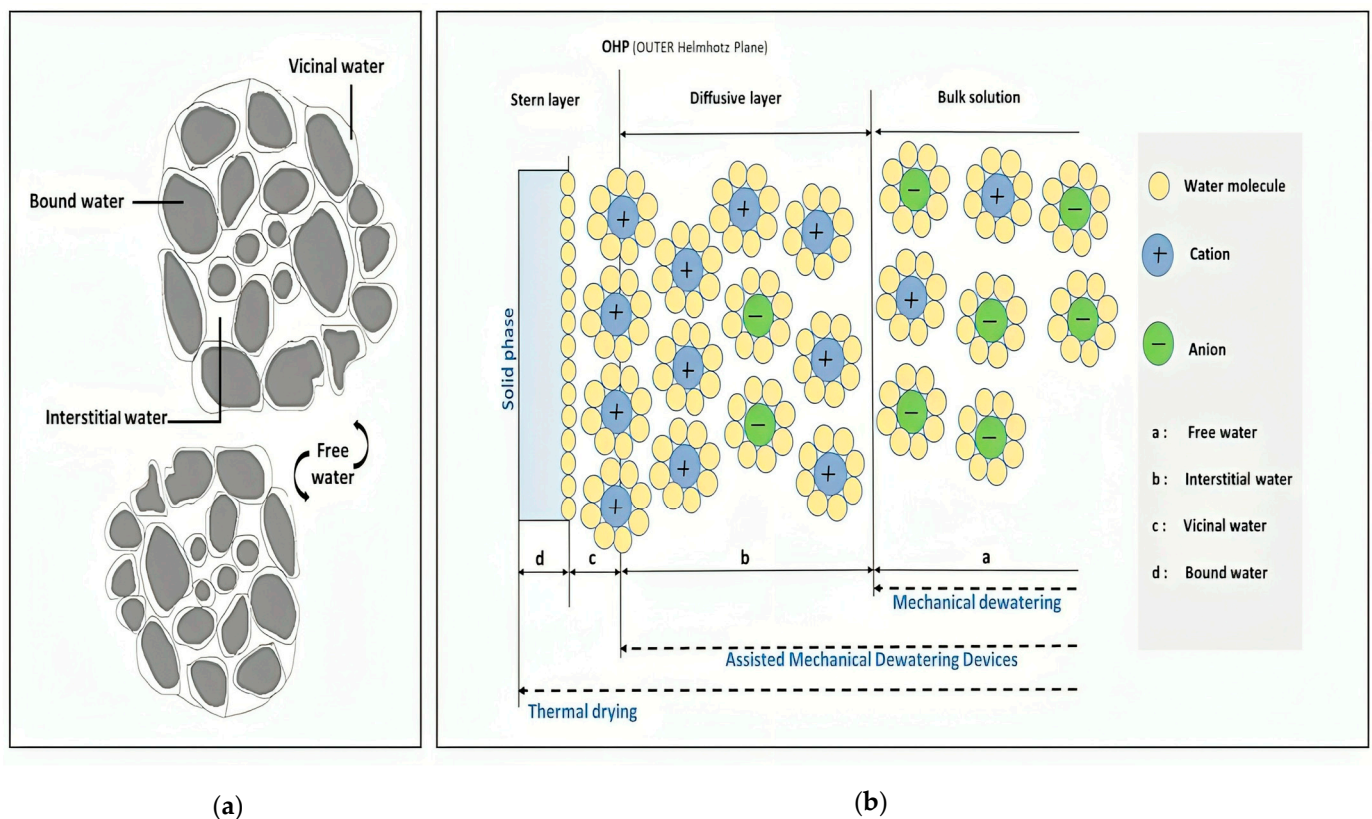
Figure 5. Dewatering methods and their relationship to water distribution in materials (**a**) water distribution in the materials and (**b**) dewatering methods inspired by [96,99].

The solids content of mine tailings is commonly used as a characterization parameter, indicating the approximate concentration of solid materials in the tailings at the time of delivery to the TSF. When considering the best available technologies (BATs) for tailings management, three categories incorporating tailings dewatering techniques can be identified: thickened tailings (usually consisting of approximately 40%–65% solids by mass), paste tailings (typically containing 65%–80% solids), and filtered tailings (with a solids content exceeding 80%). With respect to fluid dynamics, slurries can be categorized as either Newtonian or non-Newtonian fluids based on their flow characteristics. Presently, the disposal methods for tailings often involve dealing with low-concentration Newtonian mixtures. These mixtures are pumped with turbulent flow into disposal ponds. However, paste and thickened tailings typically display non-Newtonian properties [100–102]. These categories represent a spectrum of tailings characterized by varying solid concentrations and yield stresses (Figure 6).
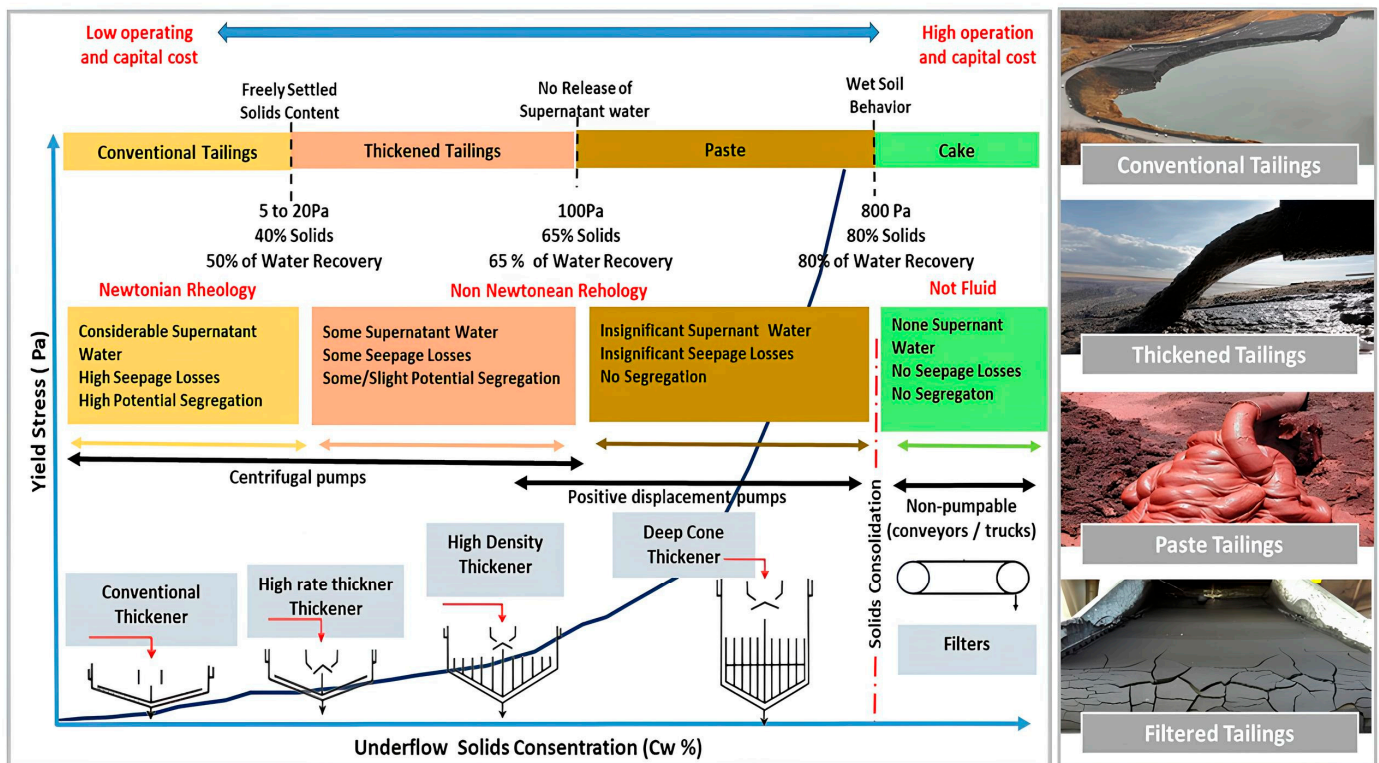
Figure 6. The tailings continuum, modified after [85,86].

5.1. Mechanical Dewatering

5.1.1. Gravitational Settling

Thickening is an industrial process used in mining and mineral processing to separate solid particles from liquids and increase the concentration of solids. Thickening utilizes gravity in large tanks called thickeners to separate particles from water, resulting in a more concentrated slurry or paste by removing a portion of the liquid [103].

The settling and interaction of particles in processes involving sludge or suspensions are influenced by two mechanisms: free settling and hindered settling. Free settling occurs when the particle concentration is low, typically below 15% by weight of solids, and when particles are well dispersed in the liquid. In this mechanism, particles settle independently and quickly, forming a compact layer at the bottom of the tank, facilitating efficient sedimentation and thickening. Conversely, hindered settling arises when the particle concentration exceeds 15%, leading to interactions among neighboring particles. This interference results in reduced settling rates due to factors like particle collisions, hydrodynamic interactions, and the formation of aggregates or flocs. Hindered settling is less efficient for separation and may require the use of flocculants or coagulants to promote particle aggregation and enhance thickening efficiency [95,104,105].

