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Ultrasonic Multi-Electrode Electrophysical Ionization for High-Purity Extraction of Precious, Base, and Rare-Earth Metals from Kyrgyzstan’s Technogenic Tailings

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ABSTRACT

An original, multicomponent technology is proposed for extracting precious, base, and rare-earth elements from Kyrgyzstan’s technogenic wastes. The core of the process is electro-physical ionisation (EPI) enhanced by cavitation-assisted ultrasound and implemented in a spatially distributed multi-electrode configuration. The study pursued a dual objective: (i) to formulate the physico-chemical rationale that ensures maximal selectivity and high energy efficiency, and (ii) to model operating regimes that minimise the generation of secondary pollutants. Feedstocks included concentrator tailings, metallurgical slags, and sludges accumulated in the country’s key mining provinces. A response-surface experimental design enabled fine-tuning of the critical parameters: potential 6–12 V, inter-electrode gap 1,0–1,5 cm, electrolyte molarity 0,5–1 M, acoustic power < 300 W, and treatment duration 30–65 min. The result was record extraction efficiencies: Cu — 96,8 %, Zn — 93,5 %, Ag — 92,1 %, Au — 88,5 %. For the rare-earth representatives, La and Nd, the respective values reached 79,7 % and 81,1 %. The purity of the recovered precipitates, verified by combined ICP-OES / SEM-EDX analysis, exceeded 99,8 ‰ (Cu) and 99,5 ‰ (Au, Ag). The synergy of ultrasonic cavitation and the multi-electrode field lowers the energetic barrier of electrochemical reactions, disaggregates the solid phase, accelerates mass transfer, and ensures uniform current distribution, thus preventing anode passivation. Comparison with conventional hydro- and pyrometallurgical routes revealed an order-of-magnitude reduction in energy consumption and complete elimination of hazardous reagents. The developed approach not only paves the way for comprehensive recycling of accumulated wastes—mitigating environmental risks—but also establishes an alternative mineral resource base for critical metals, capable of providing an additional impetus to the economy of the Kyrgyz Republic.

Keywords: Electro-Physical Ionisation; Ultrasonic Activation; Industrial Wastes; Metal Extraction; Rare-Earth Elements; Process Optimisation; Environmental Safety.

INTRODUCTION

Over the past quarter-century the global eco-technological race has triggered an unparalleled surge in metal consumption. The industrialisation of emerging economies, worldwide digitalisation, and an ambitious drive for a *green* transition have become tightly interwoven drivers of demand, causing the ore grades of valuable elements to decline inexorably and natural deposits to grow progressively poorer. A world that is expanding on metals slips into a paradox: the more it mines, the more waste it produces, and the more acutely it experiences shortages of primary feedstock. Mining and metallurgical industries—already generating billions of tonnes of by-products each year—now rank among the three largest sources of industrial waste. Metallurgy's contribution to the planetary carbon footprint is substantial: roughly 40 % of all industrial greenhouse-gas emissions and nearly one-tenth of global electricity consumption originate in this cycle. Annual extraction is approaching 3,2 billion t of minerals, yet the resulting tailings and sludges outweigh the mass of finished metals by a factor of 15–20; forecasts indicate these volumes will double by 2050—an alarming prospect for climate, biodiversity, and human health.[1,2,3]

Against this backdrop, the concept of a circular economy no longer appears academic but rather emerges as a strategic imperative. The closed-loop paradigm—resource → product → waste → new resource—shifts the focus from extensive exploitation of virgin ores to intensive treatment of technogenic stocks. Recovering metals from industrial residues thus delivers two synergistic benefits: mitigating environmental damage while creating new economic niches. One striking example suffices: aluminium recycling cuts energy demand by about 95 % compared with primary smelting of bauxite. Yet even such impressive savings fail to close the gap between global appetite and available scrap flows: today secondary raw materials cover no more than one-third of demand. Consequently, some portion of metals must still originate from mines, making full mobilisation of technogenic sources—tailings ponds and sludge dumps included—no longer an optional green measure but a cornerstone of resource security.[4]

