

RESEARCH PAPER

Intensification of non-ferrous metal leaching: a mini-review with emphasis on zinc recovery technologies

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ABSTRACT

This review examines technological and resource factors governing zinc production route selection. The mineralogical form of zinc is identified as the primary flowsheet design criterion: sulfide ores require oxidative pretreatment, whereas non-sulfide ores undergo acid leaching but risk silica gelation. Pyrometallurgical and hydrometallurgical pathways are compared regarding metal purity, energy intensity, and residue management. Modern intensification methods – microwave pretreatment, ultrasonic cavitation, and surfactant-assisted autoclave leaching – are evaluated as tools targeting distinct rate-limiting stages: matrix liberation, boundary-layer mass transfer, surface passivation. Cross-referencing with recent advances in copper bioleaching and gold microflotation confirms the universal nature of underlying physicochemical barriers.

Keywords: zinc hydrometallurgy; leaching; microwave pretreatment; ultrasonic cavitation; non-ferrous metal recovery; raw materials

INTRODUCTION

Zinc (Zn, Z = 30) is a d-block element with a density of 7.14 g/cm³ and a melting point of 419.5 °C. In terms of crustal abundance, it belongs to the widely distributed non-ferrous metals, with an average concentration estimated at approximately 65 g/t [1-6].

The dynamics of global refined zinc demand represent one of the key factors influencing market balance. All other conditions being equal, changes in demand are reflected in price levels through exchange indicators, as shown in Fig. 1.

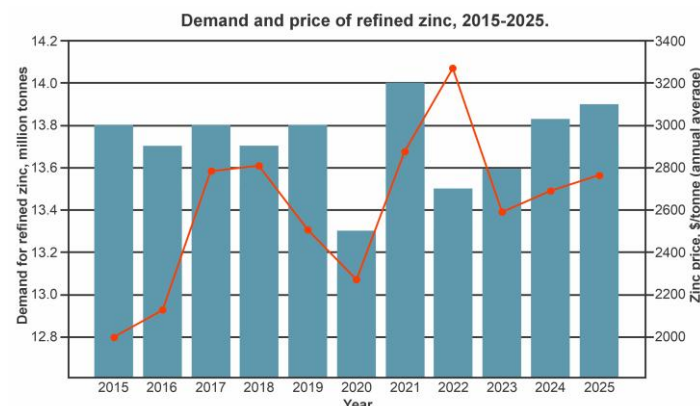


Fig 1. Global demand and price of refined zinc in 2015–2025 [7].

Refined zinc consumption in 2015–2025 generally remained within the range of approximately 13.5–14.0 Mt per year, with a noticeable decline in 2020 followed by recovery (Fig. 1). Such dynamics increase the requirements for technological efficiency: under relatively stable demand, the competitiveness of producers is determined by zinc recovery efficiency within the processing flowsheet, specific production costs, and consistent reproducibility of metal quality.

The main driver of demand is corrosion protection for steel and alloy production. At the same time, the distribution of end-use consumption is heterogeneous and strongly concentrated within a single application group.

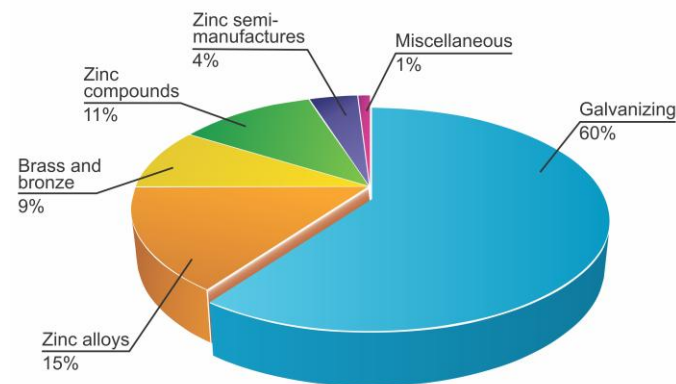


Fig 2. Industrial use of zinc: consumption structure, % [7], [8].

As shown in Fig. 2, galvanizing accounts for approximately 60% of final Zn consumption, followed by alloys (~15%), brass and bronze (~9%), chemical products (~11%), intermediate processing (~4%), and other applications (~1%) [8].