Settling Rate Enhancement

Several factors play a pivotal role in influencing the intricate sedimentation process, including particle size and shape, the concentration of solids in terms of weight and volume, fluid viscosity, and the specific gravity of both the solids and the liquid.

Stokes' law establishes connections between the settling velocity, the gravitational field strength (g), the characteristic particle size (D_P) the particle density (ρ_P), and the density (ρ_f) and viscosity of the carrier fluid (μ_f) [95].

$$V_\infty = \frac{gD_P^2\left(\rho_P - \rho_f\right)}{18\mu_f},$$

(1)

According to Stokes' law (Equation (1)), it is evident that particles in the larger size fraction settle at a significantly faster rate compared to silts and clays. Due to their small particle size, ultrafine tailings possess a significant specific surface area and high reactivity, which makes them challenging to settle rapidly within a limited time through gravity alone [106].

Enhancing gravity sedimentation involves various strategies, such as increasing particle size, adjusting particle density, reducing particle concentration, optimizing tank design, and using settling aids like flocculants or coagulants [107].

The presence of fine solids in mineral tailings represents a significant obstacle in various industrial processes, particularly in mining and mineral processing operations. These fine particles, often micron-sized, have a propensity to remain suspended in water for extended periods, leading to complications such as increased viscosity, reduced settling rates, and compromised water quality. One of the primary challenges in dealing with fine solids suspension is their inherent stability, which stems from surface charges and electrostatic repulsion preventing the particles from agglomerating and settling. This stability makes conventional sedimentation methods ineffective, as fine solids remain suspended rather than settling out of the solution. As a result, alternative approaches are necessary to induce particle aggregation and facilitate their removal from the liquid phase. Coagulation and flocculation are two widely employed techniques for destabilizing fine solids and promoting their agglomeration [108]. Coagulants, such as metal salts or polymers, are added to the suspension to neutralize surface charges and facilitate particle collisions. Common coagulants used in mine tailings dewatering include aluminum sulfate, ferric chloride, and lime. Flocculants are then introduced to promote the formation of larger, settleable aggregates from the destabilized particles. It involves the addition of polymer flocculants, which are water-soluble polymers that can form flocs from individual small particles in a suspension through various mechanisms such as bridging, charge neutralization, electrostatic patching, and depletion flocculation [109]. There is a wide range of polymer flocculants on the market, which can be categorized into two main types: nonionic polymers and polyelectrolytes (including cationic and anionic). Synthetic organic polymers, such as polyacrylamide (PAM), polydiallyldimethylammonium chloride (PDMDAAC), and polyethylene oxide (PEO), are extensively employed in thickening operations within mineral processing [110,111]. Together, these processes enable the formation of larger, denser flocs that can settle more rapidly under gravity, facilitating the separation of solids from the liquid phase.

While synthetic polymers have been predominant, concerns over potential harm from residual monomers have led to efforts to develop safer alternatives. Natural polymers, such as moringa seeds, cactus pads, pectin, starches, guar gum, tannins, chitosan, and sodium alginate, offer non-toxic alternatives. Moreover, there is a growing interest in bio-based synthetic polymers that replicate the non-toxic and biodegradable characteristics of natural polymers, aiming to strike a balance between functionality and environmental safety [83,112].

The characteristics of polymers, including molecular weight, charge density, and types of charges, significantly impact flocculation and destabilization processes [110]. Studies have shown that anionic flocculants with lower ionic strength and molecular weight, as well as cationic flocculants with higher ionic strength and molecular weight, demonstrate better settling efficiency. Additionally, the molecular weight and charge type of polymers affect the size, density, and reversibility of flocs [93,110]. In the context of mine tailings, high-molecular-mass anionic polyacrylamides are generally preferred due to their ability to achieve high initial settling rates at relatively low dosages and costs [113]. However, the effectiveness of flocculation in enhancing gravity sedimentation may vary depending on the type of tailings. Conducting research on the effectiveness of flocculation in different tailings types, such as clay-based tailings, would be beneficial.

Over the years, research efforts have been dedicated to optimizing sedimentation processes for various types of mine tailings, such as copper sulfide, coal, iron, and phosphate tailings [91,114–118]. Overall, these studies emphasize the need for tailored approaches to optimize sedimentation processes for different types of mine tailings, taking into account the complex interactions between operational conditions, particle characteristics, and aggregate behavior. For instance, Arjmand et al. [91] conducted a study on iron ore tailings and found that flocculation efficacy increases with higher slurry pH and flocculant dosage coupled with lower slurry solids content. Conversely, Dash et al. [81] observed a different trend in their study on iron tailings. They found that lowering pH resulted in a decrease in settling rate, while higher pH levels led to poor supernatant clarity, indicating ineffective flocculation for very fine particles. This highlights the complexity of tailings behavior and the need for nuanced adjustments in operational conditions. In addition, depending on the physical and chemical conditions during the flocculation/coagulation process, aggregates can exhibit variations in their structural characteristics, including size, porosity, shape, and fractal dimension [119,120]. Increased agitation results in a more pronounced breaking of bonds within the particle or aggregate networks forming the slurry, which occurs prior to the sedimentation phase. This renders the aggregate formations more delicate and porous. Consequently, greater mixing intensity is linked to reduced yield stress values and reduced aggregate size [119].

To recapitulate, thickening performance relies on three key factors: (i) particle surface chemistry, particularly of the fine particle constituents, which encompass common clays like kaolinite and smectite; (ii) water chemistry, including aspects like dissolved salts, pH, salinity, and polymer properties; and (iii) hydrodynamic conditions that facilitate effective mixing. The accurate characterization of tailings plays a crucial role in achieving an effective thickener design. This characterization involves not only defining the average particle size distribution but also considering the average particle size and the variability of this distribution, along with specific gravity, clay content and type, and how these parameters vary over time. Understanding the interplay of these factors is crucial for designing large-scale units and optimizing water management. Notably, the interaction among these factors is intricate, and enhancing our comprehension of them holds significant value [114,121].

Thickener Types

The evolution of thickening technologies in mining, particularly in the context of dewatering and water recovery relating to mine tailings, marks a transformative journey since the inception of Dorr thickener in 1905. This innovation initiated the continuous extraction of water from dilute pulps, enabling the concurrent discharge of thick pulps with consistent density and clarified solutions [122].

Distinct types of thickeners are differentiated by their tank design, each with varying degrees of openness: conventional, high rate, high density, and paste thickeners [95,101]. Conventional gravity thickeners (CTs) form the foundational type of thickener, relying on gravitational forces to settle solid particles within tailings. These typically consist of cylindrical tanks with wide diameters (ranging from 25 to 200 m) and shallow depths (1 to 7 m), with a cone angle between 2 and 5 degrees [95,101,123]. However, they often result in lower concentrations in the underflow, around 30%–45%, necessitating relatively low energy consumption for operation [124,125].

The introduction of synthetic polymers as flocculants in mining led to the development of high-rate or high-capacity thickeners (HRTs). These thickeners are characterized by cylindrical tanks of varying diameters, typically between 4 and 18 m, and a 5-degree cone angle. They are specifically designed to incorporate feed dilution and are capable of settling at a faster rate than conventional thickeners [126]. They achieve a higher solids concentration in the underflow (45%–60%) and yield stresses of less than 30 Pa through enhanced settling facilitated by flocculants or coagulants. While effective, their high use of flocculants can escalate operational costs [85,101,127]. In large copper mining operations, this technology is favored due to its superior performance in handling higher solids

content and its flexibility compared to conventional thickening methods. Additionally, this technology allows for smaller equipment diameters or fewer thickeners, resulting in more favorable economic evaluations [128].

High-density thickeners (HDTs) or high-compression thickeners (HCTs) represent a technological advancement from HRTs, utilizing deeper mud beds to expedite thickening and boost underflow density. While sharing some design elements with paste thickeners, their operation results in an underflow slurry characterized by a significantly high yield stress, typically around 100 Pa. As a consequence, HDT underflow slurries commonly demonstrate non-Newtonian rheology. HDTs are meticulously engineered to generate a slurry that can be efficiently transported using a centrifugal pump [129].

The deep cone thickener (DCT) stands out as an advanced sedimentation technology, employing steep cone angles (15–30°) and deep mud beds to achieve efficient dewatering and high underflow densities (up to 70% *w/w*). The design facilitates handling fine particle sizes and challenging tailings compositions [101,130,131]. This approach not only optimizes land use but also enhances safety by reducing environmental risks associated with tailings management, thereby promoting sustainable mining practices.

The adoption of high-density or paste thickening technology has significantly increased due to its processing efficiency. With increased solid content in thickener discharge, the yield stress escalates, requiring rheological modifiers or shear thinning systems. Transporting high-solid tailings often necessitates costly positive displacement pumps with high energy consumption. This poses a challenge, especially in scenarios where cost-effectiveness and energy efficiency play crucial roles in determining the overall project viability [128,132].

