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Mechanical Activation in Metallurgical Processing: Mechanisms, Applications and Industrial Perspectives

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ABSTRACT

Original Research Article

Mechanical activation (MA) has emerged as an effective process-intensification strategy in metallurgical processing, modifying the structural and energetic state of solids through high-energy milling. Unlike conventional comminution, MA produces lattice defects, crystallite refinement, amorphization, and increased surface free energy, thereby significantly enhancing the reactivity of minerals and residues. This review critically examines the mechanisms of mechanical activation and its influence on hydrometallurgical and pyrometallurgical processes, including increased leaching rates, reduced reagent consumption, lower reaction temperatures, and improved reduction kinetics. Applications to primary ores, industrial residues, slags, tailings, and electronic waste are analyzed, with emphasis on the role of activation in enabling the treatment of refractory and low-grade materials. Particular attention is given to energy demand, process efficiency, and techno-economic feasibility, since the additional milling step may offset the metallurgical benefits if not properly integrated into the flowsheet. Emerging trends such as mechanochemistry, reactive milling, and hybrid activation routes are also discussed, highlighting their potential to improve selectivity and reduce overall energy consumption. The review identifies key research gaps, including the lack of standardized reporting of activation energy, limited correlation between specific energy input and metallurgical performance, and insufficient life-cycle and techno-economic evaluation. Mechanical activation is considered a powerful but energy-intensive tool, and its industrial application depends on an integrated assessment of kinetics, energy balance, scalability, and environmental impact.

Keywords: Mechanical activation, Mechanochemistry, Reactive milling, Hydrometallurgy, Refractory minerals, Process intensification.

Highlights

- Mechanical activation increases mineral reactivity through defect generation, amorphization, and surface energy increase.
- Significant improvements in leaching rate, reduction kinetics, and dissolution of refractory phases are widely reported.
- Energy demand remains the main limitation for large-scale industrial implementation.
- Reactive milling and mechanochemistry show potential to reduce temperature and reagent consumption.
- Applications to secondary resources enable recovery from slags, tailings, and electronic waste.
- Industrial feasibility requires integrated evaluation of energy, recovery, cost, and environmental impact.

Graphical Abstract

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Introduction

The depletion of high-grade ores and complex mineral resources challenges modern extractive metallurgy. Today's ores often contain fine intergrowths, refractory phases, and complex mineral associations, limiting conventional beneficiation and metallurgical processes. Additionally, secondary resources such as slags, tailings, residues, and e-waste increase the need for methods that enhance reactivity without excessive energy or reagents (Agrawal, 2021; Odebiyi, 2022; Sim, 2025).

Conventional comminution is energy-intensive, yet size reduction alone often doesn't improve metallurgical performance because of mineral stability, passivating layers, or the low reactivity of crystalline phases. As a result, approaches that alter the physicochemical state of solids have gained attention (Odebiyi, 2021; Subasinghe, 2023).

Mechanical activation (MA) uses high-energy milling to create lattice defects, reduce crystallite size, and sometimes induce partial amorphization, altering reaction pathways in hydrometallurgy and pyrometallurgy, resulting in faster reactions, lower temperatures, and less reagent use (Alrbaihat, 2022; Subasinghe, 2023).

Recent research highlights mechanical activation in sulfide ores, laterites, slags, fly ash, catalysts, and battery wastes. Adding chemical additives enhances reactivity through mechanochemical milling. However, industrial use is limited by high energy consumption, media wear, lack of standards, and poor integration with process design and economics (Odebiyi, 2022; Ippolito, 2022; Pereira, 2025).

Previous reviews have addressed specific aspects of mechanical activation, such as mechanochemical kinetics, hydrometallurgical applications, or processing of particular mineral systems. However, a comprehensive assessment that links mechanistic understanding, metallurgical performance, energy demand, and industrial feasibility remains lacking (Alrbaihat, 2022; Subasinghe, 2023).

This review examines mechanical activation as a process-intensification tool in metallurgy, discussing mechanisms, effects on hydrometallurgy and pyrometallurgy, secondary resource use, energy, sustainability, and techno-economic factors. It highlights the link between milling energy and performance and current limitations for industrial use.

To ensure a consistent and transparent literature survey, the selection and analysis of references were conducted using a structured review methodology, as described in the following section.

Methodology

This work was conducted as a structured literature review focused on mechanical activation in metallurgical processing. The objective was to identify, classify, and critically analyze published studies dealing with high-energy milling, mechanochemistry, and reactive attrition applied to primary ores, secondary resources, and metallurgical residues.

The survey used databases such as Scopus, Web of Science, ScienceDirect, and Google Scholar, searching for terms including mechanical activation, mechanochemistry, reactive milling, high-energy ball milling, leaching, carbothermic reduction, slag recycling, and hydrometallurgy. Only peer-reviewed articles, reviews, and relevant conference papers were included.

The initial search returned a large number of publications in powder metallurgy, materials science, and cement chemistry. These were screened to retain only studies related to extractive metallurgy, mineral processing, recycling, or process intensification. Further filtering prioritized works reporting kinetic effects, changes in reactivity, energy consumption, or metallurgical recovery.

The selection procedure followed the general principles recommended for systematic reviews, including identification, screening, eligibility, and inclusion. The flow of the selection process is summarized in Figure 1.

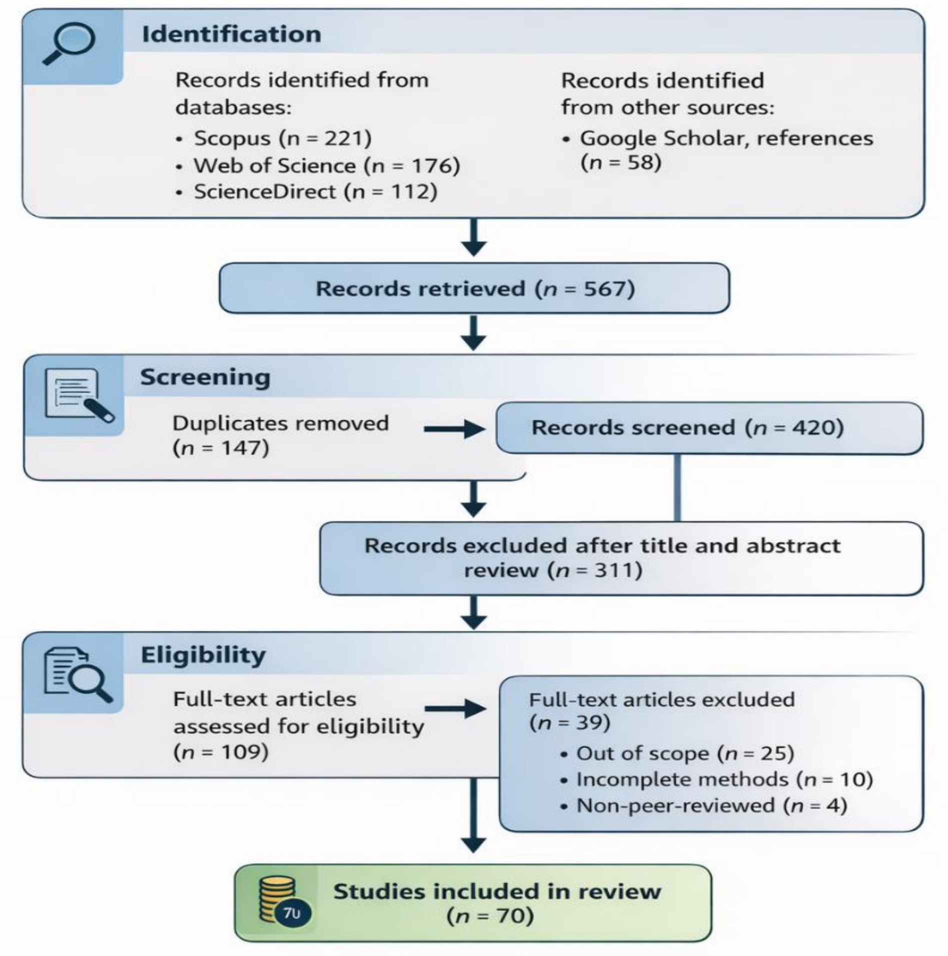

Figure 1. Literature selection procedure used in this review, based on the PRISMA 2020 guidelines (adapted from Page et al., 2021).

The final database included experimental studies, review papers, and techno-economic or sustainability analyses. Main topics such as mechanical activation, hydrometallurgical effects, pyrometallurgical applications, secondary resources treatment, energy efficiency, environmental aspects, and industrial feasibility are grouped under the references. This classification enabled consistent comparison across different materials and processing routes despite varying experimental conditions.

This section covers the basics of mechanical activation, including milling methods, structural changes, and mechanochemical effects that influence the reactivity of activated solids.

Fundamentals of Mechanical Activation

Mechanical activation employs high-energy milling to change solids' structure, microstructure, and chemistry beyond mere size reduction. In mineral processing, it enhances dissolution, phase stability, and reaction temperature for refractory minerals, oxides, and residues that conventional grinding can't activate effectively (Odebiyi, 2021; Alrbaihat, 2022; Subasinghe, 2023).

Mechanical activation depends on mill type, impact intensity, milling time, ball-to-powder ratio, atmosphere, and additives. These parameters control the energy transferred to the solid and the resulting structural disorder.

Types of Mills

Different milling devices produce mechanical activation with varying efficiency based on impact energy and frequency. Common systems in metallurgical studies include high-energy ball mills, planetary mills, attritors, and vibratory mills (Odebiyi, 2021; Svietkina, 2020; Subasinghe, 2023).

Planetary mills generate high forces causing defects and small crystals. Attritors with vigorous agitation allow continuous, scalable processing. Vibratory mills have high collision rates and are well suited for mechanochemistry, whereas traditional ball mills activate materials but require longer times (Saberi, 2022; Sathiyamoorthi, 2024).

The choice of mill impacts energy input and structural changes. Comparing studies requires considering milling conditions, not just time. Different mills, such as planetary, attritors, vibratory, and high-energy ball mills, have distinct collision regimes that affect defect creation and disorder. Mill type is crucial when comparing results. Figure 2 compares common milling devices.

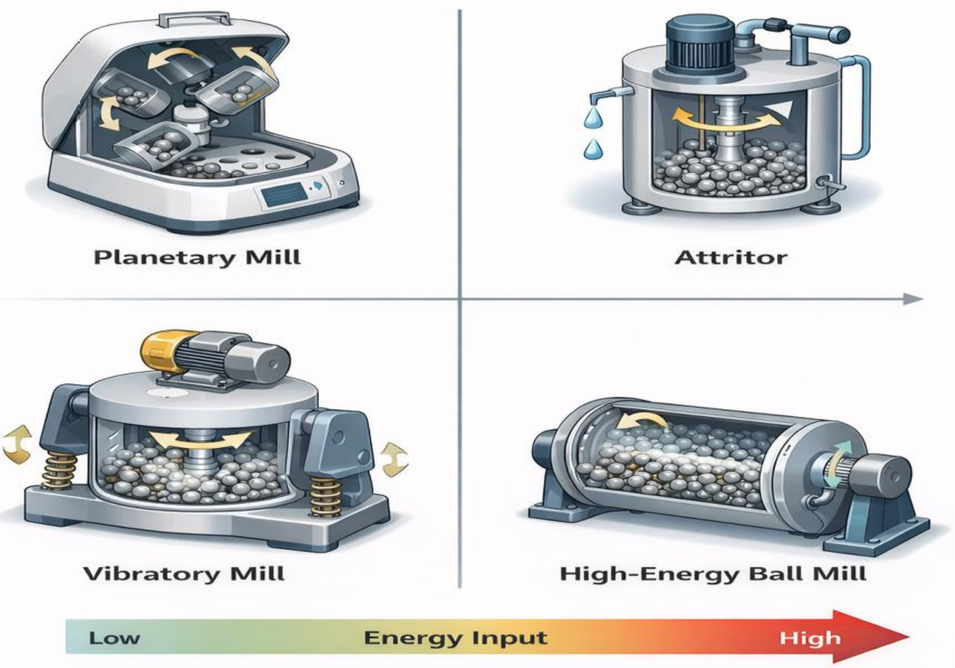

Figure 2. Schematic comparison of common milling devices used for mechanical activation, including planetary mills, attritors, vibratory mills, and high-energy ball mills (adapted from (Odebiyi et al., 2021; Subasinghe & Ratnayake, 2023).

Figure 2 shows common milling devices for mechanical activation: planetary mills, attritors, vibratory mills, and high-energy ball mills. These vary in impact, collision, and energy input, affecting defect and disorder levels. Choosing the right system is crucial for comparing activation results.

Physical Mechanisms of Mechanical Activation

Mechanical activation causes disorder via impacts, friction, and deformation, leading to defects, amorphization, smaller crystallites, and higher surface free energy. These changes can affect mineral thermodynamics and kinetics (Akhgar, 2024; Bai, 2022; Yang, 2022).

Defect generation occurs early in high-energy milling, with dislocations, vacancies, and grain boundaries accumulating in the lattice. This raises internal energy and reduces activation barriers. Continued milling decreases crystallite size and increases disordered regions, possibly leading to partial amorphization (Khezri, 2021; Liu, 2024).

In sulfide minerals such as chalcopyrite, mechanical activation may disrupt passivation layers and expose reactive surfaces, resulting in faster leaching rates. In oxides and silicates, lattice distortion can facilitate diffusion and solid-state reactions (Akhgar, 2024; Yang, 2022).

Repeated impacts can induce mechanochemical reactions at room temperature, as seen in reactive milling, high-entropy alloys, and mechanically alloyed materials. Mechanical energy can drive phase transformations (Giordana, 2020; Moskovskikh, 2020; Ershova, 2023).

Mechanical activation causes structural defects like dislocations, microcracks, and lattice strain during high-energy milling, raising free energy and increasing chemical reactivity. This transition from crystalline to disordered structures improves performance in hydrometallurgical and pyrometallurgical processes. Figure 3 shows typical structural changes.

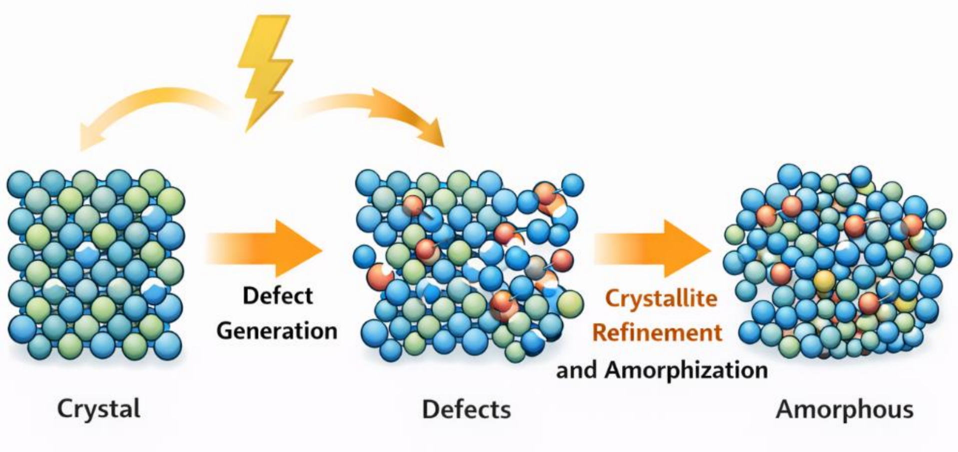

Figure 3. Schematic representation of defect generation, crystallite refinement, and amorphization during mechanical activation (adapted from (Akhgar et al., 2024; Yang et al., 2022).

The graphical scheme shows the progressive structural changes during mechanical activation, from defect generation to crystallite refinement and partial amorphization. High-energy milling introduces lattice defects, reduces crystallite size, increases stored energy, and boosts chemical reactivity. These transformations improve leaching, reduction, and solid-state reaction kinetics observed after activation.

Structural Characterization of Activated Solids

Structural changes induced by mechanical activation are typically assessed using diffraction, spectroscopy, and surface area measurements. X-ray diffraction is the most widely used technique, and peak broadening is commonly interpreted as reflecting both reduced crystallite size and lattice strain (Akhgar, 2024; Liu, 2024).

Spectroscopic techniques such as FTIR and Raman can detect changes in the bonding environment, particularly in silicates and oxides. These methods are useful for identifying structural disorder that is not readily apparent in diffraction patterns. Surface area measurements, typically obtained by BET analysis, provide additional information on the increase in reactive surface area generated during milling (Gui, 2025; Zhu, 2023).

An increase in surface area alone does not fully explain improved metallurgical performance. Studies show that particles of similar size can exhibit different leaching behavior depending on lattice disorder, indicating that mechanical activation involves microstructural and energetic effects (Nadirov, 2020; Yang, 2022).