This consumption structure explains why zinc metallurgy must rely not on average product quality but on reproducible compositional control. Impurities such as Pb, Cd, Fe, Cu, and several associated elements deteriorate electrodeposition behavior, increase electricity consumption, and influence both the corrosion performance of coatings and the properties of alloys. Under laboratory conditions these deviations usually do not result in significant deterioration of technological characteristics.

The operational advantages of Zn in coatings arise from two mechanisms. First, a dense corrosion product film (oxide-hydroxide and carbonate phases) forms on the surface, reducing further interaction with moisture and oxygen [9,10].

Second, in the case of local coating damage, zinc provides additional electrochemical protection of steel by acting as a sacrificial anode in the Zn/Fe galvanic pair.

The technological properties of zinc are also important: at room temperature Zn is relatively brittle, however, in the temperature range of approximately 100–150 °C it becomes ductile, which facilitates forming operations and various processing steps for products and semi-finished materials [11–13].

It should be emphasized that the intensification strategies discussed below for zinc systems – namely microwave pretreatment, ultrasonic cavitation, and interfacial modification with surfactants – are by no means metal-specific. Analogous approaches to overcome kinetic, diffusion, and surface passivation barriers are being actively developed for processing copper-bearing, gold-bearing, and polymetallic raw materials, including technogenic feedstocks. In particular, recent investigations within the framework of integrated energy-efficient beneficiation, leaching, and smelting technologies for non-ferrous and precious metals have demonstrated that bio-oxidative pretreatment of sub-economic copper ores using chemolithotrophic bacteria *Acidithiobacillus ferrooxidans* in combination with aliphatic amino acids increases copper recovery by 8–10%, while the application of multi-component microflotation employing highly active emulsion microbubbles enhances gold extraction from both primary ores and processing tailings by 4.8–6.6% [14–20]. These findings corroborate the notion that the principal barriers to process intensification – matrix liberation, boundary-layer mass transfer, and passivating-film management – share a common physicochemical origin regardless of the target metal, and that a systematic analysis of these barriers, supported by digital tools for process modeling and regime optimization, constitutes a prerequisite for the rational selection of an appropriate intensification method.

The increase in demand (Fig. 1) combined with the dominance of galvanizing (Fig. 2) sets a clear technological objective for the industry: to develop extraction and refining processes capable of ensuring high Zn recovery, stable cathode metal quality, and minimal losses in intermediate products and residues at acceptable cost levels and controlled emissions. Within this framework it is reasonable to consider technological routes for processing zinc raw materials and secondary resources as well as the criteria for selecting them [14–16, 21–24].

MATERIAL AND METHODS

Mineralogical Forms of Zinc in Ore Systems

In natural ore deposits of industrial significance, zinc is predominantly concentrated in sphalerite (Zn,Fe)S, the principal zinc ore mineral in most genetic types of Pb–Zn deposits. The most typical association involves sphalerite with galena (PbS) and iron sulfides. In a considerable number of large Pb–Zn systems, silver occurs as a by-product and is already considered at the beneficiation stage and during the selection of metallurgical processing routes for concentrates [25].

The predominance of sulfide mineralization determines the basic technological logic of zinc metallurgy. Prior to hydrometallurgical extraction, sulfidic sulfur must be oxidized to form a ZnO-containing product or solution, since direct dissolution of ZnS in aqueous systems is kinetically and selectively limited. This factor makes the control of impurities and the distribution of associated elements between process streams particularly critical, especially for polymetallic Pb–Zn concentrates [26].

In the supergene zone, primary Zn sulfides transform into non-sulfide minerals such as carbonates and hydroxycarbonates (smithsonite ZnCO_3 , hydrozincite $\text{Zn}_5(\text{CO}_3)_2(\text{OH})_6$, hydrosilicates (hemimorphite $\text{Zn}_4\text{Si}_2\text{O}_7(\text{OH})_2 \cdot \text{H}_2\text{O}$), and more rarely oxide phases (zincite (Zn,Mn)O). These minerals form non-sulfide Zn ores typically processed by acid leaching. However, when silicate varieties (especially hemimorphite) are treated, colloidal silica formation and gelation may occur, thereby impairing filtration and complicating deep-solution purification [27–28]. The predominance of sulfide and non-sulfide forms of Zn in ores determines fundamentally different technological routes for its extraction. Correct selection of the processing scheme requires linking the mineralogical form of zinc with the mineral class and the typical liberation mechanism (oxidative roasting, acid leaching, silica-related limitations, etc.). The main zinc minerals and their technologically significant characteristics are summarized in Table 1.