5.1.2. Advanced Centrifugal Techniques for Sedimentation and Filtration

Efficient separation and dewatering of particles are critical processes in various industries. While larger particles under 5 mm can be efficiently dewatered using gravity-driven methods like screens, dealing with finer particles is more complex. These fine particles retain more moisture, presenting a significant challenge. To address this challenge, centrifugal techniques and advanced filtration systems are employed [133].

Mechanical separation technologies using centrifuges employ centrifugal force to separate components in a mixture based on density differences. In this process, solids are influenced by the centrifugal force, which is determined by their distance from the rotating axis and the speed of rotation. Nowadays, centrifugal forces of 29,420 m/s^2 ($3000 \times g$) are commonly used to dewater various types of sludge. With centrifuge technology, over 90% of the process water can be recovered, making it suitable for reuse in mineral processing operations and significantly improving water efficiency within the mining community [134,135].

These centrifuges machines are meticulously crafted to serve two distinct yet interconnected purposes: thickening and filtering suspensions. Centrifugal sedimentation can be carried out using either hydrocyclones or sedimenting centrifuges, while centrifugal filtration is accomplished using filtering centrifuges [95,123,136].

Hydrocyclones

Hydrocyclones rely on centrifugal force to either concentrate or classify solids within the feed suspension [137]. However, due to their inherent characteristics like size, shape, and density-based classification, it is unavoidable that one stream will carry a lower percentage of solids with finer particles while the other stream will contain coarser particles with a higher solid content [138]. Numerous hydrocyclone sizes are available, with cylinder diameters ranging from 1 to 30 cm and cone angles between 25° and 50° [127]. Hydrocyclones, being high-capacity devices, have the capability to handle feed rates of up to 7200 m^3/h and can concentrate solids up to 50% (*w/w*) in the underflow discharge [18].

Several factors impact the efficiency of cyclones in the design of TSFs. These factors encompass the material's feeding characteristics, including parameters like solids percentage, particle size distribution, and mineral composition. The cyclone configuration, involving dimensions, vortex finder diameter, spigot dimensions, inlet pressure, and cone angle, plays a crucial role in determining its efficiency [139,140].

Hydrocyclones can achieve optimal dewatering performance by configuring them with the right geometry and inlet pressure, as researchers have found that a conical-shaped extension improves overall productivity [127,141]. The potential application of hydrocyclones for dewatering copper concentrate tailings in cement paste backfill showed that using smaller apex diameters and larger vortex finder diameters resulted in a higher solid content in the underflow [138]. Additionally, reducing the cone ratio led to a decrease in the solid content of the underflow. By selecting the appropriate geometry and solid content, a potential increase of up to 71% was achieved [138].

Sedimenting Centrifuges

Centrifuges are vital machines in both production and operation, with key factors such as bowl diameter, length, throughput, feed concentration, and particle size playing critical roles. They come in various sizes, with bowl diameters ranging from 15 to 150 cm; the length of the centrifuge bowl is typically about twice its diameter. Throughput, a critical parameter, ranges from 0.5 to 50 m^3/h for liquids and 0.25 to 100 t/h for solids, influenced by factors like feed concentration and particle size. Centrifuges handle feed concentrations from 0.5% to 70% solids and a wide range of particle sizes, from 12 mm to as fine as 2 μm, facilitated by flocculation [95].

The final moisture content can vary widely and typically falls within the range of 5%–20%. However, an increase in the fine fraction percentage can lead to the moisture content increasing to 40%. In various industrial settings, data from centrifugation processes have shown a broad range of results, with lime cake solids concentrations ranging from 55% to 70% by weight, whereas alum sludge centrifugation only managed to attain 12% to 20% solids by weight. The specific outcome depends on the application and the desired properties of the separated components [95,127,142–144].

There are various types of industrial sedimenting centrifuges used for a range of applications, including mine tailings dewatering. Among these, we find the solid bowl decanter, basket, disc stack centrifuge, and tubular bowl, all of which are currently employed in the coal industry. The solid bowl centrifuge, commonly referred to as a decanter, holds immense importance in the minerals industry due to its impressive versatility and continuous solid discharge capability [123,127,145,146]. In this example, a horizontal decanter centrifuge is employed to treat flocculated mine fine tailings (MFTs). It processes a feed rate of 270 m^3/h, producing a solid product with a 60% (*w*/*w*) ratio while simultaneously recovering process water containing less than 1% solid content [147].

Filtering Centrifuges

Filtering centrifuges, also known as centrifugal filters, operate through a distinct separation mechanism. These centrifuges utilize a filter medium, often in the form of a porous wall or screen, to facilitate the separation process. In this method, a liquid mixture is subjected to a spinning motion, causing the liquid to pass through the filter while retaining solid particles on the filter medium. This approach proves effective for separating particles that exceed the size of the filter's pores.

The primary application of filtering centrifuges lies in scenarios requiring precise separation of fine particles or clarification of liquids. These centrifuges employ centrifugal forces to achieve batch and continuous cake filtration on surfaces that are either cylindrical or conical and semi-permeable. Furthermore, many filtering centrifuges are equipped to perform displacement washing operations and efficiently remove liquid from the filtered cake.

There are various types of industrial filtering centrifuges. Among these, we find screen bowl centrifuges, screen scroll centrifuges (worm screen), baffle centrifuges, and

filtering basket centrifuges such as pusher, pendulum, and peeler baskets [127,148]. For larger particle sizes, the vibratory centrifuge and screen scroll centrifuge are commonly employed. The former employs vibrations to facilitate particle movement, whereas the latter utilizes a screw conveyor. For smaller particles, typically under 1 mm in size, both the screen scroll centrifuge and the screen bowl centrifuge are popular options due to their effective handling of fine particles [133]. It is possible to directly add flocculants to the solid bowl section of the screen bowl, thus counteracting the high shear stress that breaks apart flocs [127]. The attributes of some sedimenting and filtering centrifuges are outlined in Table 2.

Table 2. Characteristics of sedimenting and filtering centrifuges [127,142,148].

Typical Use	Centrifuge Type	Centrifugal Force (g)	Rotational Speed (rpm)	Throughput of Solids (m³/h)	Particle Size (µm)	Feed Concentration
Sedimentation	Tubular bowl	10,000–65,000	Up to 50,000	Up to 4	0.1–100	<5% *w/w*.
	Basket	Up to 1600	Up to 3500	6–10	0.1–100	<5% *w/w*.
	Disc stack or Disc bowl centrifuges	Up to 14,000	Up to 10,000	Up to 200	0.1–100	0.05%–10% *w/w*
	Scroll decanter	2000–6000	Up to 6000	Up to 100–120	1–5000	4%–60% *w/w*.
Filtration	Pusher	500–1700	N.A	Up to 80	40–7000	10%–40% *w/w*.
	Peeler basket or horizontal axis basket centrifuge	800–2200	Up to 1500	Up to 15	2–1000	4%–30% *w/w*
	Screen scroll centrifuge or Worm screen	500–2600	Up to 700	Up to 150	60–5000	10%–40% *w/w*

N.A.: Not available.

Flocculant Considerations

The presence of a flocculant plays a pivotal role in the dewatering process of mine tailings through centrifugation. Using alkoxysilanes as flocculants for oil sands dewatering, particularly bis(3-trimethoxysilylpropyl)amine in conjunction with centrifugation, has yielded significant outcomes. These include achieving a capillary suction time of less than 20 s, reaching over 42 wt% solids content in sediments, minimal supernatant solids (0.2 wt%), and low turbidity [149]. Furthermore, Nguyen et al. [145] demonstrated that a combination of chemical reagents and solid bowl centrifugation could achieve a 98.6% solid recovery while maintaining a 38.9% moisture content in fine coal tailings cake. These diverse approaches highlight the potential for enhancing dewatering processes using a combination of centrifuge technology, polymer treatments, and chemical additives.

However, challenges can arise in this process. One of the primary challenges is selecting the right type and dosage of flocculant for the specific composition of the mine tailings. Moreover, controlling flocculation poses greater difficulty than a belt filter, given that the entire process takes place internally within the machinery. The centrifuge principally subjects flocs to significant forces (2000–4000 g), risking their rapid destruction if the polymer is improperly chosen or dosed. Operational issues include black and unusually colored centrate due to particles returning to the process, gray foamy centrate indicating problems, and low dryness of the sludge cake with a lower solid content than desired [144].

5.1.3. Filtration Techniques

The filtration of tailings, an established mining practice, ensures a consistently unsaturated state in disposed tailings. This state offers several benefits, such as eliminating the need for dams and enabling the recovery of process water, which is otherwise lost to

evaporation or seepage [150]. Filtration involves using porous media such as woven fabric or non-woven materials to separate solids from liquids. The procedure lets liquid (filtrate) pass through while retaining solid particles on the surface of the filter, resulting in a filter cake. This process comprises five stages: cake formation, moisture reduction, possible cake washing, cake discharge, and medium washing [151].