Mechanical activation induces structural changes such as crystallite refinement, defect formation, amorphization, and surface modification, thereby affecting mineral reactivity. These are detectable with various analytical techniques. Recognizing these effects ensures accurate identification of true activation versus particle-size reduction. Table 1 summarizes common structural changes and the methods used.

Table 1. Typical structural changes observed during mechanical activation and corresponding characterization methods (adapted from (Liu et al., 2024; Zhu et al., 2023).

Structural change	Description	Typical effect on reactivity	Characterization method	Typical observation
Crystallite size reduction	Fragmentation of crystalline domains during high-energy milling	Increased dissolution rate due to higher surface area	XRD	Peak broadening, reduced crystallite size
Defect generation	Formation of dislocations, vacancies, and lattice strain	Higher chemical reactivity and faster kinetics	XRD / TEM	Peak shift, lattice distortion
Amorphization	Loss of long-range order in crystal structure	Increased solubility and lower activation energy	XRD / Raman	Halo pattern, reduced peak intensity
Surface area increase	Creation of fresh surfaces and micro-fractures	Improved leaching accessibility	BET	Increase in specific surface area
Surface chemical modification	Change in oxidation state or surface functional groups	Enhanced interaction with reagents	FTIR / XPS	New bands or chemical shifts
Phase transformation	Formation of metastable or intermediate phases	Lower reaction temperature	XRD / DSC	New diffraction peaks
Particle size reduction	Reduction of particle diameter by milling	Faster diffusion and reaction rate	Laser granulometry / SEM	Shift to smaller particle size
Microcracking	Formation of internal cracks in particles	Increased permeability to leach solution	SEM	Fractured or porous particles

Table 1 summarizes structural changes during mechanical activation, such as crystallite refinement, defect generation, amorphization, and surface modification, which enhance chemical reactivity and kinetics. Proper characterization distinguishes true activation from particle size reduction and links it to metallurgical performance.

Chemical-Assisted Mechanical Activation (Reactive Milling)

In addition to purely mechanical effects, activation may be enhanced by adding chemical reagents during milling. This approach, often referred to as mechanochemical activation or reactive milling, promotes reactions that would not occur under conventional grinding conditions (Fang, 2023; Li, 2025).

During reactive milling, solid–solid or solid–liquid reactions may occur at contact points between particles. Local temperature rise and high defect density create favorable conditions for phase transformation. As a result, new compounds, metastable phases, or activated surfaces may be formed before any thermal or hydrometallurgical treatment (Su, 2023; Liu, 2024a).

This approach has been successfully applied to the treatment of fly ash, slags, battery materials, and refractory oxides. In many cases, the addition of salts, alkali reagents, or oxidizing agents during milling reduces the temperature required for subsequent processing or increases leaching efficiency (Liu, 2024b; He, 2025; Zhang, 2023; Xie, 2021).

Reactive milling may also improve selectivity. By controlling the reagent added during attrition, it is possible to activate specific phases while leaving others relatively unchanged.

This feature is particularly attractive for complex ores and secondary resources (Wang, 2022; Wang, 2025; Odebiyi, 2025).

In some systems, mechanical activation occurs alongside chemical reactions, known as mechanochemical or reactive milling. This involves adding reagents during milling for solid–solid or solid–liquid reactions under mechanical energy. Such processes can create metastable phases, partial reduction or oxidation, and heightened reactivity before thermal or hydrometallurgical processing. Figure 4 shows the pathway in which milling and chemical transformation occur simultaneously.

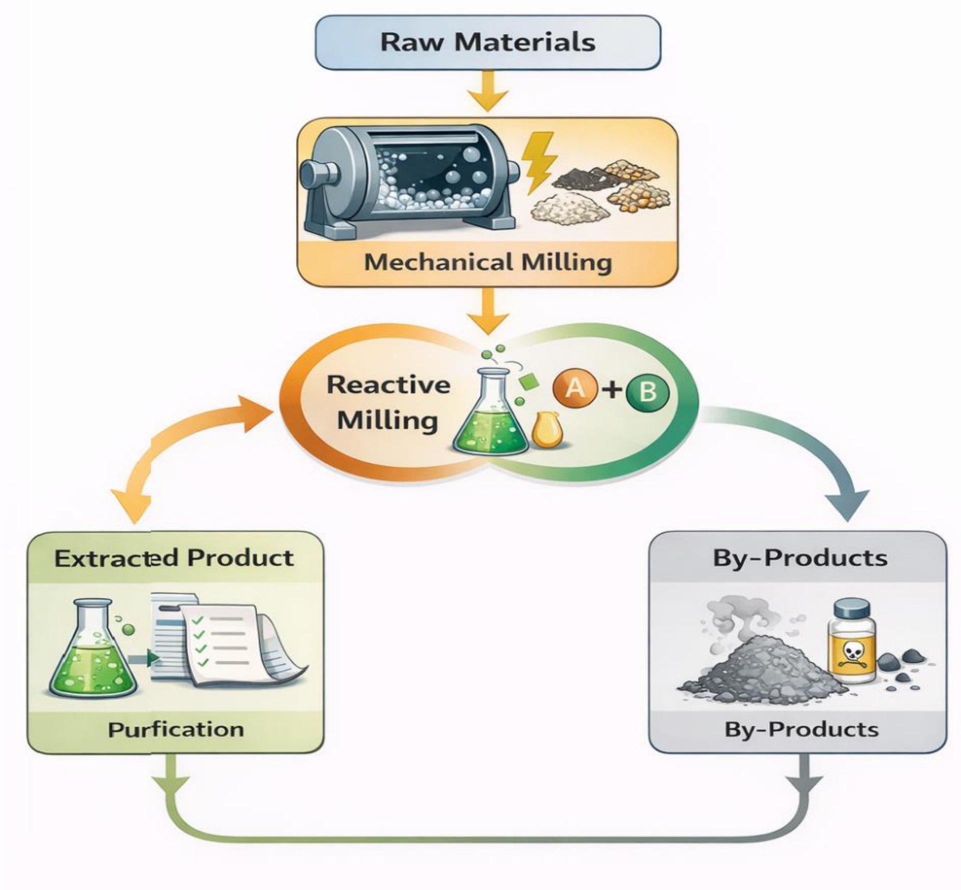

Figure 4. Mechanochemical activation pathway showing simultaneous milling and chemical reaction steps (adapted from Fang et al., 2023; Li et al., 2025).

The flowchart shows a simplified process for mechanochemically assisted processing. Mechanical milling boosts reactivity and allows reactive milling, where chemical changes happen during activation. The activated material can then be leached, reduced, or separated to produce valuable products while reducing inert residues. This scheme highlights how mechanochemical routes can simplify metallurgical flowsheets.

Mechanical activation, therefore, modifies not only particle size but also structure, surface energy, and chemical state. These changes directly influence dissolution behavior, as discussed in the next section.

The structural and energetic modifications described above strongly affect the interaction between solids and leaching solutions. For this reason, mechanical activation has been widely investigated as a method to improve hydrometallurgical processing, as discussed in the following section.

Influence on Hydrometallurgical Processing

Mechanical activation has been widely investigated as a method to improve hydrometallurgical performance. The main effects reported in the literature include higher leaching rates, lower reagent consumption, improved dissolution of refractory phases, and changes in reaction kinetics. These effects are related to defect generation, increased surface energy, and partial amorphization produced during high-energy milling. However, the magnitude of the improvement depends strongly on milling conditions and mineralogy, and direct comparison between studies is often difficult (Bai, 2022; Yang, 2022; Odebiyi, 2021).

Increase in Leaching Rate

Mechanical activation consistently accelerates leaching, leading to shorter induction periods, faster dissolution, and higher recovery than conventional grinding (Khezri, 2021; Bai, 2022).

In chalcopyrite systems, mechanical activation disrupts passivation layers, thereby increasing reactive sites and enhancing copper extraction during acidic and glycine leaching (Bai, 2022; Khezri, 2021; Yang, 2022). Similarly, defect formation in lateritic ores facilitates the dissolution of nickel and cobalt at atmospheric pressure (Acquah, 2025; Tunç Parlak, 2025).

Enhanced leaching occurs in oxide and silicate systems. Mechanical activation of molybdenum ores, lithium minerals, and concentrates boosts dissolution rates through lattice distortion and increased surface energy (Liu, 2025; Wang, 2025; Zhang, 2022). A common effect of activation is faster leaching, with shorter induction times, quicker dissolution, and higher recovery. These are due to defect creation, larger surface area, and better access to reactive phases. The kinetic effect is indicated by a steeper reaction curve and an earlier onset of dissolution. Figure 5 compares activated and non-activated samples.

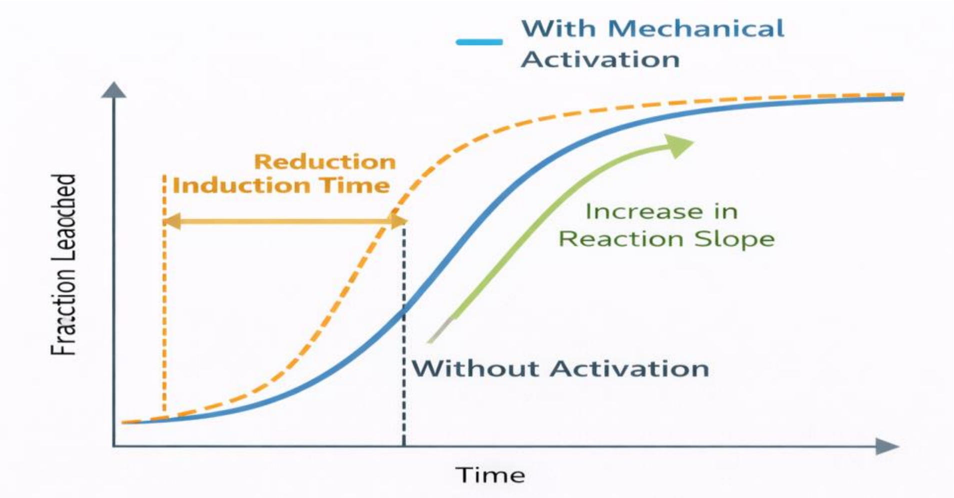

Figure 5. Typical effect of mechanical activation on leaching rate showing reduction of induction time and increase of reaction slope (adapted from (Bai et al., 2022; Acquah et al., 2025).

The graphic illustrates how mechanical activation speeds up leaching by reducing induction time and increasing reaction rate, resulting in faster metal extraction. This is due to defect creation, larger surface area, and better access to reactive phases after high-energy milling.

Reduction of Reagent Consumption

Mechanical activation can reduce reagent requirements for the same recovery by increasing the reactivity of activated solids, enabling dissolution at lower acid concentrations, temperatures, or shorter times (Fang, 2023; Gui, 2025).

Mechanochemical activation with chemical additives enhances metal recovery and reduces acid consumption in fly ash, silicate, molybdenum, and rare-earth materials, enabling lower leaching intensity for the same extraction (Fang, 2023; Yang, 2025; Kenzhaliyev, 2025; Li, 2022).

Activation improves selectivity by stabilizing unfavorable phases and boosting the reactivity of the target phase, thereby reducing reagent use and easing purification (Zhou, 2023; Liu, 2024). It increases leaching rates and decreases chemical reagent consumption in hydrometallurgy. Structural disorder, larger surface area, and defects promote stronger solid-liquid interactions, enabling lower acid or alkali usage while maintaining or increasing metal recovery. This has been shown in several ores, slags, and residues. Table 2 lists examples where mechanical activation cuts reagent use in various hydrometallurgical processes.

Table 2. Reported reduction of reagent consumption after mechanical activation in different hydrometallurgical systems (adapted from (Fang et al., 2023; Kenzhaliyev et al., 2025; Zhou et al., 2023).

Material / Feed	Activation method	Leaching system	Reagent reduction	Additional effect
Coal fly ash	High-energy ball milling	Acid leaching (H_2SO_4)	Lower acid concentration required	Higher Al / Li extraction
Molybdenum ore	Mechanical activation + acid leaching	HNO_3–H_2SO_4 system	Reduced acid consumption	Faster dissolution kinetics
Copper tailings	Water-assisted mechanical activation	Sulfuric acid leaching	Lower acid dosage	Improved Mo selectivity
Chalcopyrite concentrate	High-energy milling	Glycine leaching	Reduced oxidant demand	Increased leaching rate
Laterite ore	Planetary mill activation	Atmospheric leaching	Lower acid requirement	Higher Ni–Co extraction
Vanadium slag	Mechanochemical activation	Alkaline leaching	Lower NaOH consumption	Increased V recovery
Tailings (polymetallic)	Mechanical activation	Acid leaching	Reduced reagent dosage	Higher metal recovery
Titanium slag	High-energy milling	Acid leaching	Lower acid concentration	Faster dissolution

Table 2 shows that mechanical activation reduces reagent use in hydrometallurgy. Defect formation and increased surface area enhance dissolution, allowing lower acid or alkali concentrations while maintaining or increasing metal recovery. Reagent savings may offset milling energy, depending on the activation energy, chemical use, and recovery for each material.

Dissolution of Refractory Phases

Mechanical activation enhances the leaching of minerals with strong crystal structures, surface passivation, or diffusion limitations, such as sulfides, silicates, spinels, and complex oxides.

Activation of chalcopyrite and other sulfides increases defect density and destabilizes surface layers, thereby enhancing copper extraction (Akhgar, 2024; Bai, 2022; Yang, 2022). In laterites, structural distortion improves access to nickel phases (Acquah, 2025; Tunç Parlak, 2025).

Gold-bearing refractory concentrates benefit from activation, particularly after roasting or pressure oxidation. Mechanical treatment can break encapsulation, thereby increasing exposure of gold particles (Lee, 2022; Li G., 2025).

In oxide systems, activation has been applied to molybdenum ores, spodumene, vanadium slags, and titanium-bearing materials, with lattice distortion facilitating dissolution (Kenzhaliyev, 2025; Liu, 2024; Wang, 2025; Zhu, 2023).

Industrial residues react similarly. Mechanical activation boosts metal recovery from slags, tailings, and fly ash by increasing surface reactivity and weakening silicate matrices (Mussapyrova, 2021; Nadirov, 2020; Golik, 2020; Golik, 2023a; Golik, 2023b; Golik, 2023c; Yang, 2025). Refractory minerals often show low reactivity due to stable crystal structures and limited surface accessibility. Mechanical activation creates lattice defects, microcracks, and structural disorder, raising reactive sites and improving leaching. Activated materials dissolve faster and yield higher metal recovery. Figure 6 shows how defect generation during activation enhances mineral reactivity and leaching.

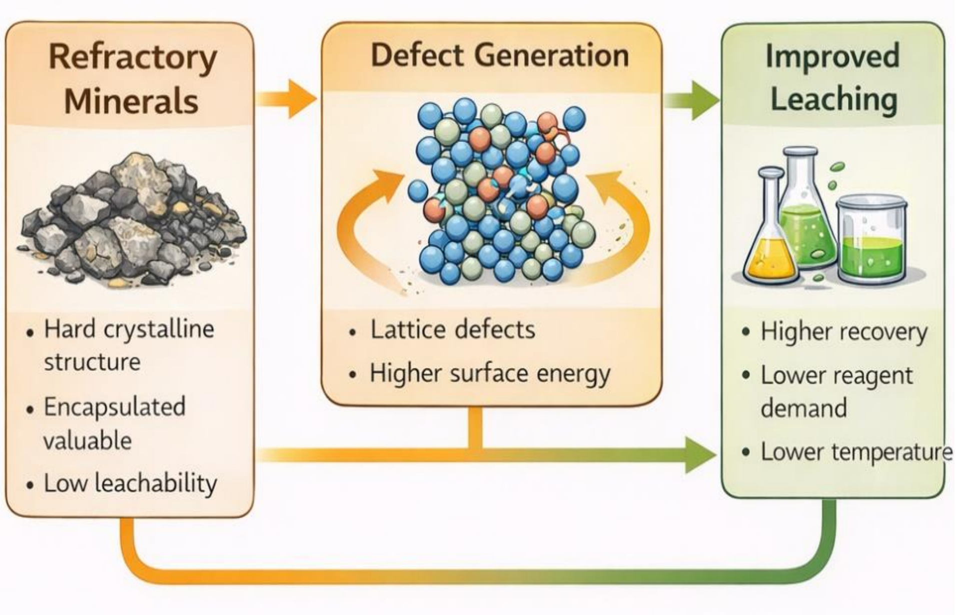

Figure 6. Effect of mechanical activation on refractory minerals showing defect generation, increased reactivity, and improved leaching (adapted from (Akhgar et al., 2024; Golik et al., 2023a).

The flowchart shows that mechanical activation improves refractory mineral processing by creating lattice defects and increasing surface energy, boosting reagent interaction. This results in higher recovery, less reagent, and sometimes lower temperature, explaining its use for low-leachability minerals.