Critical metals—most notably rare-earth elements (REEs), whose importance for electronics, electric vehicles, and modern power systems rivals that of oil during the industrial age—occupy a special place in this equation. Their recycling rate is dismally low (below 1 %), whereas base non-ferrous metals achieve 30–70 %. Production of primary REEs also records the highest specific CO_2 emissions per kilogram of output. Because more than 60 % of REE mining and 90 % of processing are concentrated in China, any trade restrictions instantly propagate into a global shock. This reality sets a dual task: to develop efficient, environmentally benign techniques for re-extracting REEs from technogenic streams and, by doing so, to reduce geopolitical risks and strengthen supply-chain resilience.[5]

The Kyrgyz Republic offers a particularly vivid example of the challenge. Endowed with abundant mineral resources, the country simultaneously bears the legacy of decades of extraction: about 100 million t of industrial and domestic waste have already accumulated within its confined territory. Mining accounts for the lion's share, represented by 35 tailings repositories and 25 waste-rock dumps scattered nationwide. The annual growth of toxic technogenic masses further intensifies pressure on ecosystems, propelling the search for technological solutions capable of turning this potential ecological debt into a strategic reserve of valuable and rare metals.

Between the global imperative of sustainability and region-specific challenges, a clear chain of necessity has emerged: the more lucidly the world recognises the limits of traditional mining, the more actively it turns to the resources lying literally underfoot—in tailings, slurries, slags and fly ash. An efficient, environmentally sound technology for extracting metals from these streams thus becomes not merely a technological innovation but a pivotal link in the architecture of future metallurgy, where "waste" ceases to mark the end of a value chain and instead becomes a new point of departure.

Kyrgyzstan's largest industrial deposits—Kumtor, Taldy-Bulak Levoberezhny, and Terek-Sai—have in recent decades produced a veritable "glacier" of technogenic waste that inexorably encroaches upon the nation's economy and environment. At Kumtor alone, 17 305 kg of gold were mined in 2022, drawing on a resource base that, as of December 2020, comprised 73,3 million tonnes of ore averaging 2,66 g Au t^{-1}. Every tonne of such ore, after passing through the processing plant, leaves behind tailings still hosting significant residual metal content. Terek-Sai is following suit: construction of its own concentrator and a new tailings storage facility commenced in 2020—another harbinger of escalating waste accumulation. The 2022 ban on the export of ferrous-metal scrap, tailings and gold-bearing concentrates eloquently signals that the Republic intends to keep these resources at home, maximising added value and abandoning the familiar raw-materials export model.(6)

The technological footprint of mining, however, is far from benign. A substantial fraction of tailings-storage facilities (TSFs) have long outlived their design life or fallen short of current sanitary standards, turning into powder kegs. History has already issued invoices for negligence. In 1998 a road tanker at Kumtor plunged into the Barskaun River, spilling over a tonne of cyanide; more than 2500 people suffered acute poisoning. An even more tragic episode unfolded in 1958: an earthquake and torrential rains ruptured Tailings Dam No. 7 of the Mailuu-Suu combine, releasing 600 000 m^3 of radioactive slurry that coursed forty kilometres downstream, killing livestock and irradiating the local population. Decades later, uranium levels in Mailuu-Suu waters remain 10–15 times above background. Add the region's high seismo-tectonic activity, unconsolidated slopes, and avalanche-debris flows, and one obtains a textbook case of cascading risks. Even the Issyk-Kul basin—promoted to tourists for its "therapeutic" waters—registers elevated anthropogenic Cr and As concentrations in its rivers, planting a delayed-action mine beneath public health.(7)

Against this backdrop, the strategic logic of processing technogenic stocks becomes non-negotiable. Open-pit operations at Kumtor officially cease in 2023, and the full processing cycle will conclude by 2031; primary ore throughput will therefore dwindle. Concurrently, the state has amplified its commitment to developing a rare-earth mineral base, as REEs are indispensable for green and high technologies. Consequently, the volume of waste potentially containing Y, Nd or La will only grow—so bringing these "secondary deposits" into circulation transforms an environmental liability into an economic opportunity. In other words, a properly orchestrated "mining renaissance" could not merely prolong the life of Kyrgyzstan's extractive sector but also convert the industrial era's legacy into a springboard for the nation's future economy.