The filtration process involves separating the water from the solid particles in the slurry using various types of filtration equipment. Different filtration methods can be used, including vacuum filtration, pressure filtration, and centrifugation [146]. The moisture content of the filter cake from tailings is typically between 15% and 25% by weight [150,152], but certain mining operations may request higher moisture levels up to 30% [133,143,153]. Research literature indicates that the moisture content of dehydrated solids depends on the dewatering methods employed and the particle size. Filtration techniques typically result in the formation of high-moisture-content cakes at smaller particle sizes, generally below 200 μm [154].

Vacuum Filtration

Overall, filtration occurs by generating a vacuum on the backside of the filter material using a liquid ring vacuum pump. The filtered liquid is accumulated in a filtrate container and subsequently pumped out using a sealed pump or a barometric leg system. This liquid is then directed toward the circulating water system or the plant's effluent stream [146]. There are various types of vacuum filters: rotary drum filters, rotary disc filters, and horizontal belt filters [155].

Horizontal rotary tilting pans and horizontal belt vacuum filters are typically capable of handling particle sizes ranging from 20 to 80,000 μm and feed concentrations spanning 5 to >30% w/w. This configuration effectively separates solids from liquids and accommodates a wide range of particle sizes and concentrations. In contrast, rotary drum and rotary disc filters specialize in a narrower range of particle sizes. The rotary drum filter focuses on particle sizes ranging from 1 to 600 μm and feed concentrations of 1%–20% w/w, while the variants of the rotary disc filter excel in handling particle sizes from 1 to 700 μm and feed concentrations of 5%–20% w/w. Importantly, rotary disc filters boast impressive throughput capabilities, scaling up to 100 metric tons per hour, making them well-suited for high-volume processing scenarios [127].

Horizontal belt filters and disc filters are widely used for the dewatering of fine coal. Horizontal belt filters offer a distinct advantage in terms of enhanced performance compared to other types of filters, as they provide a substantial horizontal dewatering area. They also allow for easy control of belt speed and feed rate. The primary disadvantage remains concerning the fact that the unit exhibits a low dewatering rate per square footage of floor space [133]. The high-performance vacuum disc filter, specifically the Boozer disc filter, is successfully used for dewatering tailings in various applications, such as mining (gold/copper, zinc, and gold/silver), the alumina industry, and coal slurry dewatering [150].

Pressure Filtration

Pressure filtration represents a significant advancement over vacuum filtration, as it employs a much stronger driving force for solid–liquid separation (SLS), leading to enhanced filtration speed and notably reduced moisture content in the final cake. The filtration process can be divided into two primary categories: batch filtration and continuous filtration. Continuous filtration includes processes such as rotary drum filters, screw press, and rotary disc filters. On the other hand, batch filtration involves plate and frame filters and pressure leaf filters, for example [155]. Continuous pressure filters are designed to handle particle sizes ranging from 1 to 200 μm, with feed concentrations ranging from 0.2% to 30% by weight. On the other hand, batch pressure filters, like filter presses (plate and frame or recessed plate press), typically manage particle sizes between 1 and 100 μm and feed concentrations ranging from less than 1% to as high as 30% by weight [127].

The commonly used types of filter presses for dewatering tailings include the belt-type filter press, box-type filter press, vertical filter press, and plate–frame filter press [132,156]. Belt filter presses require feed pretreatment, often involving flocculation, and typically offer capacities of 3.6 to 10 t/h/m for fine tailings, producing materials with a composition ranging from 45% to 70% solids. Belt presses are characterized by moderate initial investment expenses, but their operational costs are significantly elevated due to the substantial need for flocculants. On the contrary, filter presses like the plate-and-frame type are more expensive; however, they allow for nearly complete retention of solids. This results in a final product containing surface moisture ranging from 18% to 30% by weight [18,133]. In addition to purely economic analysis, there is potential for filtration to become more appealing when considering sustainability. Despite advancements in pressure filtration equipment capacity and industrial testing, the results have not met expectations, and there is not enough technical maturity for large-scale implementation in mining projects. Suppliers are still refining pressure filtration technologies to increase processing capacity for potential integration into large-scale mining operations. However, filtering the total tailings from a plant processing around 100 ktpd would require numerous filters, leading to complex filtration cycles and necessitating a conveyor and stacking system, which are operationally challenging.

Filtration and Centrifugation

Although the centrifugal dewatering process has been shown to be efficient in filtering larger particles (>200 μm), the current methods utilized for removing water from small particles are ineffective when it comes to reducing moisture content or recovering solids. To address these issues, a new advanced method for dewatering very fine particles has been developed, known as hyperbaric centrifugation or CENTRIBARICTM technology. This innovative apparatus combines g-force and air pressure in a single filtration unit, significantly surpassing the moisture reduction achievable with traditional dewatering systems. Experimental results demonstrate that applying air pressure to the centrifugal vessel significantly reduces filter cake moisture content. In testing, a prototype unit utilizing both centrifugation and pressure filtration on a fine coal slurry achieved a product moisture level below 20%, accompanied by a dry solids recovery rate of over 97%. This success was observed even when the initial feed material was largely composed of particles smaller than 44 μm. This advancement eliminates the energy-intensive thermal drying method, known for its costliness and environmental impact. Moreover, this innovation holds promise for dewatering various organic and inorganic fine particles, presenting a solution to lower costs and address environmental concerns in fine-particle processing plants [154,157].

Operational Considerations

The challenges in filtering and dewatering tailings stem from the specific properties of tailings. These characteristics encompass a range of factors, including the fine particle size (ranging from 10 to 100 μm), which results in difficulties during the filtration process. The filter cakes that are formed often possess a sticky consistency, thereby complicating their removal from the filter fabric. Moreover, the pH levels can vary significantly, with either acidic or alkaline conditions prevailing, leading to corrosion issues that impact the functionality of the equipment. Furthermore, the presence of clay content in certain tailings, attributed to the source ore, presents an additional obstacle to effective filtration due to its cohesive and fine-grained nature. This attribute has the potential to cause filter clogging and impede the separation of water from the solids. The variability in moisture content, influenced by factors such as grain size and mineral composition, further compounds the challenges by affecting the performance of the filtration process and ultimately impacting the quality of the final tailing product [150,153].

Overall, the use of flocculants helps to optimize filtration processes by reducing the impact of fine particles or slimes on filter performance. It is important to choose the appropriate flocculant type and dosage based on the specific characteristics of the particles and the filtration system to achieve the desired results. Flocculants with lower molecular weights are mainly utilized since they create smaller aggregates, resulting in a more uniform and permeable filter cake. The use of these flocculants leads to a filter cake that possesses a consistent and porous structure. This configuration enables effective dewatering, allowing water to quickly pass through the pores while retaining fine particles within the cake [95,151].

5.1.4. Hybrid Mechanical Dewatering Methods (Dewatering Circuit)

The role of a dewatering circuit is to remove water from the slurry, typically through a series of stages that involve different methods of dewatering. This system aims to enhance operational efficiency, refine output quality, and provide flexibility in material handling.

A typical dewatering circuit includes several stages. Firstly, in the preliminary dewatering stage, methods like sedimentation or gravity separation are employed to eliminate larger particles and water. Following this, the primary dewatering stage utilizes techniques such as filtration or centrifugation to further reduce the water content. Then, in the secondary dewatering stage, thermal methods like drying or chemical treatments are applied to eliminate any remaining water, achieving the desired level of dryness. Finally, in cases where it is feasible, water is recovered and treated for reuse in the process, promoting water recycling.

Hydrocyclones, screens, or a combination of both are extensively employed as alternative technologies for achieving dewatered mine tailings. Using hydrocyclones in the dewatering circuit does not mean eliminating the thickener and the filter from the process. Instead, these pieces of equipment will process the overflow stream from the hydrocyclone. This flow sheet can potentially enhance the overall performance of the circuit since the thickener receives a lower solids concentration. Consequently, a higher solids concentration is expected from the thickener's underflow [138]. In this situation, there is an elevation in the fine fraction of the thickener feed, potentially posing a thickening challenge. Additionally, the increase in residence time of the sediments in the thickener is a consequence of a decreased feed flow rate, which could potentially provide benefits [140]. Figure 7 presents examples of dewatering circuits that incorporate mechanical dewatering devices.
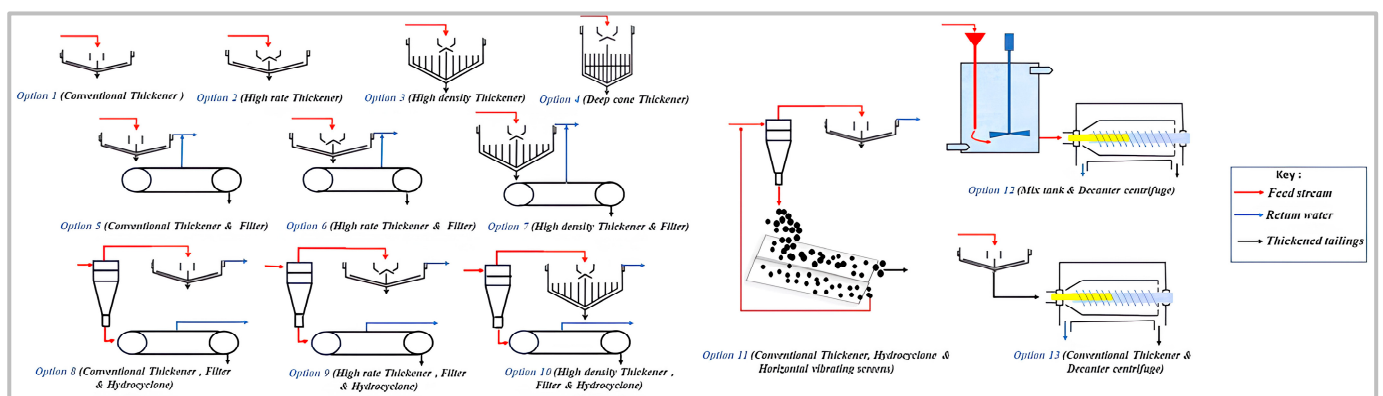

Figure 7. Examples of dewatering circuits that incorporate mechanical dewatering devices.

