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Mineral waste recycling, sustainable chemical engineering, and circular economy

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ABSTRACT

The mineral processing industry is pivotal in natural resource extraction and historically contributes to environmental damages like land degradation and groundwater contamination. In the face of resource scarcity and environmental pollution, sustainable solutions are increasingly vital. The circular economy focuses on reusing, recycling, and reducing waste, which turns unwanted by-products into valuable assets. Sustainable chemical processes offer innovative solutions in waste material reclamation and integration into the production chain. These practices not only mitigate waste but also enable resource recovery, turning waste management costs into profits. Repurposing mineral waste reduces mining's environmental impact, lessens new mining needs, and yields economic advantages.

1. Redefining waste

The mineral processing industry, a cornerstone in the global economic structure, plays a pivotal role in the extraction and refinement of a multitude of vital resources. At its core, this industry is responsible for transforming raw ore into valuable minerals and metals, processes that are vital to the production of countless products and technologies we rely on daily [1,2]. However, beyond the well-known environmental impacts caused by mineral waste [3], the construction and management of tailings dams present significant safety risks [4]. These risks have been underscored by alarming statistics revealing that, from 1961 to the end of 2022, a total of 154 major tailings pond accidents occurred worldwide (wise-uranium.org), with 144 between 1961 and 2020 [as shown in Fig. 1]. These incidents resulted in tens of thousands of fatalities and injuries, as well as severe environmental and public health hazards. For instance, the 2008 tailings pond failure in Xiangfen, China, led to a catastrophic "man-made mudslide," claiming 277 lives and causing substantial environmental damage [5].

Historically, the approach to managing the large volumes of waste by-products generated has been primarily containment or disposal. Massive tailings ponds and waste heaps are a testament to the industry's significant environmental footprint, presenting challenges from land degradation to groundwater contamination. These practices, deeply rooted in a linear economy paradigm, view these wastes as the inevitable end-point of mineral extraction – a necessary consequence to be managed.

However, in the face of escalating challenges such as resource scarcity, environmental degradation, and climate change, it is increasingly clear that these old paradigms are insufficient. The modern era demands sustainable solutions that push beyond traditional boundaries and redefine waste not as an endpoint but as a new beginning. This calls for a reimagining of waste management in the mineral processing industry, transforming waste from a mere by-product to be contained or disposed of, into a resource that marks the start of sustainable and innovative

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practices. As we grapple with these pressing issues, the industry is urged to adopt a more circular approach, viewing waste not as an inevitable consequence of mineral extraction but as an opportunity for environmental stewardship and sustainable development [6]. The history of tailings pond accidents, with their devastating human and environmental costs, serves as a stark reminder of the urgent need for change in how we approach and manage the by-products of our vital mineral extraction processes.

To address these challenges and shift away from such unsustainable practices, a new paradigm is emerging. Enter the concept of a circular economy, a model that emphasizes the importance of reusing, recycling, and reducing waste [7,8]. At its heart, the circular economy challenges industries to reimagine their waste streams, transforming them from liabilities into assets. It's a concept that encapsulates the ethos of resource efficiency, waste minimization, and environmental stewardship. In the context of the mineral processing industry, embracing the principles of the circular economy means looking beyond the waste heaps and tailing ponds and recognizing the untapped potential they possess [9–11]. Sustainable chemical processes emerge as the champions in this endeavor, offering innovative pathways to reclaim, repurpose, and reintegrate these waste materials back into the production chain [12,13]. These sustainable chemical methods are not just about waste reduction [14–16]. They pave the way for resource recovery, extracting valuable metals and minerals from what was once deemed "waste". For instance, certain tailings contain trace amounts of rare earth elements, which, through the implementation of advanced hydrometallurgical processes such as leaching, solvent extraction, and electrowinning, can be effectively extracted and reused (as detailed in the provided Table 1) [17]. These practices, which include techniques like heap leaching and agitation leaching for optimal metal recovery, not only augment resource supplies but also significantly reduce the environmental impact of mining and mineral processing. Embracing these sustainable chemical processes is crucial for enhancing resource efficiency and aligning with the principles of a circular economy, thereby transforming waste into valuable materials while minimizing ecological footprints.