Recovering valuable and critical metals from industrial wastes—particularly from dilute solutions containing only single- to double-digit ppm levels of target elements and from heterogeneous matrices rich in interfering species—remains a formidable technological challenge. Traditional hydrometallurgical approaches (ion exchange, solvent extraction) perform reliably at high metal concentrations; however, their efficiency drops sharply in "lean" systems, leading to higher specific energy consumption, reduced selectivity, and ultimately uneconomical product costs. Elevated concentrations of Fe^{3+} and Al^{3+} further complicate treatment by masking analytical signals or forming stable complexes that block sorbent active sites.

Ionic liquids, often promoted as next-generation "green" solvents, were expected to mitigate these issues. Yet they frequently suffer thermal and electrochemical degradation and, due to their strong solvation power, migrate into secondary aqueous phases, thus complicating downstream purification. Consequently, fundamentally different solutions—combining precise process control, moderate energy demands, and minimal environmental impact—are urgently needed.

Electrochemical technologies, as a logical extension of ion-based separations, theoretically meet these criteria: charge transfer is governed by electrode potential, reagent consumption is negligible, and side products are minimal. In practice, however, challenges arise. Wastewater compositions are seldom fully characterized, hampering precise potential-programming. Organic ligands abundant in process streams form strong chelates with Cu^{2+}, Ni^{2+}, Co^{2+}, and REE^{3+}, slowing electrodeposition and requiring high current densities. Mass-transfer limitations, electrode corrosion, and the difficulty of scaling up to industrial volumes further exacerbate the problem.

To overcome these barriers, we propose electro-physical ionization (EPI) in a multi-electrode configuration, synergistically enhanced by ultrasonic cavitation. Cavitation micro-jets and shock waves disaggregate solid phases, remove diffusion barriers, and continuously renew boundary layers, thereby intensifying mass transfer and boosting metal recovery.[3,4]

Research Objective

To develop a scientifically sound, technologically adaptable methodology for extracting Au, Ag, Cu, Ni, Zn, Mg, Ca, and rare-earth elements La and Nd from technogenic wastes in key mining regions of Kyrgyzstan using EPI supplemented by ultrasonic activation.

Specific Tasks

1. Raw-material inventory: conduct a detailed geochemical audit of tailings, sludges, and slags; map spatial distribution and estimate reserves of these elements across the country's geo-industrial provinces.
2. Engineering design: build a laboratory-scale EPI setup with an optically transparent reactor, integrated ultrasonic module, and adjustable electrode spacing; develop a mathematical model for coupled charge and mass transfer in the solid–liquid–electrode system.
3. Parametric optimization: apply design-of-experiments methods (Taguchi, response-surface methodology) to identify optimal voltage, electrode spacing, electrolyte concentration, ultrasound frequency/power, and exposure time that maximize yield while minimizing specific energy consumption.
4. Experimental validation: monitor kinetics and yields via ICP-OES; analyze precipitate morphology and phase composition by SEM/EDX; benchmark energy use and selectivity against conventional flowsheets.
5. Techno-economic comparison: compare EPI with pyrometallurgical and classical hydrometallurgical routes in terms of CAPEX/OPEX, carbon footprint, and resource sustainability.
6. Scaling-up: evaluate the transition from laboratory cell to pilot module: select corrosion-resistant electrode materials, integrate renewable energy sources, and design a closed-loop water-reagent circuit.

This comprehensive science-to-industry roadmap aims to transform problematic waste streams into sustainable sources of strategic metals, thereby strengthening the circular economy in the Kyrgyz Republic.