Combining hydrocyclone particle classification with dewatering using horizontal vibratory screens presents a viable alternative process for dewatering mine tailings. This alternative technology, referred to as HC-HVS, involves extracting water from the coarse fraction of the tailings (sands) through two hydrocyclone stages. Subsequently, the cycloned tailings sands are subjected to a dewatering stage on horizontal vibratory screens, reducing their moisture content and forming a solid "cake." These dewatered mine tailings are then collected from the screens and either directed to a designated collection area or conveyed for disposal or further processing. This method offers several advantages in terms of efficiency and water recovery, making it an appealing option for certain mining operations [158]. Gomes et al. [159] conducted a study on the combination of hydrocyclone particle classification and various dewatering techniques, including screening, thickening, and filtering, to dewater iron mine tailings at a pilot scale. These tailings, resulting from mineral processing and classified within the 45-µm range, were subjected to a series of processes. First, they underwent thickening and filtration using a horizontal filter press at a rate of 200 t/h for particles smaller than 45 µm. Then, dewatering screening was performed at a rate of 100 t/h for particles larger than 45 µm. This process yielded a final moisture of 15%, which was suitable for storing the dried tailings. Considering the projected project duration, an estimated USD 35 million is needed to maintain the dam's operational capability. This sum is equivalent to seven times the initial capital investment (CAPEX) of USD 5 million, which was initially needed for the installation of the dewatering circuit, including screening, thickening, and filtering. Figure 8 indicates that HC-HVS technology is competitive for water recovery from mine tailings, coming in second place with an 89% efficiency rate, just behind filtered tailings. This suggests its appeal for environmentally conscious tailings management and maximizing water recovery. However, while HC-HVS technology shows potential for dewatering non-fine and low-plasticity tailings, concerns arise about its scalability for larger production operations exceeding 25,000 metric tons per day [158].
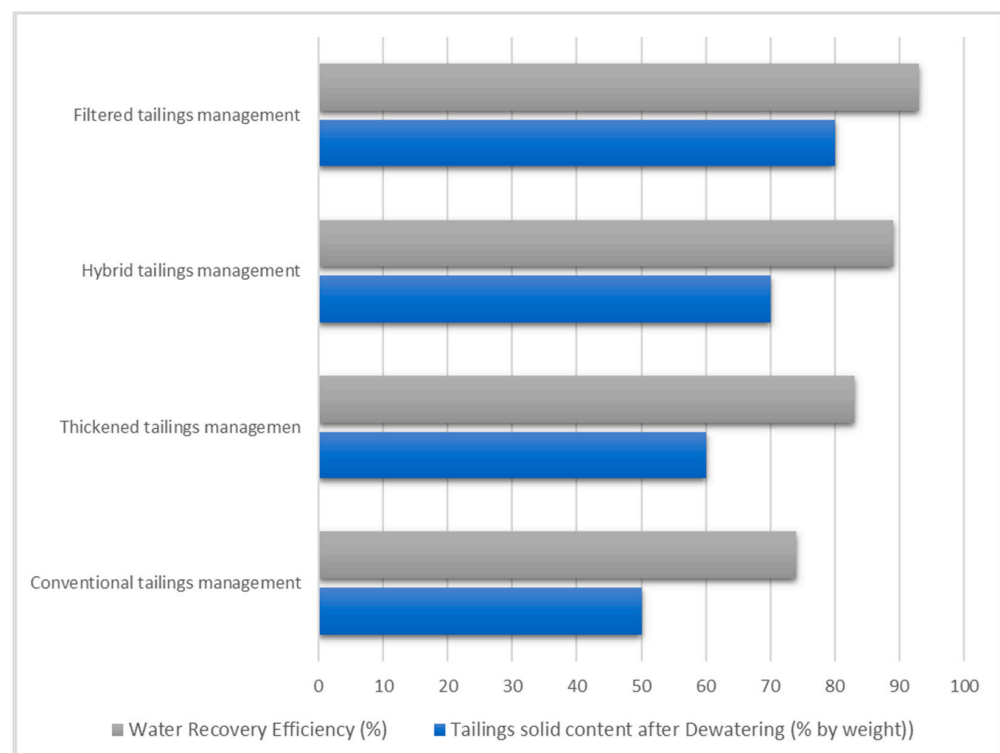
Figure 8. Comparative assessment of water recovery in diverse mine tailings management approaches [158].

5.2. Innovative Techniques for Enhanced Tailings Dewatering (Assisted Mechanical Dewatering Devices)

Conventional techniques for separating water from suspensions, sludges, and slurries, such as vacuum filtration, centrifugation, vibration screening, thermal drying, and ponding, have long been employed. However, these methods present certain challenges, including issues like blockage caused by fine particles, the complexity of separating colloidal and small-particle suspensions, elevated energy consumption, and the generation of dust-related problems. To address these challenges, alternative and advanced separation techniques have emerged, offering solutions [160]. These include methods involving ultrasound and/or magnetic fields, the application of combined forces such as electric and ultrasonic forces, and the integration of microwave-assisted dewatering, among others. When combined with traditional mechanical methods, these approaches create a synergistic effect, resulting in a highly efficient dewatering system [97,160–162].

5.2.1. Electrical Mechanical Dewatering

Mechanical dewatering techniques like filtration and centrifugation are commonly used to remove free water from sludge. In contrast, electro-dewatering aims to eliminate both vicinal and capillary water through the application of electric fields. Electro-dewatering is proposed as an alternative approach to address the challenges of energy consumption and the environmental impact associated with traditional drying methods. This technique presents several advantages, including reduced energy consumption compared to traditional mechanical dewatering methods, the possibility of treating sludges with higher initial moisture content, high efficiency, and the prevention of filter media blockage due to concentrated sludge particles [96,98].

Electro-dewatering utilizes various electrokinetic phenomena such as electrophoresis (movement of charged particles in an electric field), electroosmosis (movement of water through porous media), ion electromigration (movement of ions), and dielectrophoresis (particle movement due to electric field gradients) to aid in water removal. To harness these phenomena, various processes have been developed. These include electroosmotic dewatering, electrowashing, dielectrophoretic separation, and electrofiltration (or other similar processes, depending on the type of mechanical separator they are employed with, such as electrosedimentation, electrocentrifugation, etc.) [156,163]. Both dead-end electrofiltration and electroosmotic dewatering use similar devices, with "electroosmotic dewatering" specifically involving the application of an electric field during the solid–liquid expression phase [98]. Early application of electrokinetics in tailings management involved the removal of moisture from coal tailings [164]. Further research has investigated the use of electro-dewatering in mining and other industries to reduce moisture in different materials, including Cu tailings [165], bauxite tailings [166], mineral sands tailings [167], Au mill tailings [168], mineral drilling sludge [169], oil sands tailings [170], phosphate clay [171], kaolin suspension [172], silica suspension [173], and bentonite suspension [174].

Electro-dewatering involves placing electrodes within sludge and passing an electric current to enhance dewatering, while electric field-assisted dewatering combines electric fields with pressure to improve separation. The current promotes the movement of water within the sludge towards the electrodes, causing the water to be separated from the solid components and eventually discharged in a more concentrated form. The most efficient method involves using direct current (DC) or alternating current (AC) and voltages ranging from 10 to 200 V to assist in pressure dewatering (PDW) [85,175,176]. Furthermore, raising the voltage (or current density) results in a drier sludge cake. The electro-dewatering system involves setting up an electrochemical cell with an anode and a cathode. Electrochemical reactions occur at the electrodes due to the applied electric field. At the anode, oxidation reactions take place, resulting in the release of oxygen and the generation of protons (H^+ ions). At the cathode, reduction reactions occur, leading to the generation of hydrogen gas and the consumption of protons. The electrochemical reactions at the electrodes can cause changes in the pH of the sludge or wastewater. An increase in pH at the

cathode (due to the release of hydroxide ions, OH^-) and decrease at the anode (due to the release of protons) can have significant effects on the properties of the sludge. The changes in pH, along with the movement of ions caused by the electric field, affect the behavior of water molecules and solid particles in the sludge. The electrochemical reactions and pH changes can disrupt the surface tension of the water and alter the interactions between particles, leading to improved dewatering [96,177,178]. Cost-effective electrode materials like aluminum, copper, and steel are frequently employed in these processes due to their electrical conductivity and widespread availability. Nevertheless, a notable challenge associated with using these materials as electrodes is their susceptibility to rapid corrosion [85,179].