From an environmental standpoint, repurposing mineral waste signifies a diminished need for new mining activities, activities which often disrupt ecological systems and are energy-intensive [31,32]. By tapping into existing waste repositories, we not only conserve our cherished natural landscapes but also shield ecosystems from harm, all the while reducing the carbon footprint associated with fresh excavations. Moreover, the economic ramifications are significant. Waste reclamation, paired with its subsequent integration into the production sequence, introduces new revenue avenues, morphing former expenses tied to waste management into centers of profitability [33]. Furthermore, extracting valuable components from these wastes allows industries to insulate themselves from market volatilities and the unpredictable price fluctuations associated with raw material scarcity. Additionally, in the broader context of waste management, the introduction of landfill taxes

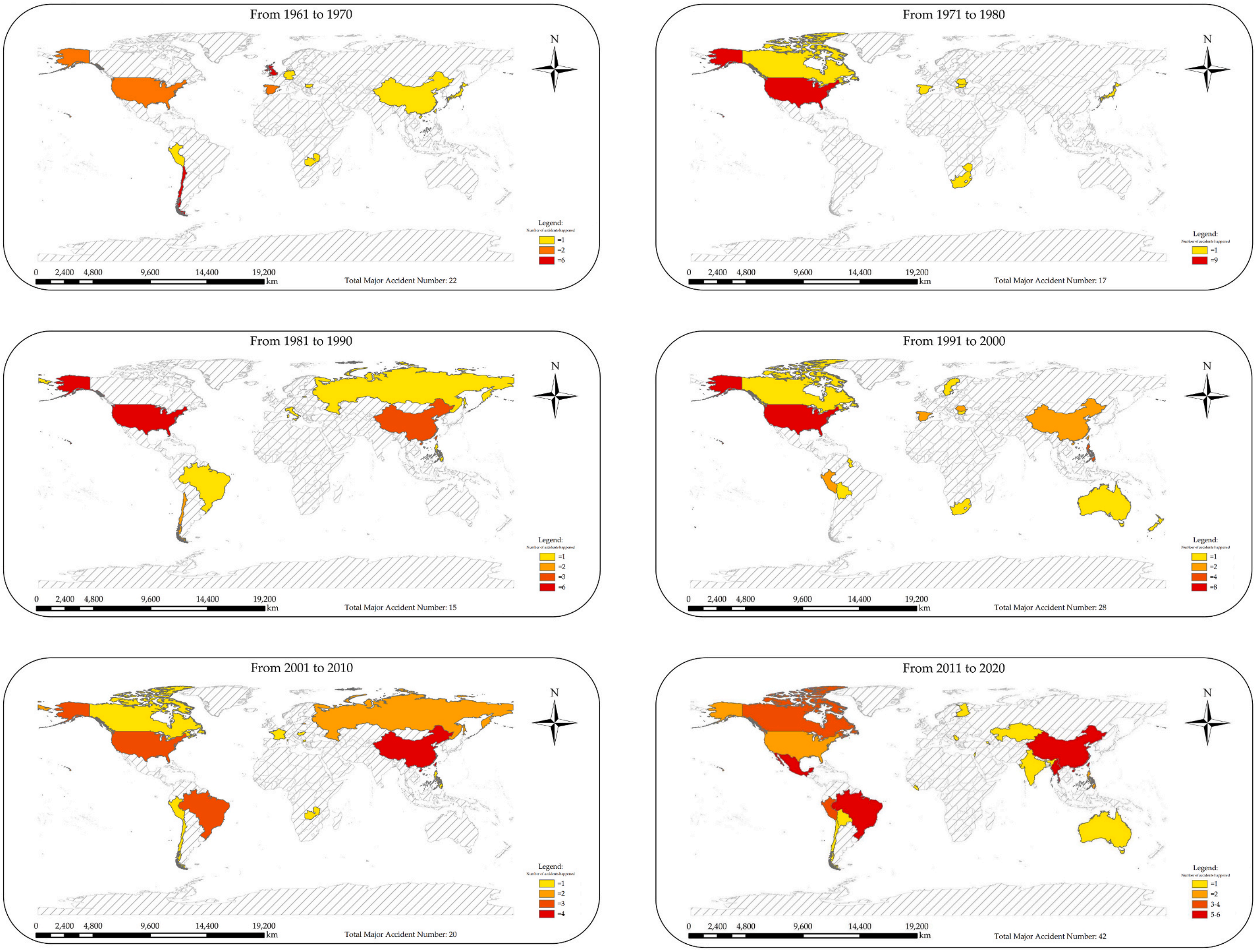


Fig. 1. Distribution of major tailings pond failure accidents from 1961 to 2020.

Table 1
Overview of several sustainable chemical processes in mineral waste recycling.

Process Category	Specific Process	Description
Hydrometallurgical Processes	General	Use of aqueous solutions for metal recovery from ores and recycled materials [18].
Leaching Techniques	In-situ Leaching	Drilling and fracturing ore deposits for solution penetration [19].
	Heap Leaching	Spraying leach solution over piled ore [20].
	Vat Leaching	Contacting reduced material with leach solution in vats [21].
	Agitation Leaching	Using agitated tanks for enhanced reaction kinetics [22].
	Autoclave Leaching	High-temperature reactions for faster rates [23,24].
Solution Concentration and Purification	Various	Concentration of metal ions and removal of impurities [25,26].
Metal Recovery	Electrolysis, Gaseous Reduction, Precipitation	Producing metals for sale or further refining [27].
Electrowinning & Electrorefining	Electrodeposition	Recovery and purification of metals using electrodeposition [28,29].
Precipitation in Hydrometallurgy	Chemical Precipitation	Precipitation of metals or contaminants from solutions [30].

represents a key economic mechanism [34]. This approach provides valuable insights and a reference point for the management of mineral waste. By incentivizing the minimization of waste sent to landfills, these taxes encourage recycling and reuse, aligning economic incentives with environmental sustainability.