Effect on Reaction Kinetics and Shrinking Core Behavior

Mechanical activation often shifts leaching from diffusion to surface-reaction control, reducing structural barriers (Odebiyi, 2021; Bai, 2022).

Shrinking-core modeling describes these effects. After activation, the apparent activation energy decreases, and the reaction constant increases, confirming higher solid reactivity (Yang, 2022; Liu, 2024; Odebiyi, 2025).

The literature reports variable kinetic parameters, mainly due to differences in milling energy, ball-to-powder ratio, and atmosphere, often not reported consistently. Mechanical activation can change the rate-controlling step in heterogeneous reactions. Many leaching and solid–fluid systems initially follow a diffusion-controlled shrinking-core model. After activation, increased defect density, surface area, and microcracking reduce diffusion resistance, potentially shifting the mechanism to surface-reaction control. This leads to faster kinetics and shorter induction periods. Figure 7 shows the conceptual change in shrinking-core behavior after activation.

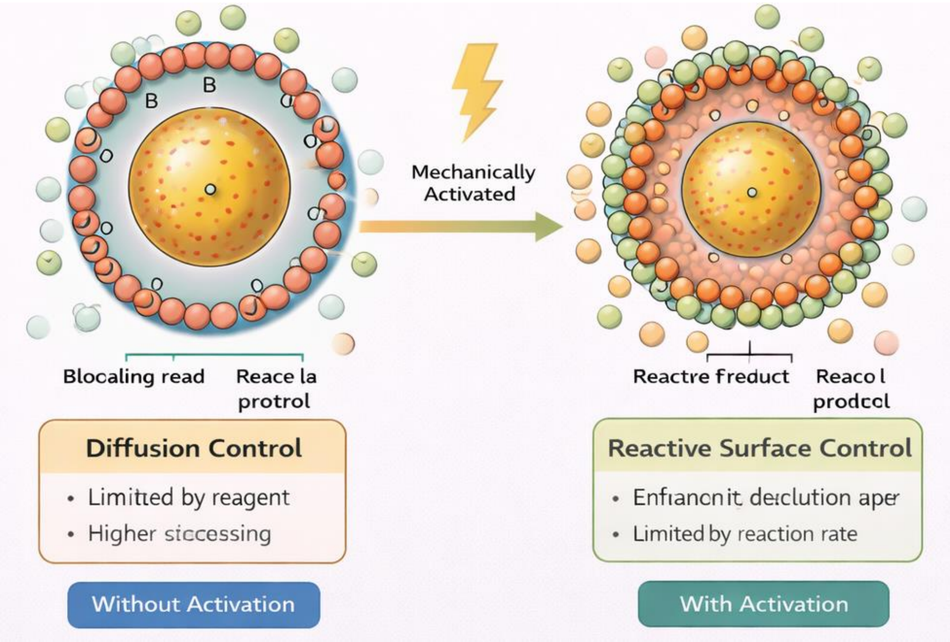

Figure 7. Influence of mechanical activation on shrinking-core kinetics showing transition from diffusion control to surface-reaction control (adapted from (Odebiyi et al., 2021; Yang et al., 2022).

The scheme illustrates how kinetic regimes change post-mechanical activation. Non-activated particles are reaction-controlled by diffusion through product layers, whereas activated particles, with higher surface reactivity and shorter diffusion paths, shift control to surface reactions. This explains the increased leaching rate seen after high-energy milling.

Critical Gap: Correlation between Specific Energy and Reactivity

Despite many studies showing improved leaching after activation, there's a limited quantitative link between milling energy and performance. Many only report milling time, not specific energy input, complicating comparisons (Odebiyi, 2021; Subasinghe, 2023).

Without a consistent energy basis, it remains difficult to determine if recovery gains offset activation energy, hindering industrial implementation.

Mechanical activation alters dissolution kinetics, reagent demand, and phase stability, explaining its interest in extractive metallurgy. Similar effects occur in high-temperature systems, lowering the reaction temperature and accelerating solid-state reactions, as discussed next.

Influence on Pyrometallurgical Processing

Mechanical activation influences high-temperature processing by lowering reaction temperatures, accelerating reactions, and facilitating carbothermal reduction through defect creation, increased contact, and metastable structures during milling (Subasinghe, 2023; Saberi, 2022).

Reduction of Reaction Temperature

Mechanical activation in pyrometallurgy often lowers the temperature for phase transformation or reduction by inducing lattice disorder and increasing internal energy, thereby reducingthe activation barrier for the reaction (Moskovskikh, 2020; Ershova, 2023).

In carbothermal and solid-state systems, activated mixtures react at temperatures several hundred degrees lower than non-activated materials, as seen in oxide reduction, alloy formation, and ceramic synthesis (Giordana, 2020; Sathiyamoorthi, 2024).

In recycling, activation allows roasting or reduction at lower temperatures, saving fuel and increasing efficiency (Li, 2025; Su, 2023). Mechanical activation lowers the temperature needed for phase changes and reduction reactions by storing mechanical energy, creating lattice defects, and increasing surface area during high-energy milling. This reduces the activation energy of thermal processes, common in carbothermal reduction, roasting, and decomposition of refractory compounds. Figure 8 illustrates the typical shift in temperature to lower values after mechanical activation.

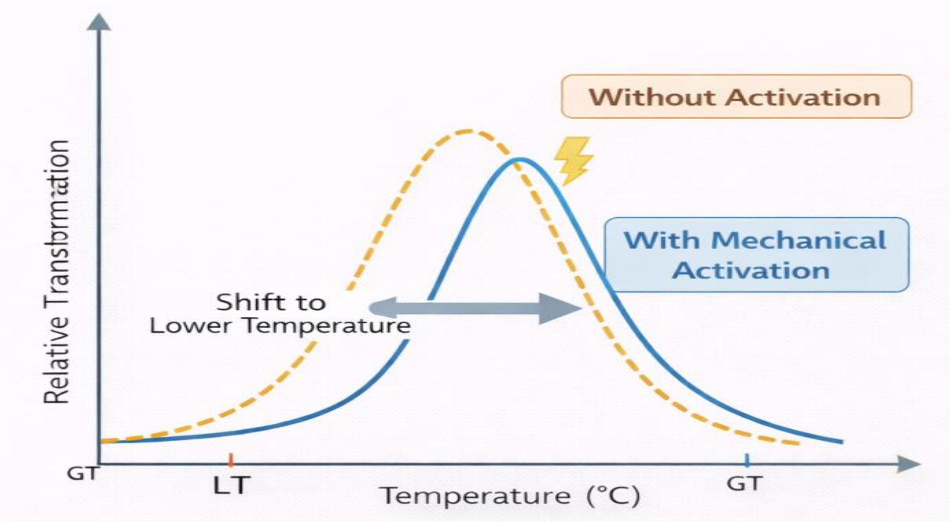

Figure 8. Effect of mechanical activation on reaction temperature showing shift of transformation to lower temperature after high-energy milling (adapted from (Moskovskikh et al., 2020; Ershova et al., 2023).

The graphic shows that the reaction temperature decreases after mechanical activation due to increased defect density, surface energy, and diffusion distance. This explains lower roasting or reduction temperatures after high-energy milling, though higher energy consumption for activation should also be considered.

Acceleration of Solid–Solid Reaction Kinetics

Mechanical activation greatly boosts solid–solid reaction rates by reducing crystallite size, creating fresh surfaces, and forming defective structures. These factors increase the number of reaction sites and shorten diffusion paths (Saberi, 2022; Subasinghe, 2023).

Reactive milling may cause partial reactions during milling, forming intermediate phases before thermal treatment, thus reducing roasting or reduction time (Giordana, 2020; Moskovskikh, 2020).

This behavior, seen in alloy synthesis, oxide reduction, and intermetallic formation, shows that mechanical activation can alter reaction kinetics and pathways (Sathiyamoorthi, 2024). It increases defect density, contact area, and reduces diffusion distances, boosting atomic mobility and enabling phase changes at lower temperatures or shorter times. This is relevant in carbothermal reduction, roasting, and solid-state synthesis. Figure 9 shows how mechanical activation accelerates reactions through defect formation, improved contact, and faster diffusion.

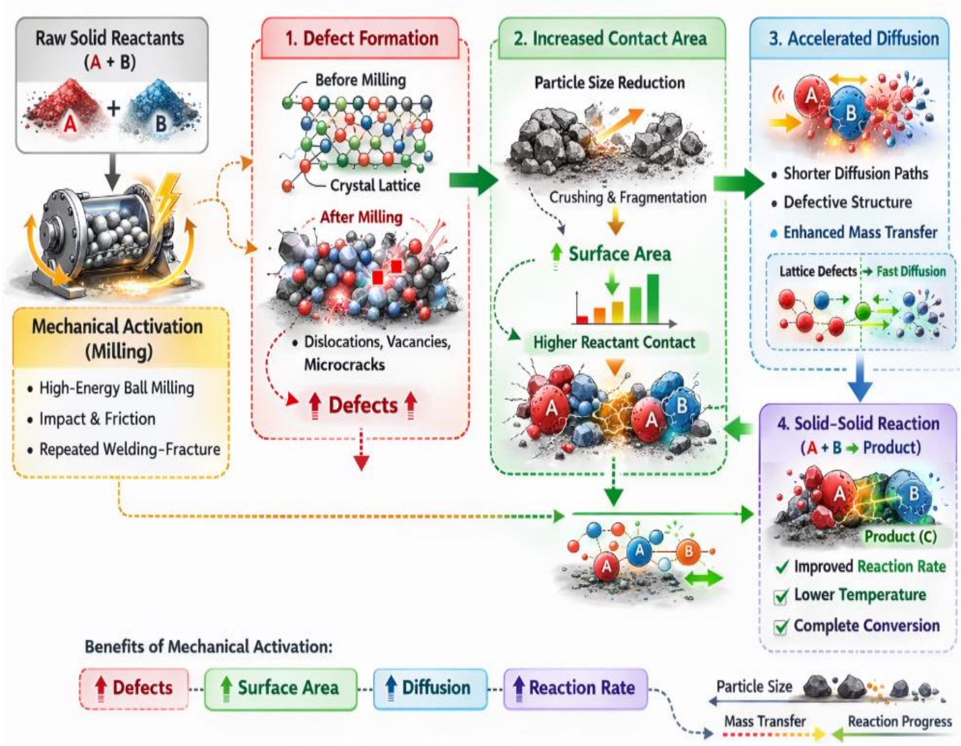

Figure 9. Influence of mechanical activation on solid–solid reactions showing defect formation, increased contact area, and accelerated diffusion (adapted from (Subasinghe, 2023; Saberi, 2022).

The flowchart shows how mechanical activation improves reaction rates by creating defects, reducing particle size, increasing contact area, and accelerating diffusion. These changes shorten diffusion paths and increase the number of reactive sites, leading to faster reactions at lower temperatures. It explains why activated systems excel in hydrometallurgical and pyrometallurgical processes.

Facilitation of Carbothermal Reduction

Mechanical activation is particularly effective in carbothermal systems, where the reaction rate is controlled by diffusion and by contact between carbon and oxide particles. High-energy milling improves mixing and increases the number of reactive interfaces, thereby promoting reduction at lower temperatures (Li, 2025; He, 2025).

In battery recycling and oxide reduction, mechanochemical activation with carbothermal treatment improves metal recovery and reduces roasting time. Reduction can occur partially during milling, especially with added carbon or reducing agents (Su, 2023; Zhang, 2023).

Activated mixtures form intermediate compounds that decompose readily upon heating, thereby accelerating reduction. This is seen in transition metal oxides, lithium compounds, and slags (Li, 2025; He, 2025). Mechanical activation alters solid-state and carbothermal reactions by increasing defect density, reducing crystallite size, and improving contact, thereby lowering temperatures, shortening times, and accelerating diffusion. It can also form metastable intermediates that speed up reduction or roasting. Table 3 shows examples of temperature and kinetic improvements after activation.

Table 3. Examples of temperature reduction and kinetic improvement in carbothermal and solid-state reactions after mechanical activation (adapted from (Li et al., 2025; Su et al., 2023; He et al., 2025).

Material / System	Activation method	Reaction type	Effect of mechanical activation	Temperature reduction / kinetic change
Spent Li-ion battery cathode	Mechanochemical activation + carbothermal reduction	Solid-state reduction	Improved mixing and defect generation	Lower reduction temperature, faster conversion
LIB cathode powder	Mechanical activation + oxidation roasting	Roasting + leaching	Formation of reactive intermediate phases	Shorter roasting time
Pyrolusite + waste salts	Mechanochemical activation + molten salt treatment	Solid-state / salt-assisted reaction	Enhanced diffusion and reactivity	Lower reaction temperature
Oxide mixtures (transition metals)	High-energy ball milling	Carbothermal reduction	Increased contact area and stored energy	Faster reduction kinetics
Cu–Al alloy system	Reactive milling	Solid-state synthesis	Formation of metastable phases	Reduced reaction time
Mg-based alloys	Mechanical alloying	Solid-state decomposition	Defect-assisted reaction	Lower decomposition temperature
Refractory oxide mixtures	Attritor / planetary milling	Carbothermal reaction	Improved carbon–oxide contact	Lower onset temperature
Battery recycling system	Mechanochemical reduction	Solid-state + leaching	Partial reaction during milling	Reduced thermal demand

Table 3 summarizes solid-state and carbothermal reactions after mechanical activation. Activation improves contact, increases defect density, and stores energy, leading to faster reactions at lower temperatures. This is crucial for refractory oxides, battery materials, and alloys, which usually need high thermal input. Mechanical activation can partly replace thermal energy, but overall energy balance varies by case.

Mechanical activation, therefore, modifies not only hydrometallurgical behavior but also high-temperature reactions. These effects are especially relevant for complex residues, where strong crystal structures limit conventional processing.

Such materials are frequently found in industrial wastes, slags, and electronic scrap, where mechanical activation may enable recovery routes that are not feasible by conventional methods. These applications are discussed in the next section.

Applications to Secondary Sources

Mechanical activation is increasingly used for secondary resources like residues, e-waste, slags, and tailings, which contain valuable metals trapped in stable matrices. Its main challenge isn't particle size but structural stability, encapsulation, or low chemical reactivity. Mechanical activation modifies these properties, enhancing recovery processes (Odebiyi, 2022; Subasinghe, 2023).

Activation of secondary resources is attractive in the circular economy because it enables recovery from low-grade or complex materials, thereby reducing environmental impact and reliance on primary ores (Sim, 2025; Dushyantha, 2024).

Mechanical activation is key in circular metallurgy as it converts low-reactivity residues into reactive feedstocks for hydrometallurgical or pyrometallurgical processing. It creates defects, microcracks, and partial amorphization, increasing chemical accessibility of normally inert phases, enabling metal recovery from slags, tailings, fly ash, and wastes. This aids reprocessing of secondary resources, reducing reliance on primary ores. Figure 10 illustrates the transition from inert residues to activated materials for metallurgical routes.

Figure 10. Role of mechanical activation in circular metallurgy showing transition from inert residues to reactive feedstock (adapted from (Sim et al., 2025; Dushyantha et al., 2024).

The scheme illustrates mechanical activation in circular metallurgy, where high-energy milling makes mining residues reactive feedstock. This enhances reactivity, recovery, creates new materials, and results in less inert residue, promoting resource-efficient closed-loop processing.

Electronic Waste and Lithium-Ion Batteries

Electronic waste and spent lithium-ion batteries hold valuable metals but have complex phases that hinder leaching or reduction. Mechanical activation is often used as a pretreatment to boost metal recovery and selectivity (Wang, 2022; Xie, 2021).

High-energy milling can break composite particles, destroy protective coatings, and enhance reactant contact. In mechanochemical systems, partial reactions during milling may lessen the severity of later thermal or hydrometallurgical steps (Babanejad, 2023; Dolotko, 2024).

In battery recycling, activation with reduction or leaching improves recovery of lithium, cobalt, nickel, and copper, while reducing temperature or reagent use (Gao, 2023; Zhang, 2023; Su, 2023; Wang, 2025).

Mechanical activation aids in recycling platinum-group metals and other elements from complex scrap, confirming its potential in processes (Ye, 2025; Yuan, 2023). It is increasingly used in lithium-ion battery recycling to promote structural disorder, enhance reactivity, and enable partial reactions during milling. Milling reduces particle size, generates defects, and initiates solid-state transformations, facilitating leaching or thermal reduction. This can lower the need for high-temperature roasting and improve efficiency. Figure 11 shows a recycling route combining milling, activation, and downstream processing.

Figure 11. Mechanically assisted recycling route for lithium-ion batteries, including milling, activation, and subsequent leaching or reduction (adapted from (Wang et al., 2022; Gao et al., 2023).