Several factors, such as voltage, pressure, temperature, electrode materials, and dewatering time, play a crucial role in the efficiency of combined mechanical and electrokinetic dewatering processes [180]. Ensuring a sufficiently high zeta potential of the sludge particles is also crucial for the effectiveness of electrodewatering. This promotes electroosmosis and electrophoresis, facilitating water separation and enhancing dewatering efficiency [181]. The electro-osmosis method has demonstrated promising results in the dewatering of various tailing materials. Laboratory-scale experiments conducted with iron ore tailings showed that applying voltage gradients ranging from 15 to 90 V increased the solid content from 43% to 48%–87%, with energy consumption varying from 0.588 to 30.645 kWh/dry ton [182]. Additionally, a separate study on copper mine tailings revealed its effectiveness, particularly with tailings containing high fines content and initial moisture [183]. The EDW process could potentially reduce energy consumption by as much as 25% while attaining a sludge dryness of up to 60% [184]. Successful dewatering, starting from an initial solids content of 45%, reached a final solids content of 75%, utilizing 20 to 30 kWh/dry ton [167]. The energy needed to remove process water from mine tailings through electro-filtration/electrokinetics varies from 1 to 1200 KWh/t of removed water, depending on the mineral composition and water content. The electrical energy consumed is affected by the applied voltage and current. As such, it is advisable to apply mechanical pressure beforehand to reduce energy consumption [165,185].

Several studies have demonstrated that the combination of electro-dewatering with flocculants and coagulants can substantially enhance dewatering efficiency [98,186]. In recent years, significant advancements have been developed in the field of sludge management, particularly with the emergence of various commercial full-scale equipment designed for sludge electro-dewatering. These innovative technologies represent a substantial leap forward in addressing the challenges associated with sludge treatment and disposal. Notable examples of such equipment include the CINETIK Linear Electro-Dewatering system by Eimco Water Technologies, the ELODE electroosmosis dehydrator developed by ACE Korea Incorporation, the EDW system offered by Water Technologies of Australia, and the Electrokinetic solution from Electrokinetic Limited in the UK. These cutting-edge solutions signify a promising shift towards more efficient, sustainable, and economically viable approaches to sludge management [163].

5.2.2. Thermal–Mechanical Dewatering and Thermal Electroosmosis Dewatering

In the context of mechanical dewatering, the cost of separation varies from 1 to 50 kWh/m^3 of removed solvent, whereas thermal drying incurs a cost of 750 to 1150 kWh/m^3. Combining thermal energy with mechanical dewatering, known as thermally assisted mechanical dewatering (TAMD), represents a potential solution to the high energy consumption associated with thermal dryers. Significant improvement in dewatering can be attained by raising the temperature. High temperatures result in decreased liquid density, viscosity, and surface tension. Consequently, the volume of water retained in the pores diminishes, causing water to be expelled from the pores naturally due to gravity [96,162,187]. In this approach, the selected operating conditions, particularly the temperature being less than 100 °C and the pressure staying below 3000 kPa, represent an innovative method that results in substantial energy conservation by maintaining the water in a liquid state [187].

This versatility makes TAMD a potentially viable option for a range of industries and applications by offering a promising avenue for achieving optimal moisture reduction.

The combination of electric voltage and temperature-induced heating was investigated for the dewatering of wastewater sludge, sewage biosolids, and mine tailings through the electroosmosis process. A study on the electroosmosis process for dewatering alumina mine tailings showed that increasing voltage doubled electric current at low temperatures and quadrupled it at higher temperatures, leading to greater water collection [188]. However, higher temperature and voltage increased electroosmotic permeability, with the most efficient dewatering observed at 45 °C and 21 V. The effect of TAMD on a variety of materials and processing conditions, including temperature (21–90 °C) and pressure (300–3000 kPa), showed 70%–95% removal of the inherent water content found in talc, cellulose, and bentonite [187]. One application of the thermal–mechanical dewatering concept is the Centridry system, developed by Baker Process in Massachusetts, USA. This system employs a unique one-step process that combines traditional centrifugal dewatering with hot gas flash drying, all within a single compact and enclosed machine [189]. Another dewatering process, known as steam pressure filtration, has been developed at the Technical University of Karlsruhe, Germany. In this innovative method, pure steam is used to initially dewater the filter cake, followed by compressed air to further accelerate drying and reduce steam consumption [97,190].

5.2.3. Acoustic and Electroacoustic Dewatering (EAD)

The dewatering process involves two main steps: flocculation–sedimentation and thickening. Flocculants are added to the tailings tank to separate unclassified tailings from the suspension, but this can be costly and time-consuming [191]. Typically, thickening in deep cone thickeners takes over 4 h to achieve the desired concentration. Research is necessary to develop a new method to speed up the flocculation–sedimentation of unclassified tailings and rapidly increase underflow concentration. Microwave and acoustics (ultrasonics) technology, a recent development, offers a promising solution for improving tailings processing [192,193].

Ultrasound is a type of vibratory energy that operates at frequencies higher than 20 kHz. When ultrasonic waves propagate through a medium, they create intense localized compression and rarefaction forces due to their high frequency. In the case of a medium composed of two distinct phases, such as liquid and solid, the forces of compression and rarefaction between these phases are expected to be significantly amplified. These heightened compression and rarefaction forces are likely to disrupt surface tension and facilitate the separation of liquids from solids [160,191]. Ultrasonics can enhance dewatering in several ways: (i) absorption of acoustic energy generates heat, leading to vaporization, increased chemical reaction rates, and reduced fluid viscosity; (ii) cavitation generates ions, erosion, and local high temperatures and pressures; (iii) shear waves alter the viscosity of non-Newtonian fluids; (iv) stresses in press cake induce fractures, creating new fluid escape channels; (v) vibrational motion facilitates net liquid displacement through the press cake in the direction of gradients (gravity, pressure, or electric field); and (vi) a clean filter surface is maintained, preventing clogs [96]. Details on the mechanisms and applications of ultrasonic pretreatment of sludge are available elsewhere [96,194,195].

Ultrasound is widely used in mineral processing due to its significant impact, including vibration, cavitation, and other factors, along with its concentrated power, long-range transmission, and high efficiency, making high-power ultrasonics a preferred choice in industrial processes [196]. Ultrasound is a cost-effective and environmentally friendly technology that can improve the dewatering process of sludge, leading to a reduced need for flocculant additives [197]. The literature suggests that low-frequency ultrasound, typically ranging from 20 to 100 kHz but sometimes as low as 16 kHz, can enhance the separation of solids from suspensions [192,198].

In the context of sedimentation, numerous scientists have investigated the dehydration of substances like sewage sludge [199] and mine tailings [197]. The impact of ultrasound parameters, such as frequency (17–25 kHz), power (50–100 W), duration (5–20 min), and start time (3–12 min), was studied on the final underflow concentration of unclassified gold mine tailings in the presence of an anionic polyacrylamide flocculant [192]. Their findings revealed that ultrasound had a significant enhancing effect on the underflow concentration of the gold mine slurry, with frequency and power being the most influential factors. Under optimal conditions, the final underflow concentration reached 71.8%, marking a 4.3% enhancement compared to free flocculation [192]. In another study, the impact of various factors, including pulp density, flocculant addition, and ultrasonic treatment, was evaluated on the sedimentation of clay [200]. The findings showed that the use of ultrasonic treatment during sedimentation had a positive effect on clay sedimentation, resulting in increased settling rates and reduced settling times.

The combination of electrical fields and acoustical forces leads to a synergistic effect in these processes. The electrical field facilitates increased electroosmosis and electrophoresis, driving the migration of ions and charged particles. Simultaneously, the acoustical forces help to ensure that electrical continuity is maintained through the material by preventing filter blockage and promoting efficient cake compaction. This combined approach results in improved performance, reduced downtime and enhanced overall efficiency in such applications [201,202]. Battelle Laboratories conducted extensive research on electroacoustic dewatering (EAD) and successfully scaled up their EAD units. They designed and tested a commercial prototype belt filter press using data from bench-scale research, achieving significantly improved solids content in sludge at an energy cost of USD 19–27 per ton of dry solids, with the added benefit of reduced belt blinding due to ultrasonics. They found that the use of ultrasonics (1.7–6.0 kW) reduced specific energy consumption and simultaneously enhanced the filtration rate [203].