Drawing from this foundation and through the lens of the circular economy, there is a clear global interconnection between mineral processing waste reclamation and advanced chemistry [35]. This perspective not only delineates the evolution and fusion of waste reclamation with sustainable chemical methods, but also mirrors a universal paradigm shift in industrial practices. At this pivotal moment, the international mining sector, with initiatives like MetGrow+ and Mineworx's collaboration with EnviroLeach, is transitioning towards a circular economy model [36]. This transformation, where sustainable chemical strategies are integrated with circular economy principles, is not just crucial, but imperative for sustaining and revitalizing the Earth's resources on a global scale. It reflects a broader recognition of the need for responsible resource utilization, with an emphasis on recycling and repurposing materials to reduce environmental impact. These efforts are part of a growing movement to align industrial activities with the sustainable objectives of reducing waste, conserving natural resources, and fostering a more resilient and sustainable global ecosystem.

2. Waste to worth

In the rapidly evolving field of mineral waste management and its intersection with chemical engineering, our research is a response to the urgent need to understand and innovate in this area [37,38]. Using the Web of Science Search Formula: ("mining waste" OR "mine waste" OR "mining waste rock" OR "beneficiation waste" OR "red mud" OR "slag" OR "tailings" OR "coal gangue") AND (recycle* OR reuse* OR retrieve* OR re-extract* OR "circular economy") AND ("chemical engineering" OR "chemical process" OR "chemistry") from January 1, 1993, to August 31, 2023, we have charted the trajectory of relevant studies. The Literature Visualization Tool, Citespace V6.1 R6, helped us in this endeavor, enabling a comprehensive analysis of the 116 studies identified. This body of research presents a critical examination of the intrinsic properties and potential recycling paths for various types of mineral waste, including red mud, slag, and fly ash. It underscores the significant role these materials can play in promoting sustainable chemical practices [39,40]. The evolution of these studies reflects a paradigm shift in how mineral waste is perceived: from an environmental challenge to a valuable resource for addressing contemporary ecological issues. By contextualizing our work within this broader body of research, we aim to contribute to and extend the current understanding of sustainable waste management practices, emphasizing the integration of circular economy principles with chemical engineering techniques to foster a more sustainable future.