Table 1. Types of zinc minerals and the technological implications of their processing [29–33].

Formula	Typical genetic setting	Technologically significant implications (metallurgy)
Sphalerite (Zn,Fe)S	Primary mineralization.	ZnS requires oxidative pretreatment (roasting) to convert Zn into a leachable oxide form, while associated Fe sulfides complicate calcine composition and downstream solution purification.
Smithsonite ZnCO_3	Secondary mineral of the oxidation zone of Zn deposits.	High acid solubility ensures efficient Zn leaching, though carbonate decomposition elevates acid consumption, generates CO_2 , and necessitates strict pH and impurity control.
Hydrozincite $\text{Zn}_5(\text{CO}_3)_2(\text{OH})_6$	Secondary mineral of oxidized zones, often associated with smithsonite.	Rapid acid dissolution accelerates leaching kinetics, but CO_3/OH groups increase acid demand and CO_2 evolution, with potential filtration deterioration due to slime formation.
Hemimorphite $\text{Zn}_4\text{Si}_2\text{O}_7(\text{OH})_2 \cdot \text{H}_2\text{O}$	Secondary mineral of oxidized zones	Zn^{2+} readily transfers to solution under acid leaching, however, dissolved SiO_2 forms colloids and gels that critically impair filtration and promote impurity adsorption.
Willemite Zn_2SiO_4	Less common: secondary origin in Zn ores of carbonate sequences, locally an ore mineral	acid leaching is feasible, but Si-bearing phases generate gels and colloids that compromise filtration, purification, and overall process sensitivity to impurity composition.
Zincite (Zn,Mn)O	Rare as a natural ore mineral, specific oxide–silicate deposits	ZnO represents the most kinetically favorable form for acid leaching, though it rarely occurs naturally and is typically produced via sphalerite roasting.
Franklinite ZnFe_2O_4	Certain metamorphosed oxide–silicate Zn deposits	The refractory spinel structure demands aggressive leaching conditions, an inadequately designed flowsheet results in elevated Zn losses to solid residues.

Major zinc deposits and reserves worldwide

The global zinc resource base is characterized by a substantial gap between resources (a geologically identified base) and reserves (the economically recoverable portion). According to USGS (United States Geological Survey), identified Zn resources worldwide are approximately 1.9 billion t, whereas total global reserves are estimated at ~230 million t [34].

Zinc production and reserves are geographically concentrated: China holds leading positions in production, while Australia leads in reserves, significant contributions to production and/or reserves are also made by Peru, the United States, Mexico, Russia, Kazakhstan, and India. Comparable data on mine production (2023–2024) and the latest available reserve estimates are presented in Table 2.

Table 2. World mine production of Zn and reserves by country.

Country	Production (2023), Mt	Production (2024 estimate), Mt	Reserves (latest USGS estimate), Mt
China	4.06	4.00	46.00
Australia	1.09	1.10	164.00
Peru	1.47	1.30	20.00
United States	0.77	0.75	9.20
Mexico	0.58	0.70	14.00
Russia	0.30	0.31	29.00
India	0.85	0.86	9.80
Kazakhstan	0.34	0.37	7.60

Sweden	0.22	0.24	3.90
South Africa	0.20	0.12	5.90
Bolivia	0.49	0.51	n/a
Other countries	1.69	1.70	25.00
World total	12.10	12.00	230.00

Interpreting **Table 2** requires distinguishing between production and reserves. Production reflects current asset utilization, ore/concentrate availability, infrastructure, and the economics of processing, whereas reserves reflect long-term supply security and are sensitive to cut-off grades, prices, and exploration rates. Therefore, leadership in production and reserves need not coincide: a

country may maintain high production with moderate reserves (due to high asset engagement) or hold a large reserve base with relatively low production (due to capacity-buildout constraints, logistics, or project economics).

The distribution of production and reserves describes the upstream raw-material contour, however, the actual market configuration is also shaped by trade in refined zinc. A mismatch between resource endowments and trade roles arises from uneven distributions of metallurgical capacities, differences in domestic demand structures, and the export orientation of specific producers. This “superstructure” over the resource base is clearly reflected in the geography of the largest exporters and importers of refined Zn (**Fig. 3**).