The flowchart shows a mechanochemically assisted lithium-ion battery recycling process. Mechanical activation boosts defect density and surface area, improving reduction and leaching. This increased reactivity from milling enables lower processing temperatures, faster dissolution, and better metal recovery, supporting closed-loop recycling.

Slags, Tailings, and Historical Residues

Slags and tailings often contain metals trapped within silicate matrices or spinel structures that resist dissolution. Mechanical activation can weaken these structures and increase the accessibility of metal-bearing phases (Mussapyrova, 2021; Nadirov, 2020).

Studies show that activated metallurgical slags have higher leaching rates due to increased defects and destruction of the glassy phase (Zhou, 2023; Liu, 2024b). Activation also allows zinc, lead, and other metals to be recovered from previously unrecoverable tailings (Golik, 2020; Golik, 2023a-c).

Mechanical activation can promote selective dissolution by changing mineral phase stability, simplifying separation (Zhu, 2023). It has been used on slags, tailings, and other low-reactivity residues. Defects, microcracks, and partial amorphization increase metal phase dissolution, enabling recovery of valuable elements. This process also allows reuse of tailings and slags. Table 4 summarizes studies on metal recovery from activated slags and tailings, including methods and elements recovered.

Table 4. Examples of metal recovery from slags and tailings after mechanical activation (adapted from (Golik et al., 2023a; Mussapyrova et al., 2021; Zhou et al., 2023).

Material / Residue	Activation method	Processing route	Metal recovered	Effect of mechanical activation
Copper smelter slag	High-energy ball milling	Acid leaching	Cu, Fe	Increased leachability of the fayalite phase
Fayalite slag	Mechanical activation	Sulfuric acid leaching	Fe, Si	Higher dissolution rate after activation
Polyme tallictailings	Mechanochemical activation	Acid leaching	Zn, Pb	Improved recovery due to defect formation
Ore dressing tailings	Mechanical activation	Hydrometallurgical processing	Pb, Zn	Increased metal extraction efficiency
Polymetallic tailings	Mechanochemical treatment	Leaching + separation	Zn, Pb	Higher recovery from previously inert material
Tailings reuse material	Mechanical activation	Hydrometallurgy / reuse	Multiplemetals	Activation enabled reuse of waste
Copper tailings	Water-assisted mechanical activation	Acid leaching	Mo	Improved selectivity and lower acid consumption
Vanadium slag	Mechanochemical activation	Alkaline leaching	V	Increased dissolution of V-bearing phases
Titanium-bearing slag	High-energy milling	Acid leaching	Ti	Faster dissolution kinetics
Fly ash / aluminosilicate residue	Mechanical activation	Acid leaching	Al, Li	Breakdown of silicate matrix

Table 4 shows metal recovery from slags, tailings, and residues after mechanical activation, which increases defect density, breaks silicate or oxide matrices, and improves access to metal phases, boosting leaching and recovery. These results highlight the mechanical activation's potential for reprocessing secondary resources where traditional hydrometallurgy is less effective.

Fly Ash, Red Mud, and Other Industrial Residues

Coal fly ash, red mud, and other industrial by-products contain valuable elements like aluminum, iron, and rare earths, but strong silicate or oxide networks hinder extraction. Mechanical activation helps break these networks, thereby aiding leaching.

Mechanochemical activation with additives improves the dissolution of aluminum, lithium, and rare-earth elements, lowering the temperature and reagent use (Yang, 2025; Komnitsas, 2021; Niu, 2021).

Activation transforms materials from glassy or crystalline forms to more reactive states, enabling hydrometallurgical processing. Silicate matrices resist processing due to high polymerization, limiting reagent access, and slowing dissolution. Mechanical activation weakens silicate structures by creating microcracks and reactive surfaces, enhancing metal leaching, as shown in Figure 12.

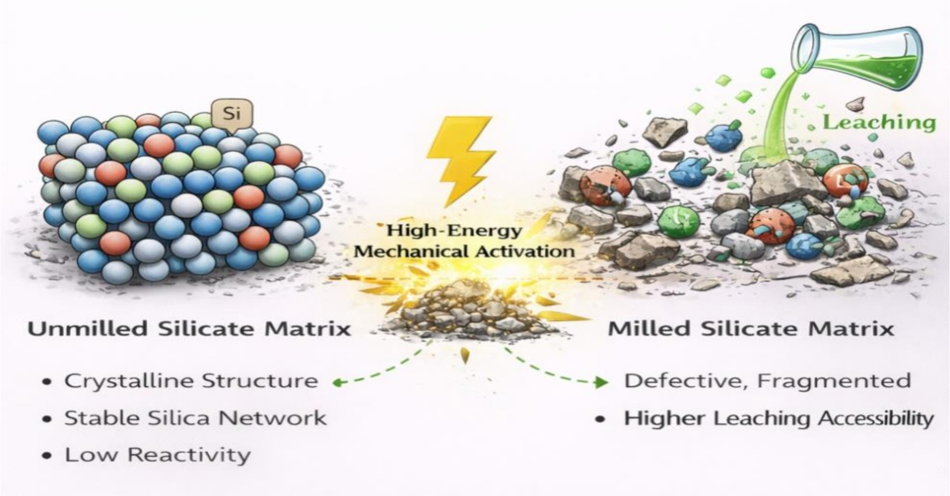

Figure 12. Effect of mechanical activation on silicate matrix showing structural breakdown and increased leaching accessibility (adapted from Fang et al., 2023; Yang et al., 2025).

The graphic shows how mechanical activation modifies silicate matrices. High-energy milling breaks down the crystalline network, creating defects and fragmentation and increasing surface area, which boosts leaching. This change explains improved dissolution in aluminosilicates, slags, and refractory oxides after activation.

Catalystsand Industrial Waste

Spent catalysts and industrial residues contain valuable metals but are chemically stable. Mechanical activation improves the dissolution, reduction, or recovery of these materials (Aslan, 2023; Qin, 2023).

Activation can break encapsulation layers, increase surface area, and promote reactions between metal oxides and reagents during milling. Sometimes, adding reagents during attrition enables partial conversion before leaching or roasting (Ye, 2025).

These results demonstrate that mechanical activation is a general pretreatment for complex industrial waste streams.

Opportunity for Reactivation of Inert Residues

A major advantage of mechanical activation is reprocessing inert materials such as old tailings, slags, and low-grade residues, which may contain significant metal values but are limited by low reactivity rather than grade (Sim, 2025; Dushyantha, 2024).

Increasing defect density and surface energy, mechanical activation may enable new processing routes previously impractical, making it attractive for the circular economy and reprocessing historical waste deposits (Nyeko, 2023; Yadav, 2022).

Mechanical activation reprocesses inert residues such as tailings, slags, and fly ash by creating defects, increasing surface area, and breaking mineral matrices, thereby enabling metal recovery through hydrometallurgy or pyrometallurgy. Figure 13 illustrates this residue reactivation process.

Figure 13. Concept of residue reactivation by mechanical activation, enabling recovery of metals from previously inert materials (adapted from (Sim et al., 2025; Yadav et al., 2022).

The diagram illustrates how mechanical activation transforms inert residues into reactive feedstock by adding defects, disorder, and surface area, enhancing reactivity for improved leaching or reduction. This aids metal recovery from tailings, slags, and industrial waste in circular metallurgy.

Mechanical activation is vital for secondary resource treatment, but industrial use depends on balancing energy input and metallurgical benefit. This is discussed next.

Energy and Process Efficiency

Energy demand limits industrial use of mechanical activation. High-energy milling enhances recovery and kinetics but adds energy costs, so activation should be evaluated within the entire process, not just in labs (Odebiyi, 2021; Subasinghe, 2023). Studies on laterites, fly ash, and battery materials show a trade-off between recovery and energy input (Acquah, 2025; Fang, 2023; Su, 2023).

Specific Energy Consumption (kWh/t)

Specific energy use depends on mill type, scale, milling time, ball loading, and mode. Many papers only report milling time, which isn't enough for comparison. Energy values vary from moderate for surface improvement to high for amorphization or mechanochemical conversion (Odebiyi, 2021; Odebiyi, 2025).

Case studies show that the energy for metallurgical benefits varies with material. In laterites, activation can enhance Ni–Co extraction under atmospheric conditions, but high energy use may offset the benefits of less-intensive leaching (Acquah, 2025; Tunç Parlak, 2025). In mechanochemical systems, activation might replace some pretreatments, but milling energy costs remain high (Su, 2023; Li, 2025).

The energy input during mechanical activation is crucial for process effectiveness. Many studies report milling time without energy data, hindering comparison. Values vary widely by mill type, scale, and conditions. Table 5 summarizes typical energy ranges used and observed metallurgical improvements.

Table 5. Reported specific energy ranges for mechanical activation and associated metallurgical outcomes in selected systems (adapted from (Odebiyi et al., 2021; Acquah et al., 2025; Su et al., 2023).

Material / System	Activation device	Specific energy (kWh/t)	Process after activation	Metallurgical improvement
Chalcopyrite concentrate	Planetary mill	50–150	Acid leaching	Increased leaching rate, shorter induction time
Nickel laterite ore	High-energy ball mill	100–250	Atmospheric leaching	Higher Ni–Co recovery
Laterite ore	Planetary milling	80–200	Acid leaching	Reduced acid consumption
Fly ash	High-energy milling	120–300	Acid leaching	Higher Al / Li extraction
LIB cathode material	Mechanochemical activation	150–350	Reduction + leaching	Faster reaction, lower roasting temperature
Vanadium slag	Attritor / ball mill	100–250	Alkaline leaching	Increased V recovery
Molybdenum ore	Mechanical activation	80–180	Acid leaching	Higher dissolution kinetics
Gold refractory concentrate	High-energy milling	60–150	Thiosulfate leaching	Improved gold recovery
Tailings	Mechanical activation	50–200	Acid leaching	Recovery from previously inert material
Lithium minerals / batteries	Mechanochemical activation	150–400	Reduction/leaching	Lower reaction temperature

Table 5 summarizes energy ranges for mechanical activation and related metallurgical improvements. Most studies report energy inputs ranging from 50 to 400 kWh/t, depending on mill type, material hardness, and activation time. Benefits include higher leaching rates, lower reagent use, lower reaction temperatures, and metal recovery from inert materials. The effectiveness of mechanical activation depends on energy input, emphasizing the need to report specific energy for comparison.

Comparison with Conventional Grinding

Mechanical activation differs from conventional grinding by inducing structural disorder rather than just reducing particle size, leading to higher recovery at similar sizes due to microstructural effects beyond surface area (Subasinghe, 2023; Odebiyi, 2021).

The benchmark is the marginal energy to reach a target recovery. If activation requires more energy than conventional milling for minimal recovery gain, it is unlikely to be attractive. However, if it allows lower temperature, shorter time, or less reagent, the extra milling energy may be justified (Fang, 2023; Wang, 2025).

Distinguish between conventional grinding and mechanical activation, both of which involve milling but have different goals. Conventional comminution mainly reduces particle size, whereas mechanical activation induces structural disorder, defects, and increased reactivity. As shown in Figure 14, it induces lattice strain, amorphization, and surface changes, thereby improving chemical reactivity across various systems.

Figure 14. Conceptual comparison of conventional grinding versus mechanical activation showing different targets: size reduction versus structural disorder (adapted from (Subasinghe & Ratnayake, 2023; Odebiyi et al., 2021).

The graphic compares traditional grinding, which reduces particle size and liberates minerals, with mechanical activation, which induces structural disorder and defects and increases surface energy. Activated particles are more reactive, enhancing leaching, reduction, or solid-state reactions.

Global Energy Balance (Activation + Leaching or Thermal Step)

The correct evaluation requires a whole-process energy balance. This includes milling power, auxiliary loads, and downstream impacts. In hydrometallurgy, activation may reduce leaching time, temperature, or acid consumption. In pyrometallurgy, activation may reduce roasting or reduction temperature. The net benefit depends on whether the downstream energy savings exceed the milling energy input (Fang, 2023; Li, 2025; Su, 2023).

A practical approach is to express results as "energy per unit of metal recovered" rather than energy per ton of feed. This metric allows comparison between ores and residues with different grades. It also aligns better with techno-economic analysis (Pereira, 2025; Odebiyi, 2025).

Proper evaluation of mechanical activation requires considering the entire process chain—milling, leaching, purification, and thermal treatment. Focusing solely on milling energy can be misleading, since activation can reduce energy requirements in subsequent steps. As shown in Figure 15, overall energy accounting indicates that additional electrical energy during activation may be offset by reduced thermal demand, reduced reagent use, and improved efficiency in subsequent hydrometallurgical or pyrometallurgical steps.

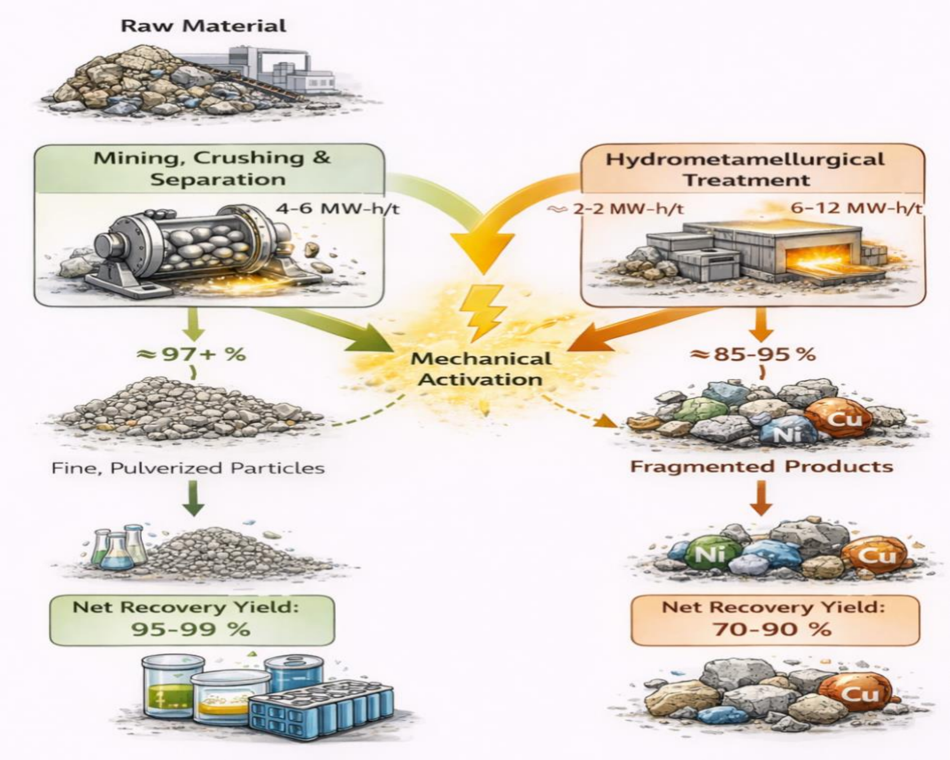

Figure 15. Whole-process energy accounting for routes including mechanical activation and downstream hydrometallurgical or pyrometallurgical processing (adapted from (Odebiyi et al., 2025; Pereira, 2025).

The flowchart contrasts conventional processing with mechanical activation, which increases energy use during comminution but can improve recovery by producing reactive fine particles. Sometimes, higher energy is balanced by better extraction and lower thermal demand, raising recovery. This highlights the importance of assessing mechanical activation throughout the entire process, not just at a single step.

Critical Question: Does Activation Energy Pay Back?

This question remains open in many fields. Studies show improved recovery but lack details on energy input, efficiency, or scale effects, hindering industrial decisions (Odebiyi, 2021; Subasinghe, 2023). Laterite case studies emphasize the need to balance gains from atmospheric leaching against increased milling energy (Acquah, 2025; Tunç Parlak, 2025).

For industrial adoption, the energy assessment must be coupled with environmental indicators, especially when activation is proposed as a "green" intensification step. The next section addresses sustainability and life-cycle aspects.

Environmental and Sustainability Aspects

Mechanical activation reduces temperature, reagent use, and processing time, lowering environmental impact. However, it consumes significant electrical energy, requiring a full process evaluation—including milling, downstream processing, and waste.

Reduction of Processing Temperature

A key sustainability benefit of mechanical activation is it allows operation at lower temperatures, as activated solids react faster and need less severe thermal treatment in systems like roasting, carbothermal reduction, and pressure leaching (Fang, 2023; Yang, 2025). Lower temperature reduces fuel use and indirect CO_2 emissions, especially when it replaces high-temperature recycling steps (Sim, 2025).

The net benefit depends on the electricity source for milling. If high electrical input from carbon-intensive energy is needed, the footprint may not decrease. A comparison between conventional and activated routes shows an energy trade-off: milling requires more electrical energy but creates defects and increases surface reactivity, enabling reactions at lower temperatures and faster rates. As shown in Figure 16, activation shifts transformations to lower temperatures, reducing energy use, costs, and emissions.