6. Tailings Dewatering Equipment Selection

The valuation of mining projects necessitates careful consideration of mine closure and rehabilitation processes. Beginning in the initial design phase, economic evaluations of Tailings Storage Facility (TSF) options must incorporate various management scenarios to ensure satisfactory closure while also meeting increasingly stringent regulatory standards and evolving stakeholder expectations.

Dewatered tailings present a feasible solution for mining projects of varying scales, provided the selection of suitable technology aligns with tailings characteristics. The selection of the most efficient and cost-effective equipment for a dewatering circuit requires a thorough understanding of the material properties, the desired water recovery level, and the specific application requirements. Table 3 provides a comparison of dewatering techniques in terms of their advantages and disadvantages, while Figure 9 presents a comparison based on the achieved moisture content level in the solid cake.

Table 3. Summary of different technologies available for tailings dewatering.

Dewatering Technique	Advantages	Disadvantages
Gravitational settling	Simple and cost-effective, requires minimal equipment, suitable for preliminary dewatering before more intensive processes.	Limited solid capture, slower process, not suitable for achieving very low moisture content.
Decanter centrifuge	Continuous process, good for materials with varying solids content, efficient separation.	Higher initial investment and maintenance costs, higher energy consumption compared to other methods, some noise and vibration, Moderate to high polymer demand
Hydrocyclones	Can achieve efficient separation of fine particles, relatively compact design, useful for pre-dewatering or size classification.	Limited dewatering capacity, not suitable for high moisture reduction, may require additional steps for further dewatering.
Vibrating screens	Simple design, suitable for coarse dewatering or preliminary screening, minimal energy consumption.	Limited efficiency for fine particles, may require multiple passes or subsequent dewatering steps, larger space requirement for high-capacity operations.

Table 3. *Cont.*

| Dewatering Technique	Advantages	Disadvantages
Vacuum filtration	Efficient for materials with fine particles, lower energy consumption compared to other mechanical methods.	Slower process, potential clogging of filter medium, may require pre-treatment to prevent clogging.
Filter press	Good solids capture, efficient for materials with high water content, relatively dry cake output.	Slower process, batch operation, larger space requirement, more maintenance, higher manual labor involvement.
Belt press	Continuous process, relatively efficient for large-scale operations, lower energy consumption compared to centrifuges, low polymer consumption and simple operation	May require chemical additives, potential for belt wear and maintenance, limited to materials that can be effectively dewatered on a belt.
Screw presses	Continuous process, low operating costs, lower energy consumption, small footprint, automated, low noise level	low capacity, high polymer use, limited particle size range, material limitations:
Electro-dewatering	Efficient dewatering, relatively quick process, reduced energy consumption compared to thermal methods, potential for use with various materials.	May require specific conditions to optimize performance, initial setup costs, potential maintenance of electrodes, limited adoption in some industries.
Thermal drying	Efficient for high-water-content materials, produces a stable, dry product, reduces volume significantly.	High energy consumption, potential for emissions depending on the heating method, may require additional treatment of exhaust gases.
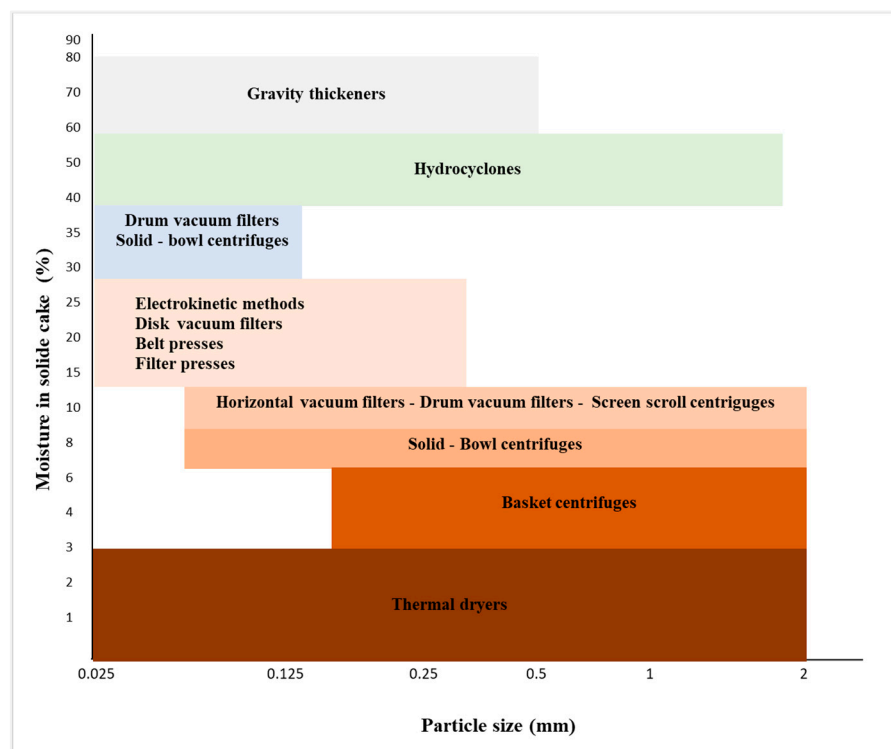
Figure 9. Application range of dewatering equipment based on particle size and product moisture [148,204].

Thickened tailings, paste tailings, and filtered tailings are various techniques employed in mining operations for tailings management and disposal. These approaches are geared towards decreasing the water content of tailings, thereby enhancing their stability and facilitating handling, transportation, and disposal processes. While these methodologies may initially incur higher costs due to their energy-intensive nature and the need for specialized infrastructure, they present long-term economic benefits by minimizing the requirement for extensive tailings storage facilities and mitigating environmental risks associated with conventional disposal methods. Moreover, by reducing water content, these techniques contribute to bolstering the stability and safety of tailings storage facilities,

ultimately diminishing expenses and liabilities related to mine closure and reclamation efforts [205].

Dewatering is not a one-size-fits-all process; its success heavily depends on the unique circumstances of each scenario. To achieve optimal outcomes in dewatering and selecting appropriate equipment, a thorough evaluation of several key factors is necessary. These factors include site conditions (daily throughput, space availability, power supply, and scalability), tailings characteristics, operating conditions, operational costs, regulatory compliance, and equipment specifications. Lab-scale tests and pilot testing are indispensable tools in the selection process of mine tailings dewatering technologies. Sensitivity and uncertainty analyses can be used as complementary valuation tools to study the impact of inputs in investment projects. This analysis involves assessing how alterations in factors like flow rate, pressure, temperature, or design influence the efficiency of water recovery from tailings. Sensitivity analysis serves as a crucial tool in the decision-making process, facilitating a comprehensive evaluation of technical feasibility, economic viability, and environmental considerations to enhance overall efficiency.

7. Challenges Facing Water Recycling in Mining Industry

7.1. The Importance of Water Recycling in the Mining Industry

Water recycling in the mineral process industry aims to achieve two main objectives: minimizing the need for fresh or raw water and reducing the volume of effluent generated and disposed of in tailings dams [31]. By reusing and treating mine wastewater used in mining operations, the industry can conserve valuable freshwater resources by reducing the demand for freshwater, alleviating the strain on local water supplies. Recycling water helps to minimize the volume of liquid waste or wastewater produced during mineral processing [31], leading to a reduced environmental impact and ensuring compliance with governing standards. Overall, water recycling is vital for the mineral industry to achieve sustainable operations, conserve resources, and mitigate environmental impacts.

Maintaining consistent water quality and ensuring compliance with rigorous regulatory standards presents a complex and multifaceted challenge in the mining industry [206]. It requires a comprehensive understanding of the diverse factors that can influence water quality, including the variability of influent water sources, the nature of processed ore, the dynamic nature of mining processes and the effectiveness of water treatment technologies [207]. Rigorous monitoring, continuous data analysis, and regular adjustments to treatment processes are necessary to uphold water quality standards consistently. The implementation of water reprocessing in mining operations presents various environmental concerns that necessitate comprehensive assessment and effective extenuation strategies [208]. Consequently, extensive passive and active treatment processes are necessary to effectively eliminate contaminants and impurities, ensuring that the water meets the required standards for beneficiation operations [209].

In light of these challenges, experimental studies have been conducted to assess the feasibility and efficacy of various water reuse strategies in mining operations. These studies have yielded valuable insights into the performance of different treatment technologies and their implications for resource utilization and cost-effectiveness.

Experimental results have demonstrated the effectiveness of advanced treatment processes such as membrane filtration, ion exchange, and biological remediation in removing contaminants from mine wastewater to meet regulatory standards. Furthermore, the integration of water reuse systems with existing mineral processing operations has shown promising results in reducing freshwater consumption and minimizing environmental impact.

The interpretation of these experimental findings underscores the importance of tailored approaches to water reuse that consider the specific characteristics of mining effluents and operational requirements. While certain treatment technologies may excel in removing specific contaminants, their practical applicability within the context of mining operations depends on factors such as scalability, reliability, and cost-effectiveness.