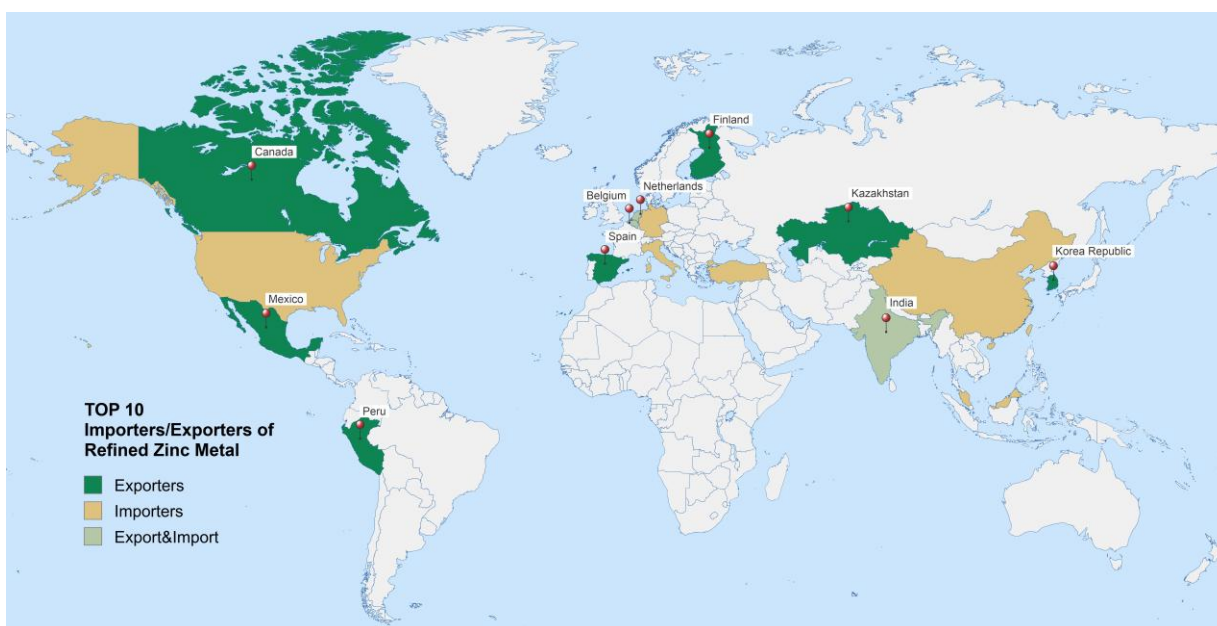


Fig 3. Top-10 exporting and importing countries of refined zinc (metal): exporters are highlighted in green, importers in yellow, and countries with a mixed role (export + import) in light green. [7]

Fig. 3 indicates that trade roles do not automatically coincide with resource endowment: having mine production and reserves does not guarantee exports of refined Zn when refining capacity is limited or domestic consumption is high, conversely, exports are possible even with a moderate raw-material base when downstream processing is developed and a metal surplus is available.

Zinc production routes

Two principal routes for producing market-grade zinc from sulfide concentrate are established in industrial zinc metallurgy: the pyrometallurgical (distillation) route and the hydrometallurgical (electrolytic) route. Both options typically rely on oxidative conversion of the concentrate (roasting) to convert ZnS into an oxide form and generate an SO₂ gas stream [17, 35-39]. Dust-gas emissions from roasting require dust collection, SO₂ should preferably be routed to sulfuric acid production, which is then used in the leaching circuit.

This integration closes the H₂SO₄ reagent loop and simultaneously reduces the load on off-gas treatment [18, 40-42]. The key technological advantages and limitations of roasting as a common upstream step are summarized in **Table 3**.

Table 3 shows that roasting should not be treated as a formal sulfur-removal operation. It determines the mineralogy and reactivity of the calcine. A regime error manifests not merely as a higher S content in the calcine, but as an increased fraction of phases that dissolve poorly and ultimately report to filter cake/residues, thereby increasing overall Zn losses and acid consumption.