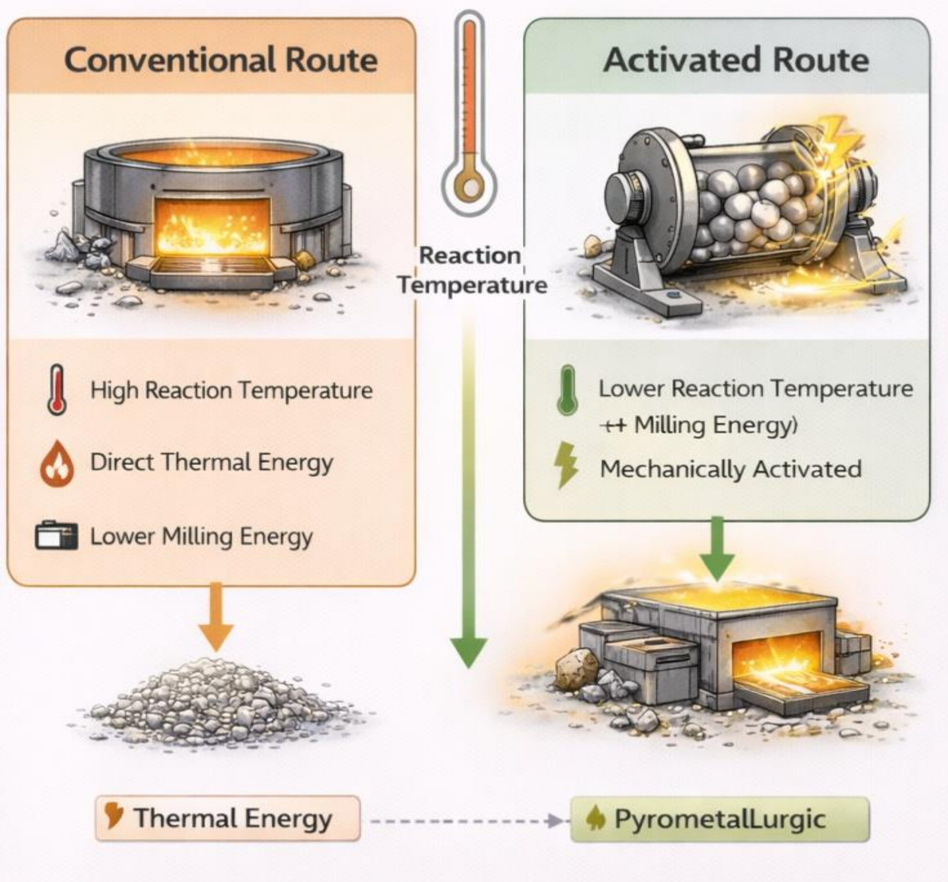

Figure 16. Conceptual comparison of conventional route vs activated route showing lower reaction temperature but additional milling energy (adapted from (Fang et al., 2023; Yang et al., 2025).

The graphic compares traditional thermal processing with methods using mechanical activation beforehand. Activation increases milling energy but allows reactions at lower temperatures, reducing thermal energy needs. The benefit depends on whether savings in furnace energy offset higher milling energy, which varies by system.

Reduction of Reagent Consumption

Mechanical activation can lower the amount of acids, alkalis, or oxidants needed during leaching. Increased defect density and surface energy boost solids' reactivity, enabling dissolution under milder conditions (Fang, 2023; Komnitsas, 2021). Lower reagent use cuts costs and environmental impact, especially with strong acids or bases, where production and neutralization add to the footprint (Ippolito, 2022).

Activation of residues such as fly ash, tailings, and laterite leach residues boosts recovery without chemicals, thereby enhancing sustainability (Niu, 2021; Yang, 2025). Mechanical activation improves dissolution, reduces reagent use, and creates structural defects that increase surface area and promote amorphization, boosting leaching. Table 6 shows activation reduced acid or alkali use while increasing metal recovery from industrial residues, slags, and ores. Activation enhances efficiency, especially for refractory aluminosilicates and fayalitic materials where dissolution is limited by crystal stability.

Table 6. Reported reductions in reagent consumption after mechanical activation in selected hydrometallurgical systems (adapted from (Fang et al., 2023; Komnitsas et al., 2021; Niu et al., 2021).

Material / Residue	Activation method	Leaching system	Reagent reduction	Additional benefit
Coal fly ash	High-energy ball milling	H_2SO_4 leaching	Lower acid concentration required	Higher Al and Li recovery
Aluminosilicate residue	Mechanical activation	Acid leaching	Reduced acid consumption	Faster dissolution kinetics
Laterite leach residue	Mechanical activation	Alkali activation / leaching	Lower alkali dosage	Improved phase reactivity
Sulfidic waste rock	Mechanochemical activation	Alkali activation	Reduced reagent demand	Enhanced reactivity of silicate phases
Copper tailings	Mechanical activation	H_2SO_4 leaching	Lower acid requirement	Improved Mo selectivity
Vanadium slag	Mechanochemical activation	NaOH leaching	Reduced alkali consumption	Higher V extraction
Molybdenum ore	Mechanical activation	HNO_3–H_2SO_4 leaching	Reduced acid consumption	Faster dissolution
Polymetallic tailings	Mechanical activation	Acid leaching	Lower reagent dosage	Higher metal recovery
Titanium slag	High-energy milling	Acid leaching	Reduced acid concentration	Increased dissolution rate
Chalcopyrite concentrate	Mechanical activation	Glycine/acid leaching	Lower oxidant consumption	Higher leaching efficiency

Table 6 shows reduced reagent use after mechanical activation, which increases surface reactivity and defect density, enabling lower acid or alkali use while maintaining or improving metal recovery. Reagent savings can offset milling energy, but overall benefits depend on activation energy, chemical use, and recovery gains.

Process Intensification and Circular Economy

Mechanical activation aligns with process intensification, boosting reactivity before the main treatment. It can cut unit operations or lessen operating severity, especially in treating secondary resources where standard methods are not feasible (Sim, 2025; Dushyantha, 2024).

Activation can also enable recovery from materials previously considered waste. Tailings, slags, and electronic scrap may become viable feedstock after structural modification. This contributes to circular economy strategies aimed at reducing disposal and recovering critical metals (Nyeko, 2023; Yadav, 2022).

Mechanical activation, a pre-treatment beyond milling, influences process feasibility. It's vital in circular metallurgy, reprocessing waste, and low-grade materials. As shown in Figure 17, high-energy milling enhances the reactivity of waste feedstock, aiding hydrometallurgical and pyrometallurgical processes and reducing thermal energy requirements for metal recovery. This supports closed-loop processing and reduces environmental impact.

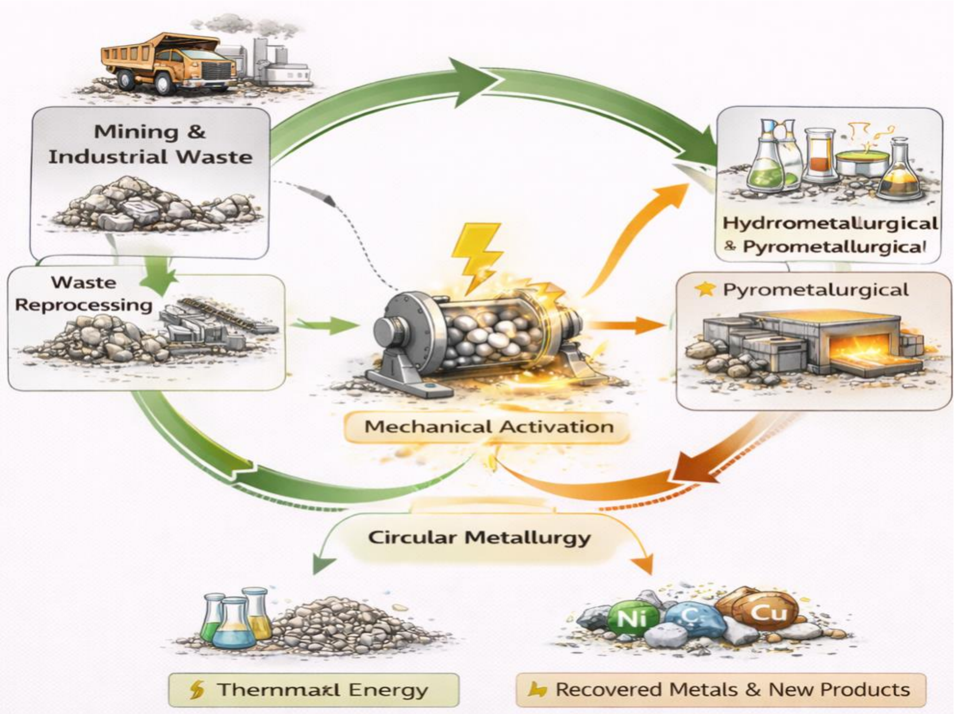

Figure 17. Role of mechanical activation in circular metallurgy showing integration of waste reprocessing and metal recovery routes (adapted from (Sim et al., 2025; Dushyantha et al., 2024).

The flowchart illustrates mechanical activation in circular metallurgy, reprocessing residues, wastes, and low-grade materials into reactive feedstock for metal recovery. This boosts reactivity, making inert materials viable sources of metal, supporting waste valorization, and reducingthe use of primary raw materials.

Carbon Footprint and Life-Cycle Considerations

Few studies have evaluated mechanical activation using life-cycle assessment. Most papers report improved recovery or lower temperature, but do not include the energy cost of milling in the environmental balance (Odebiyi, 2022; Ippolito, 2022).

Life-cycle studies indicate that the environmental benefit depends strongly on the relative contribution of thermal energy, electricity, and reagents. If activation replaces a high-temperature step, the footprint may decrease. If activation only adds energy without reducing downstream severity, the footprint may increase.

Another limitation is the lack of standardized reporting of milling energy, making study comparisons and LCA calculations difficult. A simplified life-cycle approach is needed to evaluate the true impact of mechanical activation. Figure 18 shows activation increases electrical energy during milling, but may decrease thermal energy and reagent use downstream. Overall environmental performance should be assessed across the entire process chain, not just individual steps.

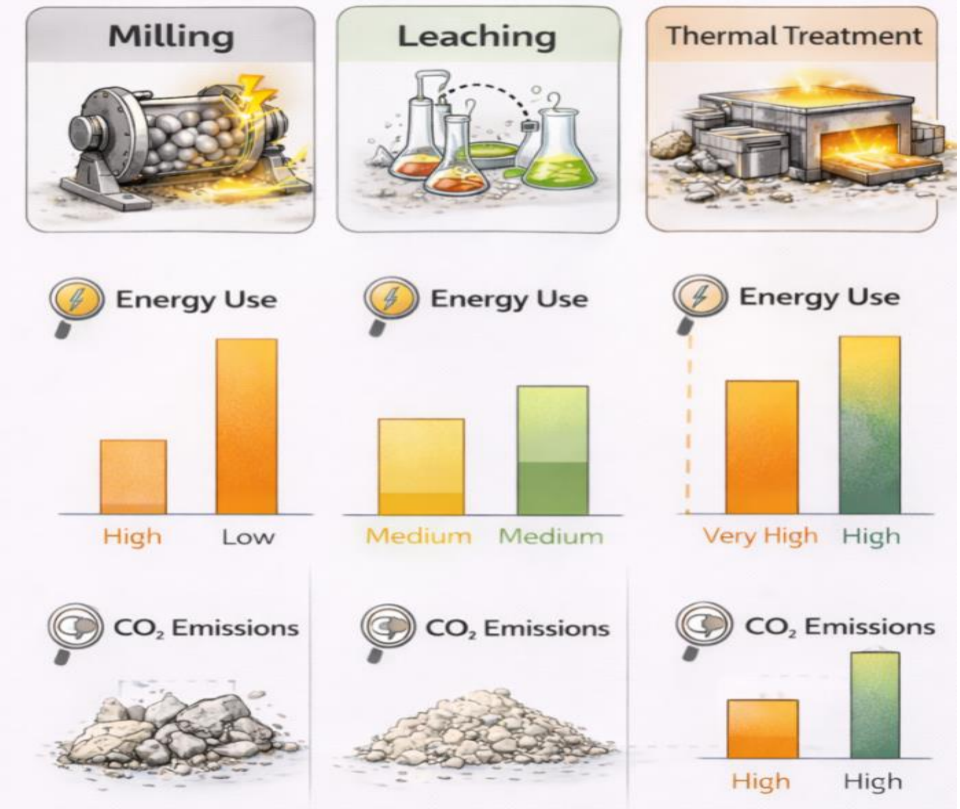

Figure 18. Simplified life-cycle comparison showing energy and emission contributions of milling, leaching, and thermal treatment (adapted from (Ippolito et al., 2022; Odebiyi et al., 2022).

The diagram compares energy use and CO_2 emissions of milling, leaching, and thermal treatment. Mechanical activation increases milling energy but can reduce thermal processing and improve leaching. Environmental impact depends on balancing higher milling energy with lower thermal energy and reagent use, underscoring the need for a full process evaluation.

Mechanical activation may boost sustainability, but only when considered alongside energy use, reagent use, and process integration. Therefore, environmental analysis must be paired with economic evaluation.

These aspects are discussed in the following section.

Techno-Economic Considerations

The industrial use of mechanical activation depends on metallurgical performance, energy demand, equipment cost, grinding media wear, and scalability. Many lab studies show improved recovery, but few analyze economic feasibility. Thus, process viability remains uncertain (Odebiyi, 2022; Subasinghe, 2023).

Mechanical activation adds a unit operation requiring energy, media, and maintenance, often in an inert atmosphere. Its benefits must offset costs through higher recovery, lower reagent use, or less thermal treatment (Acquah, 2025; Tunç Parlak, 2025).

Energy Cost and Recovery Gain

The key economic indicator is the link between energy input and recovery gain. Activation enhances extraction in many laterite and oxide systems, but the benefit may be limited given the energy needed for high-energy milling (Acquah, 2025; Tunç Parlak, 2025).

In mechanochemical routes, the situation may be different. When activation replaces part of a roasting or chemical pretreatment step, the overall cost may decrease even if milling energy is high. This behavior has been reported in battery recycling and carbothermal reduction systems (Su, 2023; Li, 2025; Wang, 2025).

A meaningful comparison reports results on a per-metal-recovered basis, not per ton of feed, allowing a fair evaluation of low-grade ores and residues (Pereira, 2025). While many studies show improvements in leaching or recovery after mechanical activation, practical use depends on balancing added milling energy against metallurgical benefits. Therefore, a techno-economic assessment is vital for determining activation's industrial potential, considering energy input, recovery gains, process complexity, and technology readiness. Table 7 summarizes selected applications evaluated from a techno-economic view.

Table 7. Techno-economic comparison of mechanical activation applications, including energy input, recovery increase, and industrial feasibility (adapted from Acquah et al., 2025; Su et al., 2023; Pereira, 2025).

Material / System	Process after activation	Energy input (kWh/t)	Recovery increase (%)	Industrial feasibility	TRL
Nickel laterite	Atmospheric acid leaching	100–250	10–25	Medium	4–5
Chalcopyrite concentrate	Acid / glycine leaching	50–150	15–30	Medium	4
Refractory gold concentrate	Thiosulfate leaching	60–150	10–20	Medium	4–5
Fly ash	Acid leaching	120–300	20–40	Medium	3–4
Vanadium slag	Alkaline leaching	100–250	15–35	Medium	4
LIB cathode material	Mechanochemical reduction + leaching	150–350	20–50	Medium–high	5–6
Tailings/slags	Acid leaching	50–200	10–30	Medium	4
Molybdenum ore	Acid leaching	80–180	10–25	Medium	4
Titanium slag	Acid leaching	100–220	15–30	Medium	4
Lithium minerals	Mechanochemical + leaching	150–400	20–45	Medium	4–5
Battery recycling	Mechanochemical route	150–350	25–50	High (pilot/industrial)	6
Feldspar / silicate activation	Acid / alkaline dissolution	80–200	15–35	Medium	3–4

Table 7 presents techno-economic data for mechanical activation in metallurgical systems. Recovery increases from 10% to 50%, requiring around 50-400 kWh/t of energy, depending on material and mill type. Most data are at lab or pilot scale (TRL 3–5), with higher readiness in battery recycling and mechanochemical routes. These figures show that industrial viability depends on balancing extra milling energy against downstream processing benefits.

Scalability and Industrial Implementation

Scale-up is a major barrier for mechanical activation. Laboratory mills use high-impact energy for small batches, whereas industrial mills handle large throughput with lower energy, making direct extrapolation difficult (Subasinghe, 2023).