First and foremost, a visual inspection of the keyword co-occurrence analysis graph [as shown in Fig. 2A] reveals a pronounced centrality of the term "Chemistry". This underscores the pivotal role chemistry and chemical engineering plays in the realm of mineral by-product recycling. Significantly, the term "Circular Economy" has risen as a standout node, underscoring its escalating significance in the domain. It's intriguing that, despite its crucial role, the "Circular Economy" concept was woven into mineral by-product recycling research only in more recent times [41,42]. Yet, its recurrent appearance, as revealed by the keyword burst analysis [as shown in Fig. 2B], testifies to its burgeoning relevance. Moreover, specific chemical processes such as "Flocculation" and "Adsorption" are recurrently mentioned, highlighting their relevance in the field. Keywords like "Fly Ash", "Red Mud" and "Slag" further indicate a concentrated research focus on specific mineral by-products, suggesting a sustained interest and active exploration in their recycling and reuse.

Drawing insights from both the keyword co-occurrence analysis and the keyword burst analysis [as shown in Fig. 2B], it becomes evident that the realms of mineral by-product reuse and the sustainable chemical industry are deeply intertwined. Within this nexus, four paramount research focal points, each with distinct characteristics, emerge as follows [as shown in Fig. 2C].

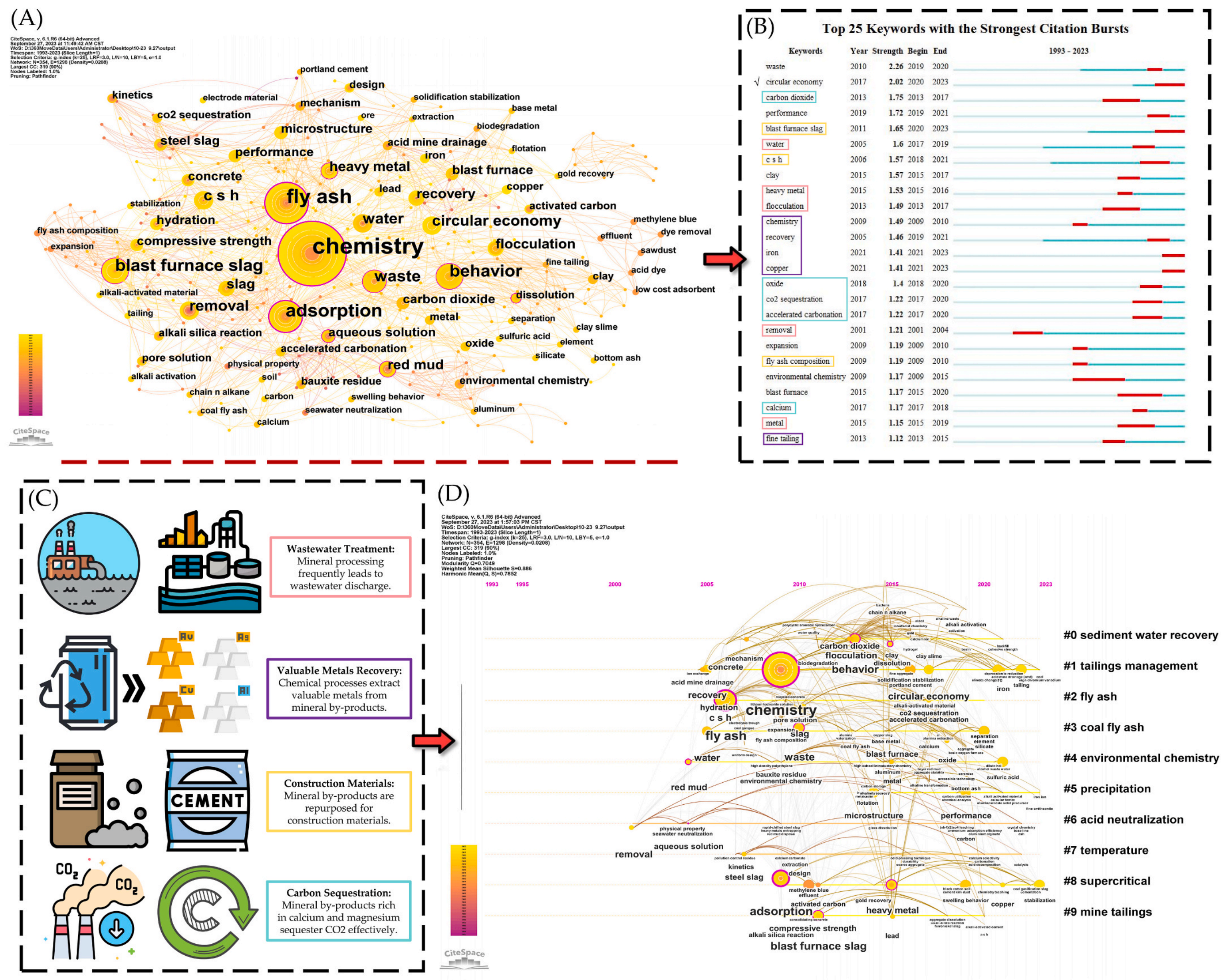
2.1. Waste water treatment

The first research focus is centered on the recovery and treatment of water from sediment-rich sources like tailings and settling ponds, where mineral by-products accumulate. This area, highlighted by terms such as "Removal" and "Flocculation" in Fig. 2B–is crucial in water and wastewater treatment to eliminate contaminants like heavy metals and large particles, enhancing water clarity and quality. The substantial volumes of water retained in tailings ponds during mineral processing present a significant opportunity for water recovery [43,44]. Techniques like the use of synthetic, high molecular weight water-soluble polymer flocculants have revolutionized dewatering processes in the mineral industry, enabling the formation of larger aggregates for increased mass throughput and reducing thickener diameters.