Table 3 Advantages and disadvantages of zinc concentrate roasting

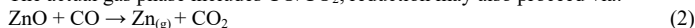
Parameter / aspect	Advantages	Disadvantages / technological risks
Chemical objective of the stage	Conversion of Zn from ZnS to ZnO (and/or to a readily extractable form) suitable for subsequent leaching/extraction	If the operating regime deviates, the fraction of poorly soluble phases (including ferrites) increases, which raises Zn losses in downstream steps
Gas circuit	SO ₂ formation enables integration of roasting with H ₂ SO ₄ production and closure of the reagent loop	Effective gas cleaning and dust collection are required, gas dilution reduces SO ₂ utilization efficiency
Energy	At high sulfur content, the process can be close to autothermal	For low-sulfur/diluted feed, external heat demand increases, risk of local overheating may occur
Solid-phase effects	Production of a reactive calcine facilitates subsequent dissolution of ZnO	Sintering/agglomeration of calcine worsens leaching kinetics and complicates filtration
Metal losses	Under a correct regime, the main metal remains in the solid phase and is routed to further processing	Dust carryover transfers Zn and impurities into the gas-dust stream, the role of recycling streams and dust processing increases
Impurities	Partial redistribution of impurities among streams (calcine/dust/gas) simplifies their subsequent management	Pb, Cd, etc. create a complex by-product circuit and increase requirements for purification and waste handling

Pyrometallurgical (distillation) route

The distillation route is based on carbothermic reduction of zinc oxide to form Zn vapors and their subsequent condensation. In industrial practice, a charge prepared from roasted zinc concentrate (zinc calcine) and a reductant (coke or fine coal) is fed into a refractory retort, where the process is carried out at temperatures ensuring stable reduction and zinc volatilization. The key process reaction is:



The actual gas phase includes CO/CO₂, reduction may also proceed via:



Followed by CO regeneration through carbon gasification reactions. Zinc vapors are directed to the condensation section. Part of the metal condenses as liquid Zn, while another portion leaves with the gas and is captured as fine dust.

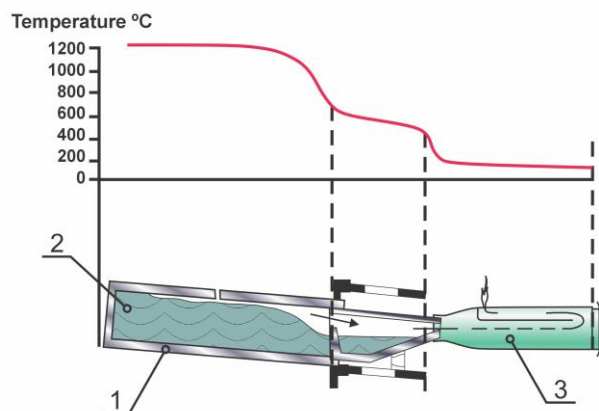


Fig. 4. Schematic of a retort unit for zinc distillation: 1 – retort, 2 – condenser, 3 – alonge [15].

Fig. 4 illustrates a fundamentally important feature of retort distillation: the temperature gradient along the “retort-condenser-along” path determines the completeness of Zn condensation. If the condensation zone is insufficiently effective, part of the Zn is carried further and accumulates in the alonge as dust (poussière). This stream is not a waste, as a rule, it is enriched in volatile components (including Cd-containing compounds) and therefore requires a dedicated processing line.

Associated oxides in the charge must also be considered. In the presence of PbO and CdO, their reduction and partial co-distillation are possible, therefore, distillation (crude) zinc contains Pb and Cd impurities and is typically sent for refining (including rectification operations). The solid residue after distillation – distillation residue – retains metal-bearing phases and, under a properly designed balance, is returned to the circuit for additional Zn recovery.

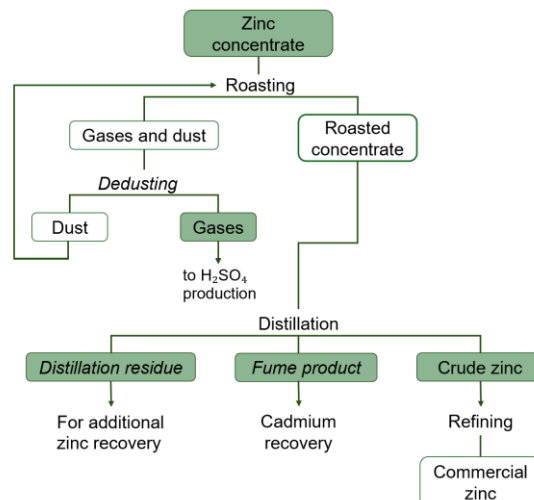


Fig. 5. General flowsheet of pyrometallurgical (distillation) zinc production: roasting – dust collection/SO₂ utilization – distillation – refining, by-products: fume product, distillation residue [15].