Attritors and stirred mills are often seen as better for industry than planetary mills, but they can still require high energy. Continuous operation adds complexity, such as cooling, wear control, and material handling (Odebiyi, 2022).

In hydrometallurgical plants, activation must be integrated with grinding circuits, which may limit energy levels. In pyrometallurgical routes, activation must justify itself by reducing furnace load or processing time. A major challenge in mechanical activation research is the gap between laboratory and industrial milling. Laboratory mills deliver high specific energy but process small amounts, while industrial mills handle larger throughput with lower energy per collision. This difference complicates scale-up and may lead to unrealistic expectations about industrial performance. Figure 19 shows this conceptual gap.

Figure 19. Conceptual comparison between laboratory and industrial milling showing differences in energy intensity and throughput (adapted from (Subasinghe & Ratnayake, 2023; Odebiyi et al., 2022).

The graphic explains why results from high-energy laboratory mills cannot always be reproduced at the industrial scale.

Wear of Grinding Media and Contamination

High-energy milling accelerates ball and liner wear, raising costs and increasing the risk of contamination. Iron from steel media may alter process chemistry or disrupt downstream separation (Odebiyi, 2022).

Wear affects energy efficiency because some input energy is converted into heat and friction rather than intostructural disorder. Over long milling periods, media replacement costs can match energy costs.

These issues are rarely discussed in lab studies, yet they are crucial for industry evaluation.

Operational Cost and Process Integration

Mechanical activation should be evaluated within the full flowsheet. The extra milling cost may be acceptable if activation provides benefits.

- lowertemperatureroasting
- loweracidconsumption
- shorterleaching time
- higherrecoveryofvaluablemetals
- processing of low-grade or waste materials

In recycling and secondary resource processing, activation enables recovery routes that would otherwise be impossible. Economic benefits primarily derive from recovered metals, not from energy savings (Ippolito, 2022; Wang, 2025). Mechanical activation affects multiple stages, so its evaluation can't rely solely on leaching or reaction rates. The extra energy for milling must be balanced against reduced reagent use, thermal energy, and processing time. A full techno-economic analysis should include upstream activation and downstream metallurgical steps. Figure 20 shows a simplified scheme for the integrated evaluation of mechanical activation.

Figure 20. Techno-economic evaluation scheme showing interaction between milling energy, recovery, reagent cost, and thermal energy (adapted from (Pereira, 2025; Ippolito et al., 2022).

The flowchart shows how milling energy, recovery, reagent use, thermal energy, and environmental impact relate to mechanical activation. While activation can increase electrical energy during milling, it reduces thermal energy and reagent needs, boosting overall performance. The scheme emphasizes assessing the benefits of mechanical activation across the whole process, not just milling.

Mechanical activation can be economically viable for refractory ores and secondary resources, but inconsistent reporting of energy, cost, and scale-up data hinders comparison.

Recent research focuses on new activation methods to reduce energy demand or enhance selectivity, as discussed in the next section.

Emerging Trends

Recent work has shifted from “activation as milling” to hybrid methods that improve selectivity and lower energy use. Most combine mechanical impacts with chemical or thermal/electromagnetic assistance. The main issue is maturity: many concepts work in laboratories, but few have clear paths to industrial scale (Fang, 2023; Wang, 2025).

Reactive Milling and Mechanochemistry

Reactive milling adds reagents during milling to promote partial conversion, control surface chemistry, and reduce downstream leaching or roasting severity. It also simplifies recycling flowsheets.

Battery recycling now uses mechanochemical routes that combine milling with reduction, complexation, or leaching, achieving high extraction and faster processing. However, energy and wear limit these methods (Babanejad, 2023; Dolotko, 2024; Wang, 2025).

In mineral systems, mechanochemical activation destabilizes oxide networks and promotes low-temperature salt-assisted transformations, reducing high-temperature steps and reagent use (Fang, 2023; He, 2025; Liu, 2024a; Liu, 2024b). Recent studies propose new routes in which mechanical activation is not merely a pretreatment but part of the reaction pathway, including reactive milling, mechanochemical reduction, salt-assisted activation, and one-step leaching, thereby enabling simultaneous structural and chemical changes. These strategies aim to lower the temperature, simplify flow sheets, and enhance metal recovery from complex materials. Figure 21 summarizes key mechanochemical route archetypes.

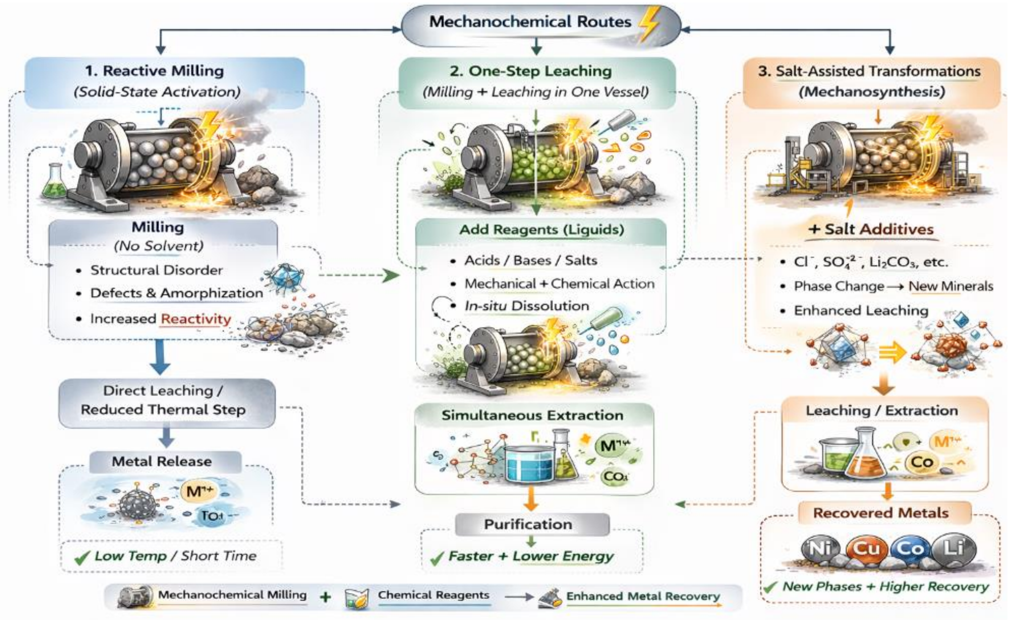

Figure 21. Emerging mechanochemical route archetypes, including reactive milling, one-step leaching, and salt-assisted transformations (adapted from Fang et al., 2023; Dolotko et al., 2024).

The flowchart shows mechanochemical routes such as reactive milling, one-step milling–leaching, and salt-assisted transformations, which combine mechanical activation with chemical reactions to enhance reactivity, enable in situ phase changes, and reduce the need for high-temperature processing. These routes can shorten flowsheets but also add complexity with reagent control, energy, and scale-up.

Solid-State Reduction and Reactive Synthesis

A second trend is the use of mechanical activation for solid-state reduction and reactive synthesis. High-energy milling boosts contact, creates metastable structures, and lowers the temperature needed for reduction or phase formation (Moskovskikh, 2020; Giordana, 2020).

These methods excel in materials processing and are now used for recycling. Activated mixtures form intermediate phases that decompose rapidly upon heating, thereby shortening thermal residence (Ershova, 2023; Wang, 2025). Mechanical activation boosts solid-state reactions by increasing defect density, reducing diffusion distance, and promoting metastable phases. This is crucial in carbothermal reduction, alloy formation, and refractory oxide decomposition, where slow diffusion limits reaction kinetics. Pre-activation by high-energy milling can lower transformation temperatures. Figure 22 shows the solid-state reduction pathway after mechanical activation.

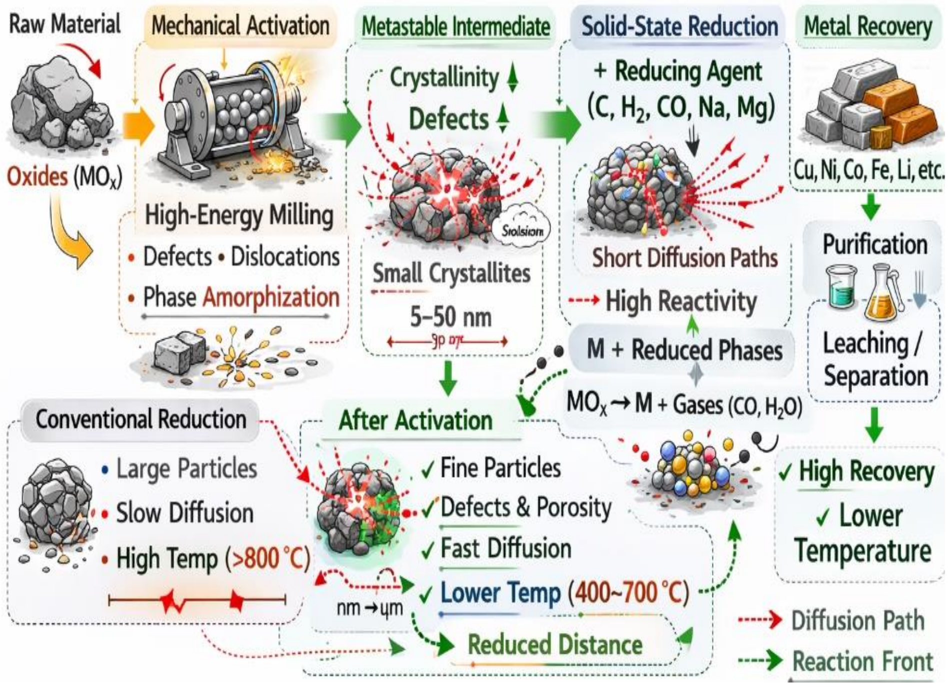

Figure 22. Conceptual pathway for solid-state reduction after activation showing metastable intermediate formation and reduced diffusion distance. adapted from Moskovskikh et al., 2020; Giordana et al., 2020.

The graphic shows mechanical activation boosts solid-state reduction by creating defects, refining crystallites, and forming metastable structures. This reduces diffusion distance and enhances reaction interface, allowing faster reactions at lower temperatures than coarse particles. It highlights activation's role in aiding solid-state methods for refractory oxides and complex feeds.

MA Combined With Microwave or Other Assisted Heating

MA, especially microwave-assisted routes, is often employed because activation boosts defect density and electromagnetic coupling, while rapid heating shortens processing time.

In practice, maturity varies. Many studies are small and lack energy accounting, and integration with continuous milling is rarely shown. While promising for bottlenecks such as slow phase changes or high-temperature roasting (Wang, 2025; Fang, 2023), recent research combines mechanical activation with thermal, chemical, or electrochemical treatments to enhance reactions, lower temperatures, or simplify processes. These methods differ in technological maturity, so it’s crucial to distinguish laboratory concepts from those with industrial potential. Table 8 summarizes hybrid activation strategies, their targets, benefits, limitations, and technology readiness level (TRL).

Table 8. Emerging hybrid activation strategies and their maturity level (TRL), with typical benefits and limitations (adapted from Wang et al., 2025; Fang et al., 2023).

Trend / Strategy	Typical target	Main benefit	Main limitation	Indicative TRL
Mechanochemical activation + leaching	LIB, fly ash, slags	One-step reaction, higher reactivity	High energy demand	4–5
Reactive milling (solid–solid reactions)	Oxides, alloys, battery materials	Formation of metastable phases	Scale-up difficulty	3–4
Mechanical activation + roasting	Refractory ores, sulfides	Lower roasting temperature	Additional processing step	4–5
Mechanical activation + molten salt	Oxides, Mn ores, slags	Faster diffusion, lower temperature	Salt handling/corrosion	3–4
Mechanical activation + carbothermal reduction	Oxides, battery materials	Reduced reduction temperature	Energy cost of milling	4–5
Mechanical activation + bioleaching	Sulfides, lithium minerals	Faster dissolution	Limited industrial validation	3–4
Mechanical activation + alkaline activation	Silicates, tailings	Higher reactivity of aluminosilicates	Reagent consumption	4
Mechanical activation + microwave heating	Refractory minerals	Rapid heating, lower energy	Equipment scale limitation	2–3
Mechanochemical reduction (direct metal recovery)	LIB, catalysts, oxides	Elimination of roasting step	Wear and contamination	4–5
Mechanical activation + selective leaching	Tailings, slags	Improved selectivity	Process control required	4
Mechanical activation + additive-assisted milling	Complex ores	Controlled surface chemistry	Reagent cost	3–4
Mechanical activation + electrochemical route	Battery materials, catalysts	High-purity products	Complex integration	3–4

Table 8 summarizes hybrid strategies that combine mechanical activation with chemical, thermal, or electrochemical methods to lower reaction temperature, enhance reactivity, or enable direct metal recovery from complex materials. Most remain at lab or pilot scale (TRL 2-5), with barriers like energy demand, scale-up, and process integration for industrial use.

MA Assisted By Chemical Additives

Additive-assisted activation is becoming more systematic, shifting focus from “more energy” to “better chemistry.” Salts, oxidants, reductants, and complexing agents are chosen to steer reactions during milling, enhancing selectivity and reducing downstream chemical load (Su, 2023; He, 2025; Liu, 2024a).

This trend is particularly evident in lithium-ion battery recycling, where mechanochemical reduction and one-step leaching simplify flowsheets and reduce waste generation (Zhang, 2023; Wang, 2025; Dolotko, 2024).

Maturity Assessment: What Is Close to Industrial Use?

Three categories can be distinguished:

1. **Near-term options (pilot potential):** stirred/attritor-based activation integrated with leaching or with mild roasting, especially in recycling flowsheets. These routes have clearer pathways for scale-up (Wang, 2025; Dolotko, 2024).
2. **Mid-term options:** reactive milling with salts or oxidants aimed at replacing a thermal pretreatment.

Needs full energy balance andwearcontrol (Fang, 2023; He, 2025).

3. **Early-stage options:** highly optimized mechanochemical “one-step” conversions that rely on very high milling intensity. Strong results, weakevidencefromindustry (Zhang, 2023; Babanejad, 2023).

These trends show that the field is moving toward process integration and selectivity. They also highlight the same unresolved issues: energy reporting, scale-up, and contamination control.

The next section consolidates these findings and frames the central research gaps that still limit industrial adoption.

Critical Synthesis and Research Gaps

The literature shows that mechanical activation improves leaching, lowers reaction temperature, and aids recovery from complex materials. These effects are seen across various systems. However, limitations restrict industrial use, as studies primarily focus on metallurgical performance, placing less emphasis on energy, scale-up, and process integration (Odebiyi, 2021; Subasinghe, 2023).

A critical analysis shows the main barrier isn't the absence of positive results but inconsistent evaluation criteria. Varying mills, milling times, and reporting methods make direct comparison of mechanical activation efficiency impossible (Alrbaihat, 2022; Odebiyi, 2022).

High Energy Demand and Uncertain Payback

Mechanical activation needs a lot of electrical energy. While recovery improves often, the energy balance isn't always positive. Studies on laterites, oxides, and recycling show that higher extraction does not always mean better efficiency (Acquah, 2025; Tunç Parlak, 2025).

Activation, replacing a thermal step or reducing reagent use, is beneficial, but adding activation without decreasing downstream severity increases energy use, which is rarely quantified (Fang, 2023; Wang, 2025). As shown in Figure 23, mechanical activation helps when recovery, reagent reduction, or lower reaction temperature offset milling energy, which is common in refractory minerals, slags, tailings, and battery materials. For easily leachable ores, high-energy milling may outweigh benefits. These findings emphasize integrated evaluation of energy, recovery, and cost rather than activation efficiency alone (Acquah et al., 2025; Pereira, 2025).

Figure 23. Conceptual comparison between metallurgical gain and energy input showing cases where activation is beneficial and cases where it is not (adapted from (Acquah et al., 2025; Pereira, 2025).

The scheme shows the energy balance during mechanical activation, which can lower the reaction temperature, accelerate reactions, or improve recovery in tough materials. However, it may be unwise if milling energy costs outweigh the benefits. This highlights the need for a full energy and economic evaluation before industrial use.

Lack of Standardization of Activation Parameters

A major challenge in the field is the lack of standardized reporting. Milling time is usually provided, but data on power, energy input, and mill efficiency are missing. Without these, it's impossible to relate activation intensity to metallurgical response (Odebiyi, 2021; Alrbaihat, 2022).

This problem hinders predictive model development and the transfer of lab results to industrial materials, which may require different energy inputs based on mill type and mode (Subasinghe, 2023). A major challenge in comparing literature results is the inconsistent reporting of milling conditions. Many studies mention milling time but omit data on specific energy, mill power, ball-to-powder ratio, or atmosphere, hindering reproducibility and assessment of activation. For meaningful comparison, a minimum set of parameters must be reported. Table 9 lists key variables used to describe mechanical activation experiments.