METHOD

Objects of resource extraction: the present study targets three representative—yet markedly heterogeneous—classes of industrial waste that have accumulated from mining and processing activities across the Kyrgyz Republic. Each class merits its own monograph, but they are outlined briefly below.

1. Ore tailings: these fine-grained "tails," produced during the beneficiation of gold-bearing, polymetallic, or porphyry-copper ores, may at first resemble an innocuous mixture of sand, silt, and clay. Under microscopic examination, however, they reveal a multiphase system in which residual precious and transition metals coexist with flotation reagents, sulfide compounds, and other chemical "ghosts" of the technological cycle. Tailings facilities thus pose a dual threat: they constitute a potential "treasure trove" of under-extracted metals and, simultaneously, a source of heavy elements prone to bioaccumulation and long-term migration within ecosystems.
2. Industrial sludges: this category spans everything from coal-washing sediments to galvanic and wastewater sludges enriched in copper, nickel, zinc, chromium, and their numerous oxide-carbonate modifications. Galvanic waste is particularly illustrative: its high concentration of readily leachable metals turns such sludge into a "chemical time bomb" capable of contaminating groundwater upon even minor breaches of containment. The fractional composition (carbonate, residual, Fe-Mn oxide fractions) dictates complex leaching kinetics and therefore demands finely tuned extraction technologies.
3. Metallurgical slags: by-products of high-temperature processing—e.g., steelmaking slags—have long ceased to be mere "stones underfoot" for metallurgists. Slags bear a distinct signature of their parent feedstock: stainless-steel slags concentrate hexavalent chromium, while ferroalloy slags harbor manganese and vanadium. Value, however, is inseparable from toxicity, complicating the reintegration of slags into economic circulation and rendering them both an environmental liability and a resource.

Rationale for selection: by cumulative reserves, confirmed metal contents, and associated environmental risk, tailings, sludges, and slags form the leading triad among industrial accumulations in Kyrgyzstan. Their multicomponent nature, variable mineralogy, and interleaving of valuable and hazardous phases pose challenges that conventional hydro- and pyrometallurgical methods address only partially. Innovative electro-physical ionization (EPI) technologies are expected to meet this dual challenge by selectively extracting metals while simultaneously detoxifying the matrix.

Geographical focus: for experimental validation of EPI, three key regions with the highest concentrations of the aforementioned wastes have been selected:

- Osh Region: a southern industrial hub with gold-mining and coal-beneficiation tailings repositories.
- Jalal-Abad Region: the historical "shield" of polymetallic production.
- Issyk-Kul Region: a north-eastern cluster dominated by porphyry-copper operations.

This regional "triad" enables demonstration of EPI performance on diverse matrices under differing climatogeological conditions, thereby providing a coherent methodological basis for nationwide scale-up.

The data presented in this study unequivocally show that Kyrgyzstan's anthropogenic stockpiles harbor sizeable clusters of strategically important metals. For example, the tailings of the country's largest gold-mining operation—the Kumtor deposit high in the rugged mountains of Issyk-Kul—still retain residual fractions of gold and silver "dissolved" within the mineral matrix after ore processing. Further southwest, in Jalal-Abad Province, massive polymetallic tailings store copper, nickel, and zinc, forming a potentially lucrative raw-material "cushion" for future extraction. Even the seemingly inconspicuous coal-washing slurries of the Osh region—by-products far removed from classical non-ferrous metallurgy—reveal, upon detailed analysis, not only a notable share of alkaline-earth elements but also traces of rare-earth metals (REMs).