The scheme in **Fig. 5** shows that the distillation method is technologically centered on the distillation stage and subsequent refining: these steps define the principal constraints on metal quality and capture of volatile impurities. In parallel, the dust–gas circuit of roasting is taken as a separate block, correct integration with sulfuric acid production increases process robustness and reduces specific emissions. Classic horizontal retorts operate cyclically and relinquish in productivity to continuous units, historically, method development proceeded through vertical/continuous retorts and electric furnaces, as well as through improvements in refining.

Hydrometallurgical (electrolytic) route

The electrolytic route is based on transferring Zn into solution as sulfate followed by electrowinning. After roasting, the calcine undergoes sulfuric acid leaching to produce a zinc sulfate solution, which – after solid–liquid separation and deep purification – is used for electrowinning. Deep solution purification is critical: impurities of transition metals and elements that catalyze corrosion degrade current efficiency, cathode quality, and electrolysis stability. The purified solution is sent to electrolysis, Zn is deposited on the cathode, oxygen is evolved at the anode, and the H₂SO₄ concentration in the electrolyte increases, enabling acid recycle to the leaching section [19–20].

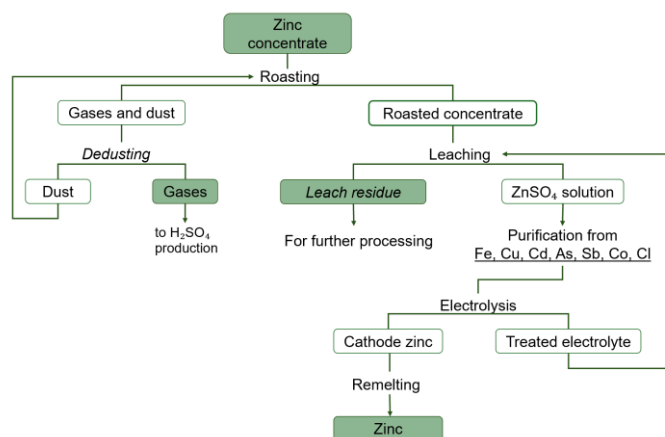


Fig. 6. Flowsheet of hydrometallurgical (electrolytic) zinc production: roasting – leaching – solid/liquid separation – solution purification – electrolysis – melting of cathode Zn, closure of acid and electrolyte loops [15].

Fig. 6 emphasizes that, in the electrolytic scheme, commercial zinc quality is determined not by electrolysis in general, but specifically by the depth of solution purification and the electrolyte circulation regime. Bottlenecks form at three transitions: calcine composition determines the solubility of Zn phases during leaching; phase-separation efficiency controls Zn losses in the filter cake; and the degree of impurity removal (Fe, Cu, Cd, Co/Ni, As/Sb, Cl⁻, etc.) governs

electrochemical stability and cathode-metal purity. High purity is achieved at an energy cost: electrowinning requires substantial electricity consumption, therefore, the route's economic attractiveness is sensitive to electricity price and the availability of a sulfuric-acid loop.

A structured comparison of the advantages and limitations of the hydrometallurgical route is given in **Table 4**.

Table 4 Advantages and disadvantages of hydrometallurgical (electrolytic) zinc production.

Aspect	Advantages	Disadvantages / technological risks
Metal quality	Production of high-purity cathode Zn, high compositional reproducibility	High sensitivity to trace impurities in the electrolyte, defects in cathode form when purification/regime is violated
Zn recovery	High overall Zn recovery with a properly built chain "roasting → leaching → purification → EW"	Zn losses increase in the presence of poorly soluble phases (including ferrites) and under unstable filtration (Zn reporting to cake/precipitates)
Environment and loops	Possibility of closing the H ₂ SO ₄ loop, controllable gaseous emissions	Solid residues (cake, iron-rich precipitates) are formed and require regulated handling, risks related to soluble salts
Energy	No high-temperature distillation at the metal production stage	Significant electricity consumption for electrolysis, economic sensitivity to electricity tariffs
Reagent base	Sulfuric acid is technologically compatible with industrial streams, possible integration with sulfuric acid production	Reagent consumption for solution purification (precipitation/cementation/neutralization), increase in salt balance
Equipment requirements	Good scalability in quality and output with stable feed	Higher requirements for construction materials (corrosion resistance), circulation regime, and temperature control

Table 4 consolidates the main conclusion: the electrolytic scheme "buys" metal quality and process controllability at the expense of stricter requirements for solution chemistry and energy. If solution purification is maintained at the required level, electrolysis is stable and produces metal of the specified purity. If critical impurities slip into the solution or poorly soluble phases enter leaching, the problem manifests quickly as a decrease in current efficiency, deterioration of cathode morphology, and increased Zn losses to solid residues.