Table 9. Main parameters required for proper reporting of mechanical activation experiments (adapted from Odebiyi et al., 2021; Alrbaihat, 2022).

Parameter	Description	Wh yis it important	Typical range/notes
Mill type	Planetary, attritor, vibratory, high-energy ball mill	Determines impact energy and collision frequency	Must always be reported
Power/mill capacity	Motor power or energy input rate	Required to estimate specific energy	kW or W
Milling time	Total activation duration	Directly controls defect generation	minutes–hours
Specific energy (kWh/t)	Energy per mass of material	Key parameter for comparison between studies	Often missing in the literature
Ball-to-powder ratio (BPR)	Mass ratio of grinding media to powder	Controls collision intensity	5:1 – 30:1 typical
Ball size / distribution	Diameter of milling media	Influences impact vs shear regime	5–30 mm typical
Rotation speed / frequency	Speed of mill or vibration frequency	Controls impact energy	rpm or Hz
Atmosphere	Air, inert gas, vacuum, reactive gas	Affects oxidation/reduction during milling	Must be specified
Additives/reagents	Solid or liquid added during milling	Enables mechanochemical reactions	Often not reported
Particle size before milling	Feed size	Affects energy demand	µm–mm
Particle size after milling	Productsize	Needed to separate grinding vs activation	µm–nm
Surface area (BET)	Specific surface area after activation	Indicates structural change	m²/g
Structural analysis	XRD, Raman, FTIR, SEM, TEM	Confirms real activation	Essential
Leaching/reaction conditions	Acid, alkali, temperature, time	Needed to correlate activation and recovery	Must be reported
Metal recovery (%)	Extraction efficiency	Main performance indicator	%
Reagent consumption	Acid/alkali / reductant use	Required for techno-economic evaluation	kg/t
Wear/contamination	Fe, Cr, WC contamination from balls	Important for scale-up	Rarely reported
Scale of experiment	Lab / pilot / industrial	Needed for TRL assessment	Often missing
Energy balance	Milling + downstream processing	Required for real evaluation	Critical gap

Table 9 summarizes key parameters for mechanical activation studies. Missing standardized reporting of energy, milling conditions, and downstream processes hampers comparisons and limits industrial assessments. Proper documentation is vital for linking activation to performance and for accurate techno-economic and environmental evaluations.

Scale-Up and Industrial Constraints

Laboratory activation uses planetary or high-energy mills, while industrial mills run continuously with lower energy, making scale-up uncertain (Subasinghe, 2023).

Wear of grinding media limits efficiency. High-energy milling increases the use of liners and balls and can lead to contamination. These factors, often overlooked in lab studies, significantly impact costs (Odebiyi, 2022).

Cooling, dust handling, and throughput are crucial for large-scale operations, which is why many promising lab results don't translate to industrial use. A key limitation is the difference between lab-scale milling, designed to maximize impact energy and defect creation, and industrial milling, which focuses on throughput, durability, and energy efficiency. Consequently, activation levels from lab tests may not directly translate to industrial settings. Figure 24 shows the gap between laboratory activation and industrial milling conditions.

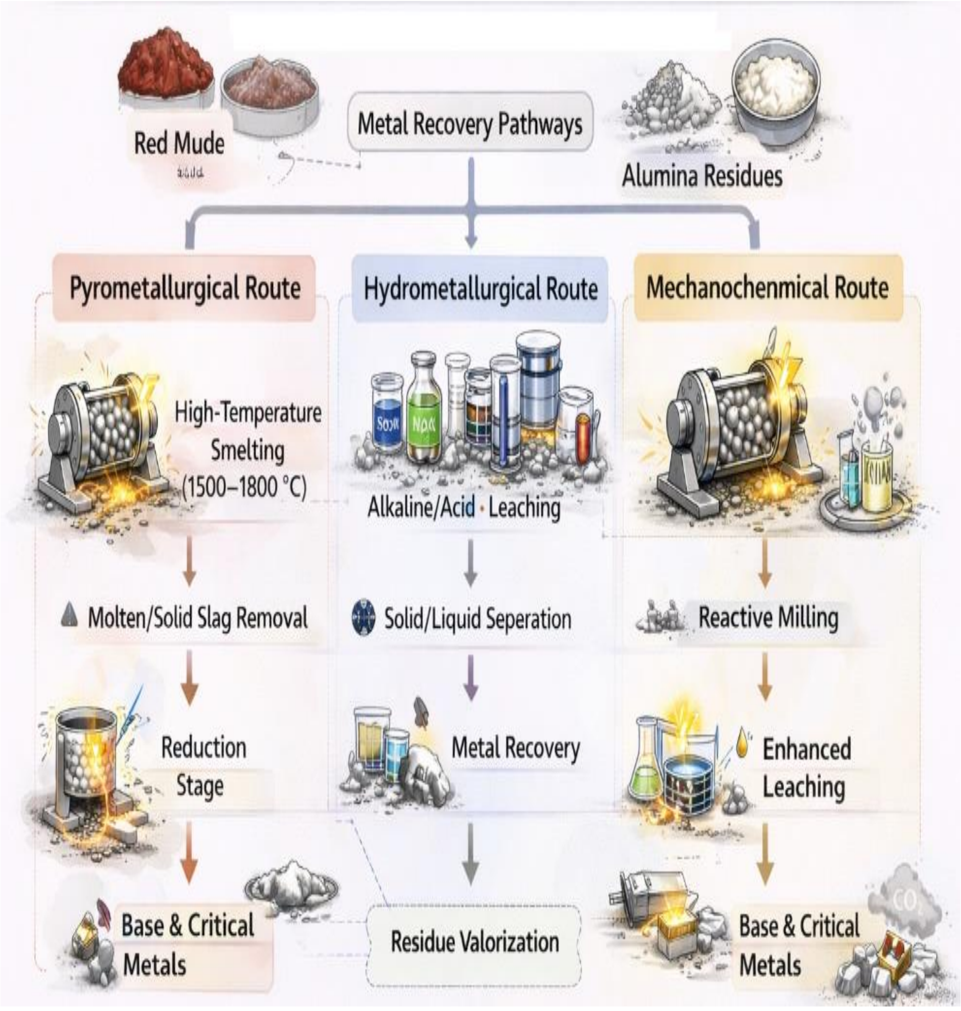

Figure 24. Gap between laboratory activation and industrial milling showing differences in energy intensity, throughput, and wear (adapted from Subasinghe & Ratnayake, 2023).

The graphic compares traditional pyrometallurgical and hydrometallurgical methods with mechanochemical methods for metal recovery from residues like red mud and alumina wastes. Mechanical activation involves reactive milling before leaching or reduction, boosting reactivity and improving metal recovery at lower temperatures or with less reagent, thereby aiding residue valorization.

Limited Integration with Kinetic Modeling

Many studies report faster leaching after activation, but few link structural changes with kinetics. Shrinking-core models are common, but they rarely account explicitly for defect density and stored energy (Odebiyi, 2021; Fang, 2023).

Without quantitative models, optimization is empirical, limiting the ability to define minimum energy for recovery. Integrating mechanical activation with reaction modeling remains an open field.

Need For Full Process and Life-Cycle Evaluation

Environmental and economic analyses should be conducted at the flowsheet level, evaluating activation alongside grinding, leaching, roasting, and purification. Life-cycle studies indicate benefits depend on downstream energy or reagent savings (Ippolito, 2022; Sim, 2025).

In recycling and the circular economy, activation allows the recovery of materials that would otherwise be discarded. Evaluation should consider avoided waste and mining, not just energy use (Sim, 2025; Pereira, 2025). Mechanical activation affects multiple metallurgical stages and should be evaluated using parameters such as energy, performance, reagents, cost, and environmental impact, analyzed at the process level. Figure 25 shows a simplified scheme for this integrated evaluation.

Figure 25. Integrated evaluation of mechanical activation, including energy, recovery, cost, and environmental indicators (adapted from Pereira, 2025; Ippolito et al., 2022).

The flowchart illustrates an evaluation framework for mechanical activation that balances energy input, recovery, costs, and environmental impact. Activation enhances reactivity and recovery but requires more energy and media. Techno-economic and environmental assessments are essential to determine if the activated process surpasses traditional methods.

Uture Research Directions

Based on the reviewed literature, the following priorities can be identified:

- correlation between specific energy and reactivity
- standardizedreportingofmillingconditions
- modeling of defect generation and reaction kinetics
- selectiveactivationusingchemicaladditives
- integrationwithcontinuousmilling systems
- full techno-economic and LCA evaluation

These directions are necessary to transition from lab success to industrial use.

Mechanical activation is powerful, but its full potential depends on metallurgical, energetic, and economic evaluation.

The main conclusions of this review are summarized in the following section.

Conclusions

Mechanical activation has been widely studied to enhance the reactivity of minerals and residues in metallurgy. Literature confirms that high-energy milling can alter the crystal structure, increase defect density, and boost surface free energy, thereby accelerating leaching, lowering reaction temperatures, and enabling treatment of refractory materials. These effects are observed in hydrometallurgical, pyrometallurgical, and recycling processes, including sulfides, oxides, silicates, slags, tailings, and electronic waste.

Despite many lab studies, industrial use remains limited due to difficulty in proving overall process benefits, despite metallurgical improvements. Mechanical activation consumes significant energy, increases wear, and adds complexity. Many reports lack specific energy data, hampering comparisons and scale-up. Consequently, the economic and environmental benefits are often uncertain.

Mechanical activation is most promising when it replaces or simplifies other processes like high-temperature roasting, severe leaching, or chemical pretreatment. In such cases, increased milling energy can be offset by lower thermal demand, reduced reagents, or improved recovery from low-grade or secondary materials. This is especially important for circular economy uses, enabling recovery from otherwise unused residues.

Recent research shows a shift from simple high-energy milling to more selective methods like mechanochemistry, reactive milling, and hybrid processes with additives or heating. These aim to reduce energy use while maintaining structural benefits. Most are still lab-scale, with industrial feasibility unproven.

Future work should establish quantitative links between milling energy and metallurgical performance, enhance reporting standards, and incorporate activation into comprehensive models including energy, cost, and environmental factors. Multiphysics modeling, continuous systems, and life-cycle assessments will be crucial to identify when mechanical activation is truly beneficial.

In summary, mechanical activation enhances metallurgy, especially for refractory ores and secondary resources. Its industrial success relies on moving from isolated experiments to integrated evaluations that consider kinetics, energy, scalability, and sustainability at the flowsheet level.

Declarations

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Conflict of Interest

The author declares no conflict of interest related to the content of this article.

Data Availability

The datasets generated or analyzed during the current study are available from the corresponding author on reasonable request.

Author Contributions

Antonio Clareti Pereira: Conceptualization, literature review, methodology design, analysis, writing – original draft, writing – review and editing.

References

1. Acquah, G., Abaka-Wood, G., Skinner, W., Addai-Mensah, J., & Asamoah, R. (2025). Effect of mechanical activation on nickel and cobalt extraction in refractory nickel laterite ore. *Powder Technology*, Advance online publication, 121655. https://doi.org/10.1016/j.powtec.2025.121655
2. Agrawal, S., & Dhawan, N. (2021). Investigation of mechanical and thermal activation on metal extraction from red mud. *Sustainable Materials and Technologies*, 27, e00246. https://doi.org/10.1016/j.susmat.2021.e00246
3. Akhgar, B. N., Kavanlouei, M., Farhoudi, S., &Rohzad, M. H. (2024). Impact of mechanical activation and mechanochemical activation on microstructural changes, leaching rate and leachability of natural chalcopyrite. *Minerals Engineering*, 217, 108962. https://doi.org/10.1016/j.mineng.2024.108962
4. Akhmadiyeva, N., Gladyshev, S., Abdulvaliyev, R., Abikak, Y., Imangaliyeva, L., Kasymzhanova, A., &Ruzakhunova, G. (2025). Activation of mineral composition via thermochemical disintegration. *Minerals*, 15(9), 1000. https://www.mdpi.com/2075-163X/15/9/1000
5. Alrbaihat, M., Al-Zeidaneen, F. K., & Abu-Afifeh, Q. (2022). Reviews of the kinetics of mechanochemistry: Theoretical and modeling aspects. *Materials Today: Proceedings*, 65, 3651–3656. https://doi.org/10.1016/j.matpr.2022.06.195
6. Aslan, B. G., Aslan, C., & Ilhan, S. (2023). Hydrometallurgical recovery of valuable metals from hazardous petrochemical industry waste and kinetic investigation. *Journal of Sustainable Metallurgy*, 9(4), 1535–1549. https://doi.org/10.1007/s40831-023-00745-7
7. Babanejad, S., Ahmed, H., Andersson, C., & Heikkinen, E. P. (2023). Mechanical activation-assisted recovery of valuable metals from black mass in the form of Fe/Cu alloys. *Journal of Sustainable Metallurgy*, 9(2), 522–536. https://doi.org/10.1007/s40831-023-00665-6
8. Bai, Y., Wang, W., Zhao, S., Lu, D., Xie, F., &Dreisinger, D. (2022). Effect of mechanical activation on leaching behavior and mechanism of chalcopyrite. *Mineral Processing and Extractive Metallurgy Review*, 43(4), 440–452. https://doi.org/10.1080/08827508.2021.1906239
9. Díaz-Tato, L., López-Perales, J. F., González-Carranza, Y., Contreras de León, J. E., & Rodríguez-Castellanos, E. A. (2025). Physico-mechanical properties of an aluminosilicate refractory castable obtained after chamotte waste recycling by firing method. *Waste*, 3(4), 35. https://www.mdpi.com/2813-0391/3/4/35
10. Dobrosmyslov, S. S., Zadov, V. E., Nazirov, R. A., Shakirova, V. A., Voronin, A. S., Simunin, M. M., &Khartov, S. V. (2023). High-strength building material based on a glass concrete binder obtained by mechanical activation. *Buildings*, 13(8), 1992. https://www.mdpi.com/2075-5309/13/8/1992
11. Dolotko, O., Gehrke, N., Knapp, M., & Ehrenberg, H. (2024). Mechanochemically induced hydrometallurgical method for recycling d-elements from Li-ion battery cathodes. *Journal of Alloys and Compounds*, 976, 172884. https://doi.org/10.1016/j.jallcom.2023.172884
12. Dushyantha, N., Kuruppu, G. N., Nanayakkara, C. J., & Ratnayake, A. S. (2024). The role of permanent magnets, lighting phosphors, and nickel-metal hydride (NiMH) batteries as a future source of rare earth elements (REEs): Urban mining through circular economy. *Mining, Metallurgy & Exploration*, 41(1), 321–334. https://doi.org/10.1007/s42461-023-00904-0
13. Ershova, O. G., Dobrovolsky, V. D., &Solonin, Y. M. (2023). The influence of Ti + TiC additive on thermal stability and decomposition kinetics of nanosized MgH_2 phase in Mg-based mechanical alloys. *Powder*

Metallurgy and Metal Ceramics, 62(5), 350–359. https://doi.org/10.1007/s11106-023-00398-x