Flocculant selection and application are vital in these processes. For instance, cationic products are common in wastewater treatment, but anionics, particularly acrylamide and acrylate copolymers, dominate mineral tailings applications due to their effectiveness in forming denser aggregates [45]. The optimization of flocculation processes involves understanding the impact of flocculants across the tailings treatment process, from feedwell flocculation to bed compaction in thickeners, and beyond which product gives the highest settling rate at the lowest dosage.

The use of flocculants in tailings ponds has been a subject of extensive research, with studies exploring different functional chemistries to promote particle aggregation. However, the choice of flocculant can significantly affect the quality of overflow water returned to the process, with high clarity being essential in many applications. Novel functional chemistries in flocculants offer potential improvements in fines capture and the overall efficiency of the water recovery process.

In sum, this research focus is aligned with the principles of the circular economy, emphasizing optimal resource utilization and advancing



Top 25 Keywords with the Strongest Citation Bursts

Keywords	Year	Strength	Begin	End	1993 - 2023
waste	2010	**2.26**	2019	2020	
√ circular economy	2017	**2.02**	2020	2023	
carbon dioxide	2013	**1.75**	2013	2017	
performance	2019	**1.72**	2019	2021	
blast furnace slag	2011	**1.65**	2020	2023	
water	2005	**1.6**	2017	2019	
c s h	2006	**1.57**	2018	2021	
clay	2015	**1.57**	2015	2017	
heavy metal	2015	**1.53**	2015	2016	
flocculation	2013	**1.49**	2013	2017	
chemistry	2009	**1.49**	2009	2010	
recovery	2005	**1.46**	2019	2021	
iron	2021	**1.41**	2021	2023	
copper	2021	**1.41**	2021	2023	
oxide	2018	**1.4**	2018	2020	
co2 sequestration	2017	**1.22**	2017	2020	
accelerated carbonation	2017	**1.22**	2017	2020	
removal	2001	**1.21**	2001	2004	
expansion	2009	**1.19**	2009	2010	
fly ash composition	2009	**1.19**	2009	2010	
environmental chemistry	2009	**1.17**	2009	2015	
blast furnace	2015	**1.17**	2015	2020	
calcium	2017	**1.17**	2017	2018	
metal	2015	**1.15**	2015	2019	
fine tailing	2013	**1.12**	2013	2015	

Wastewater Treatment: Mineral processing frequently leads to wastewater discharge.