The distillation route is rational when thermal energy is available and subsequent metal refining is acceptable, including processing of volatile by-product streams (fume product) and recycling of distillation residue. The electrolytic route is chosen when high Zn purity is prioritized, impurities are strictly controlled, and stable power supply can be ensured, it scales better in terms of quality but imposes stricter requirements on solution purification and management of leaching residues.

Modern zinc hydrometallurgy increasingly targets difficult-to-process and technogenic feedstocks (clinkers, dust, sludges), where the rate-controlling stages become mineral-matrix breakdown, mass transfer within a porous structure, and suppression of passivating films. Within this framework, methods of energy- and mass-transfer intensification are actively developing microwave (MW) treatment, ultrasonic cavitation, and the use of surfactants (surface-active agents, SAAs) under autoclave conditions [43].

MW treatment (microwave intensification)

MW energy input is used as a pretreatment prior to acid leaching: dielectric heating generates temperature gradients at "ore mineral-gangue" boundaries, leading to microcracking and facilitating reagent access to Zn-bearing phases [44–46]. In industrially oriented flowsheets, high-power continuous/semi-continuous units are used (an example configuration is shown in Fig. 7).

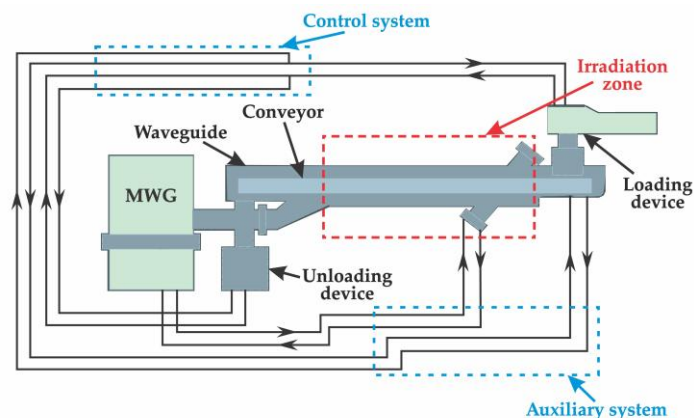


Fig 7. Schematic of the microwave system "ENERGY K-50" [44].

The breakdown mechanism at the single-particle level is illustrated by the distribution of thermal stresses in sphalerite and microcrack initiation under MW exposure (Fig. 8).

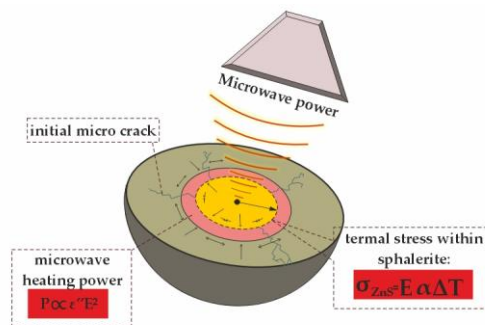


Fig 8. MW exposure of sphalerite and the distribution of thermal stresses [45].

Ultrasound (cavitation treatment)

Ultrasonic treatment increases the leaching rate primarily through cavitation: rarefaction/compression cycles initiate bubble formation and collapse, generating shock waves and microjets [46–47]. This reduces diffusion resistance (the diffusion layer becomes thinner), disperses agglomerates, intensifies micromixing, and destroying passivating films on particle surfaces (Fig. 9).

Cavitation is also associated with local extremes of thermo-baric conditions (on the order of thousands of K and hundreds to thousands of atm), which enhances the disruption of surface barriers and renewal of reactive surface area [48–49].