From these experimental conclusions, it is evident that the successful implementation of water reuse initiatives in mining requires a holistic approach that integrates technical innovation with economic feasibility and environmental stewardship. By leveraging advanced treatment technologies, optimizing operational processes, and prioritizing sustainable water management practices, mining companies can achieve significant reductions in water consumption, lower operating costs, and enhance overall environmental performance. However, continued research and development efforts are essential to address remaining challenges and optimize the long-term sustainability of water reuse in the mining industry.

7.2. Examples of Mining Wastewater Treatment Processes

The implementation of advanced treatment technologies, the maintenance of treatment facilities, and skilled personnel required for water treatment can significantly contribute to the overall expenses [210]. Striking a balance between the benefits of water reuse and the associated costs is crucial for mining companies to ensure the economic viability of water recycling initiatives while maintaining efficient mineral processing operations [211]. Several water treatment options are available to the minerals industry [212]. Among these options, the methods listed in Table 4 are highly favored due to their cost-effectiveness, featuring low capital and operating costs.

Examples of treatment processes include neutralization, oxidation, adsorption, bioremediation, precipitation, oxidation processes, coagulation/flocculation, membrane separation processes, reverse osmosis, ion exchange, and electrochemical methods, such as electrocoagulation [55,212–218]. Through their use, the industry can ensure that water meets the required quality parameters and is free from contaminants that might impede the efficiency of mineral processing operations. Adequate treatment of mine water not only improves overall processing performance by mitigating potential issues such as equipment corrosion, scaling, and fouling, but it also plays a vital role in minimizing environmental impact [215].

It is important to mention that the evaluation of wastewater treatment technologies for integrated mine wastewater treatment processes has primarily relied on lab-scale experiments. Consequently, there is a lack of sufficient data based on pilot-scale studies, which hinders the widespread application of these technologies in industrial mine wastewater treatment. Although a few pilot studies have emerged recently, demonstrating promising performance in terms of water quality, the availability of comprehensive data from larger-scale implementations remains limited [17,219–222]. The scarcity of pilot-scale data impedes the accurate assessment of these technologies' efficiency, reliability, and scalability in real-world mining operations. Thus, further pilot-scale investigations are necessary to validate the viability and effectiveness of these treatments before their full-scale implementation in the mining industry [223–229]. Additionally, it is noteworthy to mention that several articles have examined the comprehensive cost of water treatment and put forth solutions that involve the implementation of integration strategies [230]. These strategies include the adoption of hybrid systems and the utilization of renewable energy sources. These innovative approaches offer significant cost reductions by minimizing energy consumption, consequently lowering the unit production cost associated with water treatment. By combining different technologies and leveraging renewable energy options, mining operations can optimize their water treatment processes and achieve more sustainable and economically viable outcomes [231–233]. The experimental results highlight the reliance on lab-scale experiments for evaluating wastewater treatment technologies in mining. However, the lack of pilot-scale data limits their industrial application. Pilot studies show promise, but comprehensive data remain scarce. Further pilot investigations are crucial for validating technology viability. Integration strategies, such as hybrid systems and renewable energy use, offer cost-effective solutions, optimizing water treatment processes for sustainability and economic viability in mining operations.

Table 4. Technologies and methods of mine water treatment.

Treatment Process Type	Method	Wastewater Type	Application	Reference
Physical (Adsorption on solid or at an interface)	Electrocoagulation	Wastewater from iron ore processing	• Removal of various metal ions such as Fe, Cr, Cu, Zn, Mn, Pb, Al. • Monitoring of total dissolved solids (TDS), turbidity, conductivity, and salinity	[55]
	Coagulation/flocculation	Wastewater	• Removal of TSS	[214,234]
	Coagulation–sedimentation	Tannery wastewater	• Dissolved organic matter removal	[235]
	Coagulation with electrooxidation	Wastewater	• TOC removal	[214,236]
	Membrane technologies	Saline wastewater	• Removal of coarse particles and large organic compounds • Suspended solids removal • Removal of heavy metals • Removal of organic matter	[215]
	Filtration and ultrafiltration	Mine wastewater	• Turbidity removal	[208]
	Ionic resin softening method (ion exchange)	Mine wastewater	• Hardness removal	[208]
	Adsorption method	Wastewater from acid mine drainage	• Removal of heavy metals	[217]
	Reverse osmosis membrane	Mining wastewater	• Turbidity removal • Total dissolved solids removal	[237]
	Reverse osmosis	Industrial wastewater	• Heavy metals and pollutants removal	[216]
Chemical	Neutralization	Wastewater from acid mine drainage	• Removal of heavy metals	[217]
	Oxidation	Gold mining wastewater	• Fe and As removal	[218]
	Oxidation	Acid Mine drainage wastewater	• Heavy Metal Removal	[238]
Physicochemical	Dissolved air flotation (DAF)	Primary treated wastewater	• Removal of COD • Removal BOD5 • Removal TSS • Removal TN • Removal TP	[214]
	Dissolved air flotation	Electroplating wastewater	• Heavy metals removal • Noxious pollutants removal	[239]
	Dissolved air flotation (DAF)	Wastewater	• Water clarification	[240]
	Electro-Fenton process	Acid mine wastewater	• Removal of Fe(II) and Mn(II)	[241]
Biological treatment (aerobic and anaerobic methods)	• Activated sludge • Sequencing batch reactor • Biofilm and biofilter reactors • Membrane bioreactor	Saline wastewater	• COD removal	[215,242]
	Algal photo-bioreactor + DAF		• Removal of COD, BOD5, TSS, TN, TP	[214]
	Active and passive biological treatments (active bioreactors, anaerobic bacteria, anaerobic wetland)	Acid mine drainage wastewater	• Sulfate and heavy metals removal	[243]

7.3. Economic Performance of Wastewater Treatment Processes

The economic performance and optimization of mine wastewater treatment processes are critical aspects of sustainable mining operations. Effective management of wastewater

is essential not only for environmental protection but also for the economic viability of mining projects.

Optimizing wastewater treatment processes will allow mining companies to achieve higher levels of efficiency in contaminant removal. This ensures that effluent discharged from mining sites meets or exceeds regulatory standards, thereby avoiding costly fines and penalties. Additionally, by implementing innovative treatment solutions such as biochar adsorption process [244,245], electrocoagulation [246], membrane filtration, nanofiltration, and crystallization [247], etc., mining companies can effectively remove a wide range of pollutants from wastewater, including heavy metals, suspended solids, and toxic chemicals.

Other researchers working in other industrial sectors, such as the meat industry, have studied and identified the role of design and operational parameters in energy costs for a wastewater treatment plant. Their findings recommended a new comprehensive methodology for energy cost estimation for an industrial wastewater treatment plant. They reported that energy costs related to water treatment processes could be minimized by approximately 49% if wastewater reuse were applied in the plant [248]. The adoption of similar approaches in other industries has demonstrated significant benefits in optimizing resource consumption, particularly in the realms of water and energy. Therefore, it is highly promising and encouraging to consider implementing these strategies within the mining industry. Doing so holds the potential to foster overall sustainability within this sector.

In summary, by prioritizing the economic performance and optimization of wastewater treatment processes, mining operations can achieve sustainable water management practices that balance environmental stewardship with financial viability. By investing in efficient treatment technologies and adopting water conservation measures, mines can minimize their environmental impact, ensure regulatory compliance, and contribute to the long-term preservation of water resources for future generations.

8. Conclusions and Research Needs

The mining industry faces pressing environmental challenges driven by increased metal demands, including water consumption, waste generation, and dam vulnerabilities. Water recycling stands out as a pivotal solution for managing mining residues and conserving water resources, offering significant benefits in reducing environmental footprints and ensuring operational water stability. Advancements in dewatering techniques for mine tailings are essential in tackling these challenges. While technologies such as deep cone thickening, centrifugation, HC-HVS technology, and elctrodewatering have made notable progress in refining dewatering practices, persistent challenges remain, particularly in addressing the presence of clay, which significantly impacts efficiency. Surface chemistry alterations affecting clay aggregate structures pose additional difficulties, particularly in managing high volumetric flows with limited parameter adjustments [249].

Addressing the environmental challenges associated with mine tailings dewatering and water recycling is crucial to mitigate potential catastrophic disasters and long-term risks. Emphasizing advancements in fundamental science can refine existing treatment techniques and drive the development of next-generation solutions. Continued research efforts, focusing on cost-effective and sustainable technologies, alongside comprehensive evaluations and case studies, are necessary for the responsible management of mining residues and the conservation of water resources. Innovative approaches, such as exploring bio-based polymer alternatives and integrating chemicals with mining operations, hold promise for optimizing dewatering processes and minimizing environmental impacts. Evaluating the environmental impact of tailings dewatering on water quality and researching technologies for reprocessing tailings to extract valuable minerals are imperative for sustainable mining practices and mitigating adverse environmental consequences. Tackling these gaps is crucial for sustainable and efficient mine tailings management, fostering responsible resource extraction, and lessening the environmental impact of mining activities, with the primary aim of promoting sustainability by minimizing freshwater usage in line with industry demands.

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