Valuable Metals Recovery: Chemical processes extract valuable metals from mineral by-products.

Construction Materials: Mineral by-products are repurposed for construction materials.

Carbon Sequestration: Mineral by-products rich in calcium and magnesium sequester CO2 effectively.

Fig. 2. **(A)** Keyword co-occurrence analysis; **(B)** Keyword Burst analysis; **(C)** Leading trends in chemical processes for mineral by-product retrieval; **(D)** Cluster timeline analysis.

efficient waste management by transforming waste water from a liability into a valuable resource.

2.2. Valuable metals recovery

The second pivotal area of research is centered on the extraction and recovery of precious metals from mineral by-products, a topic highlighted within the purple box in the keyword list of Fig. 2B. This research area, under the umbrella term “Metal Recovery”, focuses on developing sustainable chemical processes to salvage and repurpose valuable metals from materials typically regarded as waste, such as tailings and slag [46]. These terms suggest rich sources for sustainable metal extraction and recycling, which is integral to this research theme.

The goal is to transform what is conventionally viewed as waste into valuable resources. By employing innovative and sustainable methodologies in metal recovery, this research not only enhances the accessibility of scarce resources but also significantly mitigates the environmental impacts traditionally associated with mining and mineral processing. This approach is in line with the principles of a circular economy, where waste is minimized, and the lifecycle of materials is extended.

In practice, this involves studying and developing novel chemical processes and technologies that are both environmentally responsible and economically feasible. These processes aim to efficiently extract metals, ensuring that the maximum amount of valuable materials is recovered, thereby reducing the need for fresh mining and its associated environmental toll. The research focus also explores the potential reintegration of these recovered metals into various industrial processes, thereby closing the loop in resource utilization [47].

This research focus is not just about recovery but also about redefining waste management in the mineral processing industry. It represents a shift towards more sustainable practices, where every by-product is viewed as a potential resource rather than waste. Ultimately, the objective is to contribute towards a more sustainable, efficient, and environmentally friendly approach to mineral processing, aligning with global efforts to promote sustainable development and resource conservation.

2.3. Construction materials

The third key research area involves converting mineral by-products into a variety of materials, specifically for construction purposes. Terms such as “Fly Ash”, “Red Mud”, and “Slag”, highlighted in the yellow box of the keyword list in Fig. 2B, point towards this innovative avenue [48, 49]. These materials hold great potential for being developed into novel cementitious substances. Sustainable chemical activations enable these by-products to undergo a cement-like hydration reaction when exposed to water, making them effective substitutes for traditional cement. Their utilization can notably diminish the environmental pollutants and carbon emissions traditionally associated with cement manufacturing [50].

In addressing the comprehensive analysis of activation methods, it's essential to consider a variety of techniques. These include mechanical activation, which enhances the reactivity of particles through grinding; thermal treatment, which alters the crystal structure and chemical composition; and alkaline activation, which involves the use of alkaline activators to induce a pozzolanic reaction [51,52]. Chemical activators like gypsum and lime are also pivotal in modifying the physical and chemical properties of these by-products, thereby enhancing their reactivity [53,54].

Additionally, the impact of these materials undergoing secondary reactions significantly contributes to reducing cement clinker content. For instance, the pozzolanic reaction, wherein materials like fly ash react with calcium hydroxide to form additional cementitious compounds, can improve the strength and durability of the cement [55]. Latent hydraulic reactions, particularly relevant in materials like slag, also play a crucial role in the cementitious properties of the resulting product.

Moreover, understanding how these activated materials interact in different environmental conditions is crucial. Factors such as temperature, humidity, and the presence of other chemicals in the environment can affect the hydration process and the final properties of the cementitious material [56,57].

Overall, the research in this area is not just about creating alternative construction materials but also about deepening the understanding of the chemical processes involved. This knowledge is vital for optimizing the use of mineral by-products in construction, contributing to a more sustainable and environmentally friendly building industry.