14. Fang, H., Zhou, C., Xu, S., Shi, J., Hu, Y., & Liu, G. (2023). High-efficiency extraction of aluminum and lithium from coal fly ash using a novel sodium pyrosulfate mechanochemical activation–sodium persulfate pressure leaching technology. *Journal of Cleaner Production*, 423, 138841. https://doi.org/10.1016/j.jclepro.2023.138841
15. Gao, G., Luo, X., Liu, N., Yang, T., Zhang, X., Guan, J., &Guo, Y. (2023). Exploration of sequential mechanochemical activation and complexation leaching for enhanced recovery of valuable metals from spent lithium-ion batteries. *Ionics*, 29(9), 3585–3596. https://doi.org/10.1007/s11581-023-05098-5
16. Giordana, M. F., Esquivel, M. R., & Zelaya, E. (2020). The microstructure and the phase stability of a Cu–30 at.% Al alloy obtained by reactive milling and quenching. *Metallography, Microstructure, and Analysis*, 9(6), 816–824. https://doi.org/10.1007/s13632-020-00694-7
17. Golik, V. I., Dmitrak, Y. V., & Brigida, V. S. (2020). Impact of duration of mechanochemical activation on enhancement of zinc leaching from polymetallic ore tailings. *Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu*, (5), 47–54. https://doi.org/10.33271/nvngu/20205/047
18. Golik, V. I., Mitsik, M. F., Aleksakhina, Y. V., Alenina, E. E., Ruban-Lazareva, N. V., Kruzhkova, G. V., &Khayrutdinov, M. M. (2023a). Comprehensive recovery of metals in tailings utilization with mechanochemical activation. *Resources*, 12(10), 113. https://www.mdpi.com/2079-9276/12/10/113
19. Golik, V. I., Klyuev, R. V., Martyushev, N. V., Brigida, V., Efremenkov, E. A., Sorokova, S. N., &Mengxu, Q. (2023b). Tailings utilization and zinc extraction based on mechanochemical activation. *Materials*, 16(2), 726. https://www.mdpi.com/1996-1944/16/2/726
20. Golik, V. I., Klyuev, R. V., Martyushev, N. V., Kondratiev, V. V., Tynchenko, V. S., Gladkikh, V. A., &Brigida, V. (2023c). Reuse and mechanochemical processing of ore dressing tailings used for extracting Pb and Zn. *Materials*, 16(21), 7004. https://www.mdpi.com/1996-1944/16/21/7004
21. Gui, Y., Zhu, X., Fu, H., Jiang, X., Sun, J., Wang, L., & Chen, J. (2025). Preparation of silica powder from low-grade quartz by mechanical activation acid leaching and its mechanism. *Silicon*, 17(4), 835–849. https://doi.org/10.1007/s12633-025-03240-8
22. He, S., Wang, T., Liu, Z., Jiang, T., & Liu, Z. (2025). Mechanochemistry enhanced low-temperature molten salt synergistic treatment of low-grade pyrolusite and waste salts from the electrolytic manganese metal industry. *Chemical Engineering Journal*, 506, 159338. https://doi.org/10.1016/j.cej.2025.159338
23. Ippolito, N. M., Amato, A., Innocenzi, V., Ferella, F., Zueva, S., Beolchini, F., & Vegliò, F. (2022). Integrating life cycle assessment and life cycle costing of fluorescent spent lamps recycling by hydrometallurgical processes aimed at rare earth recovery. *Journal of Environmental Chemical Engineering*, 10(1), 107064. https://doi.org/10.1016/j.jece.2021.107064
24. Jiang, W., Xue, J., Jiang, K., Jiang, X., Wang, S., Hu, J., & Ma, H. (2023). Recovery of valuable metals from polymetallic refractory concentrate by a sulfuric acid curing and leaching method. *Separations*, 11(1), 7. https://www.mdpi.com/2297-8739/11/1/7
25. Kenzhaliyev, B., Ultarakova, A., Lokhova, N., Mukangaliyeva, A., &Kassymzhanov, K. (2025). Optimized hydrometallurgical extraction of molybdenum via mechanoactivation and nitric–sulfuric leaching. *Processes*, 13(5), 1486. https://www.mdpi.com/2227-9717/13/5/1486
26. Khezri, M., Rezai, B., Abdollahzadeh, A. A., Wilson, B. P., Molaeinasab, M., & Lundström, M. (2021). Investigation into the effect of mechanical activation on the leaching of chalcopyrite in a glycine medium. *Hydrometallurgy*, 203, 105492. https://doi.org/10.1016/j.hydromet.2020.105492
27. Kim, L., Dobra, G., Isopescu, R., Iliev, S., Cotet, L., Boiangiu, A., & Filipescu, L. (2022). Short review on mechanical activation in non-metallurgical alumina production. *Romanian Journal of Ecology & Environmental Chemistry*, 4(2), 62–79. https://doi.org/10.21698/rjeec.2022.206
28. Komnitsas, K., Bartzas, G., Karmali, V., &Petrakis, E. (2021). Factors affecting alkali activation of laterite acid leaching residues. *Environments*, 8(1), 4. https://www.mdpi.com/2076-3298/8/1/4
29. Lee, S., Sadri, F., &Ghahreman, A. (2022). Enhanced gold recovery from alkaline pressure oxidized refractory gold ore after mechanical activation followed by thiosulfate leaching. *Journal of Sustainable Metallurgy*, 8(1), 186–196. https://doi.org/10.1007/s40831-021-00476-7
30. Li, G., Li, W., Wu, J., Jiao, F., & Qin, W. (2025). Enhanced gold extraction from roasted refractory gold concentrate through mechanochemical activation: Eliminating secondary gold encapsulation. *Mining, Metallurgy & Exploration*, 42(3), 1823–1835. https://doi.org/10.1007/s42461-025-01196-2
31. Li, J., Wang, M., Zhang, R., Liu, H., Huang, S., Liu, Y., & Wang, J. (2025). Enhanced leaching of lepidolite by acidophilic microorganisms under mechanical activation. *Microorganisms*, 13(2), 415. https://www.mdpi.com/2076-2607/13/2/415
32. Li, X., Li, W., Gao, Y., & Tian, G. (2022). Effect of mechanical activation on the leaching process of rare earth metal yttrium in deep eutectic solvents. *Applied*

Sciences, 12(16), 8253. https://www.mdpi.com/2076-3417/12/16/8253

33. Li, W., Li, P., Song, B., Yue, P., Gao, Y., Cao, D., & Zhu, K. (2025). Mechanochemical-assisted carbothermal reduction for recycling spent lithium-ion batteries: A green and economical recycling strategy. *Green Chemistry*, 27(43), 13811–13823. https://doi.org/10.1039/D5GC03877D
34. Liao, R., Yu, S. C., Yang, B. J., Sun, X., Wang, C. X., Qiu, G. Z., & Wang, J. (2025). Promotion effect of mechanical activation on the role of pyrite in chalcopyrite bioleaching. *Journal of Central South University*, 32(9), 3574–3590. https://doi.org/10.1007/s11771-025-6071-7
35. Liu, C. L., Chen, Z. F., Zhu, Y., & Yu, J. G. (2024). Fundamental study of leaching kinetics and mechanism of spodumene assisted by mechanical activation. *Minerals Engineering*, 218, 108936. https://doi.org/10.1016/j.mineng.2024.108936
36. Liu, Y., Zhao, S., Wang, G., & Yang, H. (2025). Copper leaching from complex chalcopyrite-rich ores: Utilizing mechanical activation and wastewater-based sulfuric acid system. *Separation and Purification Technology*, 354, 128631. https://doi.org/10.1016/j.seppur.2024.128631
37. Liu, Z., Liu, G., Cheng, L., Gu, J., Yang, J., Yuan, H., & Wu, Y. (2024a). Ultra-fast mechanochemistry reaction process: An environmentally friendly instant recycling method for spent $LiFePO_4$ batteries. *Separation and Purification Technology*, 335, 126174. https://doi.org/10.1016/j.seppur.2023.126174
38. Liu, Z., Lv, Y., Wang, S., Liu, B., Wenzel, M., Zhang, Y., & Weigand, J. J. (2024b). A facile process for the efficient extraction of vanadium from vanadium slag via iron (III) oxide-assisted mechanochemical activation coupled with alkaline leaching. *Separation and Purification Technology*, 347, 127484. https://doi.org/10.1016/j.seppur.2024.127484
39. Moskovskikh, D. O., Vorotilo, S., Sedegov, A. S., Kuskov, K. V., Bardasova, K. V., Kiryukhantsev-Korneev, P. V., & Mukasyan, A. S. (2020). High-entropy (HfTaTiNbZr) C and (HfTaTiNbMo)C carbides fabricated through reactive high-energy ball milling and spark plasma sintering. *Ceramics International*, 46(11), 19008–19014. https://doi.org/10.1016/j.ceramint.2020.04.230
40. Mussapyrova, L., Nadirov, R., Baláž, P., Rajňák, M., Bureš, R., & Baláž, M. (2021). Selective room-temperature leaching of copper from mechanically activated copper smelter slag. *Journal of Materials Research and Technology*, 12, 2011–2025. https://doi.org/10.1016/j.jmrt.2021.03.090
41. Nadirov, R., & Mussapyrova, L. (2020). Effect of mechanical activation on leachability of fayalite in sulfuric acid solution. *Current Physical Chemistry*, 10(2), 82–87. https://doi.org/10.2174/1877946810666200128152729
42. Niu, H., Adrianto, L. R., Escobar, A. G., Zhukov, V., Perumal, P., Kauppi, J., &Illikainen, M. (2021). Potential of mechanochemically activated sulfidic mining waste rock for alkali activation. *Journal of Sustainable Metallurgy*, 7(4), 1575–1588. https://doi.org/10.1007/s40831-021-00466-9
43. Nyeko, S. J., Mlay, S. V., Amerit, B., Abima, B., Among, J., Nyero, A. I., & Ogen, C. (2023). The impact of electronic-electrical waste on human health and environment: A systematic literature review. *Journal of Engineering and Technology Research*, 15(1), 1–16. https://doi.org/10.5897/JETR2021.0726
44. Odebiyi, O. S., Du, H., Lasisi, K. H., Liu, B., Wang, S., Nwakanma, C. C., &Nnyia, M. O. (2021). Effect of ball mill parameters’ variation on the particles of a mechanical activation-assisted leaching: A hydrometallurgical mechanics. *Materials Circular Economy*, 3(1), 23. https://doi.org/10.1007/s42824-021-00030-6
45. Odebiyi, O. S., Du, H., Liu, B., & Wang, S. (2022). Sustainability of valuable metals recovery from hazardous industrial solid wastes: The role of mechanical activation. *Journal of Sustainable Metallurgy*, 8(4), 1393–1421. https://doi.org/10.1007/s40831-022-00579-9
46. Odebiyi, O. S., Liu, B., Du, H., & Wang, S. (2025). Alkaline leaching of vanadium-bearing steel slag: Mechanochemical leaching–kinetics modeling. *Separation and Purification Technology*, 376, 133916. https://doi.org/10.1016/j.seppur.2025.133916
47. Page, M. J., Moher, D., Bossuyt, P. M., Boutron, I., Hoffmann, T. C., Mulrow, C. D., … McKenzie, J. E. (2021). PRISMA 2020 explanation and elaboration: Updated guidance and exemplars for reporting systematic reviews. *BMJ*, 372, n160. https://doi.org/10.1136/bmj.n160
48. Pereira, A. C. (2025). Potassium recovery from feldspar: Activation routes, dissolution kinetics, agronomic performance, and techno-economic assessment. *Technology (IKRJET)*, 1(2), 102–122. https://doi.org/10.5281/zenodo.17542110
49. Qin, J., Ning, S., Zeng, J., He, Z., Hu, F., Li, Y., & Wei, Y. (2023). Leaching behavior and process optimization of tin recovery from waste liquid crystal display under mechanical activation. *Journal of Cleaner Production*, 399, 136640. https://doi.org/10.1016/j.jclepro.2023.136640
50. Saberi, Y., & Oveisi, H. (2022). Development of novel cellular copper–aluminum composite materials: The advantage of powder metallurgy and mechanical milling approach for lighter heat exchanger. *Materials Chemistry and Physics*, 279, 125742. https://doi.org/10.1016/j.matchemphys.2022.125742

51. Sathiyamoorthi, P., & Chawake, N. M. (2024). How does powder metallurgy facilitate the preparation of intermetallics and high-entropy alloys? ASM International. https://doi.org/10.31399/asm.tb.pmamfa.t59400191
52. Schramm Deschamps, I., dos Santos Avila, D., VanzuitaPiazera, E., Dudley Cruz, R. C., Aguilar, C., & Klein, A. N. (2022). Design of in situ metal matrix composites produced by powder metallurgy—A critical review. *Metals*, 12(12), 2073. https://www.mdpi.com/2075-4701/12/12/2073
53. Sim, Y., Ankit, Tay, Y. B., Ravikumar, D., & Mathews, N. (2025). Open challenges and opportunities in photovoltaic recycling. *Nature Reviews Electrical Engineering*, 2(2), 96–109. https://doi.org/10.1038/s44287-024-00124-8
54. Subasinghe, H. C. S., & Ratnayake, A. S. (2023). Mechanical activation and physicochemical factors controlling pyrometallurgical, hydrometallurgical, and electrometallurgical processing of titanium ore: A review. *Journal of the Southern African Institute of Mining and Metallurgy*, 123(8), 399–414. https://doi.org/10.17159/2411-9717/2082/2023
55. Su, F., Zhou, X., Liu, X., Ma, Y., Tang, J., Yang, W., & Yang, J. (2023). High-efficiency preferential extraction of lithium from spent lithium-ion battery cathode powder via synergistic treatment of mechanochemical activation and oxidation roasting. *ACS Sustainable Chemistry & Engineering*, 11(43), 15685–15698. https://doi.org/10.1021/acssuschemeng.3c04752
56. Svietkina, O., Bas, K., Haddad, J., Ziborov, K., &Olishevska, V. (2020). Mechanochemical activation of polymetallic ore and further selective flotation. *Key Engineering Materials*, 844, 65–76. https://doi.org/10.4028/www.scientific.net/KEM.844.65
57. TunçParlak, T., &Yildiz, K. (2025). Investigation of the effect of mechanical activation on nickel and cobalt extraction from laterite at atmospheric pressure by kinetics and leach residue analysis. *Canadian Metallurgical Quarterly*, 64(2), 680–697. https://doi.org/10.1080/00084433.2024.2366717
58. Wang, M., Liu, K., Yu, J., Zhang, C. C., Zhang, Z., & Tan, Q. (2022). Recycling spent lithium-ion batteries using a mechanochemical approach. *Circular Economy*, 1(2), 100012. https://doi.org/10.1016/j.cec.2022.100012
59. Wang, S., Yan, S., Chen, Z., Ou, Y., Mahara, B., Chen, X., & Zhou, T. (2025). Boosting the sustainable recycling of spent lithium-ion batteries through mechanochemistry. *Green Chemistry*, 27(33), 9917–9926. https://doi.org/10.1039/D5GC02354H
60. Wang, Y., Jia, X., & Liu, H. (2025). Effect of mechanical activation on acid leaching of molybdenum from low-grade refractory ore. *Mining, Metallurgy & Exploration*, 42(3), 1877–1888. https://doi.org/10.1007/s42461-025-01269-2
61. Xie, J., Huang, K., Nie, Z., Yuan, W., Wang, X., Song, Q., & Crittenden, J. C. (2021). An effective process for the recovery of valuable metals from cathode material of lithium-ion batteries by mechanochemical reduction. *Resources, Conservation and Recycling*, 168, 105261. https://doi.org/10.1016/j.resconrec.2020.105261
62. Yadav, T. P., Srivastava, R., &Awasthi, K. (2022). E-waste management through mechanical milling: A sustainable approach. In R. Srivastava (Ed.), *Strategies to achieve sustainable development goals (SDGs)* (pp. 1–26). https://doi.org/10.1007/978-981-19-XXXX-X
63. Yang, C., Zhang, J., Wang, C., Hou, X., Li, S., Li, C., & Li, H. (2025). Exploring the synergistic activation mechanism of mechanochemical processing in the enhancement of high-alumina coal fly ash utilization. *Waste Management*, 206, 115067. https://doi.org/10.1016/j.wasman.2025.115067
64. Yang, H., Zhao, S., Wang, G., Zhang, Q., Jin, Z., Tong, L., & Qiu, X. (2022). Mechanical activation modes of chalcopyrite concentrate and relationship between microstructure and leaching efficiency. *Hydrometallurgy*, 207, 105778. https://doi.org/10.1016/j.hydromet.2021.105778
65. Ye, Q., Yu, F., Ma, X., Wang, J., Cai, K., Wang, L., & Zou, J. P. (2025). An electrometallurgical and mechanochemical approach for the recovery of platinum group metals from spent automotive catalysts. *Hydrometallurgy*, Advance online publication, 106537. https://doi.org/10.1016/j.hydromet.2025.106537
66. Yuan, W., Wu, Z., Song, Q., Huang, Q., Zhang, C., & Crittenden, J. C. (2023). Lead recovery from waste CRT funnel glass by mechanochemical reaction with reductive Al powder. *Waste Management*, 172, 43–50. https://doi.org/10.1016/j.wasman.2023.09.008
67. Zhang, L., Guo, X. Y., Tian, Q. H., Li, D., Zhong, S. P., & Qin, H. (2022). Improved thiourea leaching of gold with additives from calcine by mechanical activation and its mechanism. *Minerals Engineering*, 178, 107403. https://doi.org/10.1016/j.mineng.2022.107403
68. Zhang, S., Zhang, C., Zhang, X., & Ma, E. (2023). A mechanochemical method for one-step leaching of metals from spent LIBs. *Waste Management*, 161, 245–253. https://doi.org/10.1016/j.wasman.2023.02.031
69. Zhou, H., Liu, G., Zhou, C., Arif, M., Sun, M., Chen, Y., & Liu, Y. (2023). Water-assisted mechanical activation of copper pyrometallurgical tailings for molybdenum leaching and selective removal of environmentally hazardous elements. *Separation and*

Purification Technology, 310, 123088. https://doi.org/10.1016/j.seppur.2022.123088

70. Zhu, S., Hu, J., Zhang, C., Li, S., & Chen, W. (2023). Process optimization and kinetics of titanium leaching from mechanically activated titanium-bearing blast furnace slag. *Journal of Sustainable Metallurgy*, 9(1), 230–239. https://doi.org/10.1007/s40831-022-00562-4