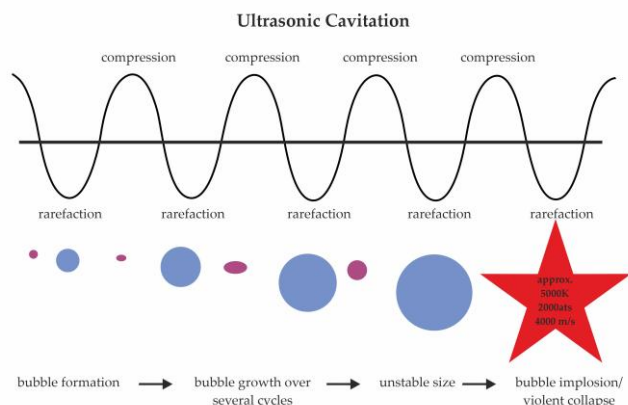


Fig 9. Ultrasonic cavitation [50].

Table 5 Tools for intensifying Zn leaching: MW pretreatment, ultrasound, and surfactant-assisted autoclave leaching.

Tool	Target (what it affects)	Main mechanism	Typical process effect	Key limitations/risks
Microwave (MW) treatment	Mineralogical matrix, phase boundaries	Selective heating → thermoelastic stresses → microcrack development	Increased reactive surface area, faster leaching, improved feed readiness for leaching	Heating non-uniformity, high requirements for equipment and operating modes
Ultrasound	“Solid–liquid” boundary layer, passivating films	Cavitation: bubble growth/collapse, local extreme T/P, microjets	Enhanced mass transfer, destruction of passivation, reduced process time	Energy intensity, effect depends on frequency/power and pulp properties
Surfactants + autoclave	Interfacial phenomena and particle wetting	Reduced surface tension, improved wetting, stabilized hydrodynamics	Improved kinetics in sulfuric-acid leaching, enhanced process stability	Need to select surfactant type and dosage, foaming, strict autoclave operating regulations

As follows from Table 5, the intensification mechanisms fundamentally differ by their point of action: MW affects the structure and reactivity of the solid phase before acid contact (and therefore often provides the most pronounced recovery gain for refractory matrices), ultrasound functions as a kinetic accelerator through mass-transfer enhancement and destruction surface barriers, surfactant-assisted autoclave operation is appropriate where interfacial interaction must be technologically stabilized under elevated T-P. Tool selection should be justified by feed type (sulfide/oxide/technogenic), the dominant rate-limiting link (matrix breakdown, diffusion, passivating layers), and site energy constraints.

CONCLUSION

Zinc remains a key metal for anticorrosion protection of steel and alloy production, under relatively stable global consumption dynamics, the market remains highly sensitive to the quality of the raw-material base and the efficiency of processing routes. The dominance of galvanizing in the end-use structure increases requirements for reproducible metal quality, impurity control, and reduction of Zn losses across process streams, because even minor compositional deviations and regime instability affect coating performance and production economics.

The evolution of the resource base has driven a shift in technological priorities: when processing rich ores and high-grade concentrates, pyrometallurgical routes were rational; however, as rich reserves were depleted and low-grade/polymetallic objects were brought into production, the industry broadly transitioned to hydrometallurgy (leaching – purification – electrowinning), which enables high-purity zinc production under strict control of solution chemistry and energy. In recent decades, an increasing share of Zn sources has been formed by technogenic products and wastes with complex matrices, where conventional leaching is limited by kinetics, passivation, and filtration/purification problems, therefore, intensification methods (MW pretreatment, ultrasonic cavitation,

From an engineering perspective, ultrasound is best viewed as a kinetic-acceleration module with limited contact time, in which the rate-controlling link is external/internal mass transfer and the presence of surface layers.

Surfactants + autoclave

The use of surfactants and their mixtures in autoclave sulfuric acid leaching is applied as a practical tool for controlling interfacial contact: they improve wetting and dispersion of the solid phase, stabilize the solid–liquid interface, and reduce the impact of surface films that hinder mass transfer at elevated T-P [49]. Selection of surfactants/mixtures and verification of their influence on autoclave leaching performance for Zn concentrate are carried out at the laboratory scale, tailored to the specific feed and operating regime. A comparative view of MW pretreatment, ultrasound, and surfactant-assisted autoclave leaching is given in Table 5.

surfactant-assisted autoclave regimes) are being developed and implemented to promote matrix breakdown and accelerate mass transfer.

Given the non-renewability of primary zinc resources, the search for technological alternatives that expand the resource base through secondary feedstocks and ensure robust extraction while controlling environmental risks is a necessary direction for the development of zinc metallurgy.

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