2.4. *Carbon sequestration*

The fourth crucial area of research investigates the transformation of mineral wastes, especially those rich in magnesium and calcium, into stabilized carbonates through chemical reactions with carbon dioxide [58]. This process, highlighted by keywords within the blue box in Fig. 2B, represents a significant stride in sustainable carbon sequestration techniques. By utilizing mineral processing residues for carbon capture, what was previously considered waste is now repurposed, embodying a dual approach to environmental stewardship. This methodology not only advocates for recycling but also plays a vital role in reducing atmospheric carbon dioxide levels, presenting a comprehensive solution to waste management, carbon sequestration challenges, and broader climate change issues.

This research explores the detailed mechanisms of how magnesium and calcium-rich mineral wastes react with carbon dioxide to form stable carbonates. Understanding these mechanisms is crucial for optimizing the process and enhancing its efficiency. This includes the study of various factors like temperature, pressure, and the presence of catalysts, which can influence the rate and extent of carbonate formation.

Furthermore, the research extends to evaluating the potential applications of the resulting carbonates. These could include their use in construction materials, soil amendments, or even as a raw material for further industrial processes. The versatility of these applications highlights the potential of this technology in contributing to a circular economy.

The process also offers an opportunity to address some of the most pressing environmental challenges of our time. By capturing and storing carbon dioxide, this technology contributes to reducing greenhouse gas emissions, a key factor in global warming and climate change [59,60]. Additionally, it provides a sustainable solution for managing mineral wastes, which are often a byproduct of various industrial processes.

In summary, this research focus not only transforms waste into valuable products but also mitigates environmental impact, showcasing an innovative approach to tackling climate change. It underscores the importance of interdisciplinary research, combining elements of chemistry, environmental science, and materials engineering, to develop solutions that are both environmentally responsible and economically feasible. This integrated approach is essential for addressing the complex challenges of sustainable development and environmental protection in the 21st century.

2.5. *Perspective: sustainable evolution in chemical engineering*

Collectively, the four research domains highlighted in this study exemplify the seamless integration of sustainable chemical engineering principles with the ethos of the circular economy, creating a dynamic system where discarded materials are rejuvenated and seamlessly reintegrated into our production processes. The historical trajectory of these developments, as illustrated in Fig. 2D, narrates a compelling story of progressive innovation and ecological mindfulness. The journey begins with a focus on water treatment, harnessing chemistry to purify and reclaim water from industrial processes. It then evolves into the realm of developing sustainable building materials, where mineral by-products are transformed into eco-friendly construction alternatives.

The narrative further unfolds into the vast potential of metal recycling, a crucial step in minimizing waste and reducing the environmental impact of mining. This evolution reaches its zenith with the innovative practice of carbon sequestration, where chemistry once again plays a central role in mitigating climate change by transforming carbon emissions into stable, useable forms. The integration of the "Circular Economy" concept around 2015 marked a paradigm shift in this landscape. This infusion not only amplified the existing narrative of sustainable resource management but also redefined it, laying a stronger emphasis on holistic ecological stewardship and the efficient utilization of resources.

At this pivotal juncture, the confluence of sustainable chemical engineering, mineral by-product optimization, and the principles of the circular economy weaves a rich and vibrant tapestry of progress, transformation, and ecological responsibility. In the face of the urgent environmental challenges of our time, this unified approach stands as a beacon of hope and innovation. Chemistry, in its pivotal role, acts as the anchor of this transformation, driving the evolution of materials and processes towards greater sustainability. The incorporation of the "Circular Economy" concept adds a profound depth and breadth to the discourse, fostering a reimagined view of resource management and ecological harmony. This harmonious fusion of principles and practices serves as a testament to human ingenuity and resilience, hinting at a future where every discarded element harbors the potential for new life, contributing to a more sustainable and rejuvenated world.

3. Embracing change

For years, the mineral processing industry has operated on a linear economic model: extract, produce, use, and dispose. This model reflects the broader societal approach to resource use. However, re-evaluating this model is imperative, given the urgent need to integrate sustainable chemical engineering with mineral by-product utilization [61,62]. The industry's traditional approach results in significant waste production, with the global mineral waste management market size reaching 167.20 billion tons in 2020, projected to grow to 208.33 billion tons by 2028 [63]. In 2022 alone, global coal consumption surpassed eight billion tonnes, highlighting the scale of waste rock and tailings, which contain hazardous substances with detrimental ecological effects [64]:

Mine exploration, construction, drilling, and maintenance contribute to land-use changes, deforestation, soil erosion, and water pollution, exacerbating environmental impacts. The EU's 2006 legislation and subsequent 2009 updates on mineral waste management underscore the growing global focus on regulating and mitigating these impacts. The Asia Pacific region, in particular, is a significant producer of mineral waste, driven by countries like China and Australia, which underscores the need for robust waste management strategies.

At the core of this discourse is the transformative potential of sustainable chemical processes in reshaping waste management in the mining industry. Traditionally, this sector has adopted a reactive stance, focusing primarily on mitigating environmental harm post-occurrence. In stark contrast, sustainable chemical engineering propels a proactive methodology [65]. It advocates for the recovery, reprocessing, and reincorporation of waste materials into valuable resources, thus redefining waste as a cyclical asset rather than an end-stage byproduct. This paradigm shift is underpinned by the principles of the circular economy, which envisions a continuous cycle of use, reuse, and regeneration of resources. This model not only recognizes but also capitalizes on the inherent economic value of materials previously designated as “waste”. Therefore, the exploration of innovative applications such as water recovery, metal extraction, and the transformation of waste into sustainable building materials exemplifies the dual advantages that this approach offers. These applications not only mitigate environmental impacts but also present significant economic opportunities [66,67]. Water recovery from tailings reduces the strain on local water resources, creating a more sustainable cycle of usage. Similarly, the extraction of metals from waste not only diminishes the need for further raw mineral extraction, thereby preserving natural resources, but also taps into new revenue streams from previously discarded materials [68]. Furthermore, converting mineral waste into sustainable building materials can revolutionize the construction industry, offering eco-friendly alternatives and reducing the carbon footprint of new structures. Together, these applications demonstrate a comprehensive approach to waste management, highlighting the synergy between environmental stewardship and economic viability, and paving the way for a more sustainable and prosperous future in the mineral processing industry [69].

However, this transformative path is not without its challenges (as shown in Fig. 3): The integration of sustainable chemical engineering principles into the sphere of waste recovery necessitates substantial investments in research, advanced technology, and robust infrastructure. Moreover, this transition is significantly influenced by market dynamics, regulatory frameworks, and societal perceptions, all of which play pivotal roles in its successful implementation. Therefore, a collaborative, multi-disciplinary approach becomes indispensable. This collaboration calls for the amalgamation of expertise from various sectors - ranging from environmental science and chemical engineering to economics and policy-making. Such a collective effort is crucial not only in navigating the intricacies of this transition but also in laying a solid foundation for a more sustainable and environmentally conscientious future in mineral processing [70].

Looking ahead, the journey towards fully realizing the potential of sustainable chemical processes in waste management is a collective endeavor. It demands a reimagining of traditional practices, fostering innovation, and embracing change. The role of education and public awareness in this transformation cannot be overstated, as societal support and understanding are critical in driving this shift. Furthermore, continuous policy evolution and financial incentives are essential in encouraging industry-wide adoption of these practices. Ultimately, this journey is about creating a sustainable legacy, where the mining industry not only minimizes its ecological footprint but also contributes positively to the circular economy, demonstrating a commitment to responsible and sustainable resource management.

Fig. 3. Sustainable transformation in mineral waste management: Pillars of progress.

Image sources

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CRediT authorship contribution statement

Haoxuan Yu: Writing – review & editing, Writing – original draft, Visualization, Conceptualization. **Izni Zahidi:** Writing – review & editing, Supervision, Project administration. **Chow Ming Fai:** Writing – review & editing, Supervision, Project administration. **Dongfang Liang:** Supervision, Project administration. **Dag Øivind Madsen:** Writing – review & editing, Supervision, Project administration.

Declaration of competing interest

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

Data availability

No data was used for the research described in the article.

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