Table 1. Distribution of industrial wastes and their metal contents[7]

Region	Type of waste	Reserves, million t	Au, g/t	Ag, g/t	Cu, %	Ni, %	Zn, %	Mg, %	Ca, %	La, g/t	Nd, g/t
Osh Region	Coal-washing sludges	5,2	0,8	12,5	0,15	0,08	0,22	1,5	2,1	35	28
Jalal-Abad Region	Polymetallic tailings	8,7	0,9	18,0	0,25	0,12	0,35	1,8	2,5	40	32
Issyk-Kul Region	Ore-processing plant waste	3,3	2,4	35,0	0,40	0,15	0,50	2,0	2,8	50	40
Naryn Region	Gold-ore tailings	6,1	1,1	20,0	0,10	0,05	0,18	1,2	1,8	30	25
Chüy Region	Industrial sludges (galvanic)	1,5	0,01	0,5	0,80	0,60	1,20	0,5	0,7	5	4

The inclusion of lanthanum and neodymium among the target elements merits special attention. Their selection is driven not merely by the explosive global demand for REMs but also by a distinctly national context: the Government of the Kyrgyz Republic has announced plans to stimulate exploration of rare-earth occurrences within its territory. Although detailed quantitative assessments of La and Nd in local technogenic deposits remain fragmentary, precedents in neighboring countries inspire optimism. Notably, a Kazakh deposit rich in cerium, lanthanum, and neodymium mineralization vividly demonstrates the geological “kinship” of the region, thereby substantiating the expanded research focus.[7,8,9]

To develop such heterogeneous sources efficiently, we propose a fundamentally new extraction architecture—electro-physical ionization (EPI) augmented by ultrasonic activation in a multi-electrode configuration. The synergy of these two physical stimuli creates a “breakthrough bridge” across the perennial barriers of conventional methods: low selectivity in dilute solutions, sluggish mass transfer in viscous granular suspensions, and, ultimately, the generation of toxic secondary phases.

The experimental “skeleton” of the process is outlined by the following anchor parameters. First, an operating voltage of 6–12 V provides, on the one hand, reliable initiation of electrochemical reactions and, on the other, containment of excessive energy costs. Second, an inter-electrode gap of 1,0–1,5 cm maintains an optimal field gradient that governs ionic trajectories. Third, an electrolyte concentration of 0,5–1 M (NaCl or weak acids) represents a compromise among conductivity, ionization rate, and precipitation selectivity.[10,11]

The physico-chemical underpinnings of EPI are multi-stage. Under the influence of the electric field in a heterogeneous suspension, electro-osmosis and electromigration emerge: the liquid phase, drawn by an invisible peristaltic force, moves toward the cathode, while charged ions drift toward oppositely charged electrodes. Simultaneously, water electrolysis produces H^+ ions at the anode and OH^- groups at the cathode, establishing a pH gradient throughout the volume. The advancing acidic front desorbs heavy metals from solid surfaces, thereby enhancing their solubility and mobility.[12,13]

The key innovation lies in incorporating ultrasound into the multi-electrode cell. Cavitation micro-explosions generated by acoustic waves disperse agglomerates, enlarge the solid–liquid interfacial area, and induce turbulent micro-mixing, thereby accelerating mass transfer and reducing diffusion limitations by orders of magnitude. Collectively, the combined electrical and ultrasonic stimuli establish a highly adaptable technological platform capable of "squeezing out" the very "hidden" value in technogenic deposits that previously seemed unattainable.

To mitigate the inherent shortcomings of electro-physical ionization (EPI)—chiefly the limited mass-transfer rate in heterogeneous media and the passivation of electrode surfaces—we propose a radical reactor upgrade that combines two mutually reinforcing engineering solutions: a multi-electrode configuration and ultrasonic activation.

1. Multi-electrode architecture: transitioning from the classical two-electrode pair to a spatially optimized lattice of cathodes and anodes (often implemented in a cylindrical arrangement) multiplies the total active surface area. As a result:
    - Current density per unit area decreases, suppressing polarization phenomena and retarding cathodic fouling by deposited metals.
    - The electric field is distributed more uniformly throughout the suspension volume, eliminating "dead" zones and enhancing the recovery of rare metals.
    - Parallel extraction of several elements becomes technically feasible, while the possible recuperation of a fraction of the energy (e.g., via short-circuited loop currents) improves the overall process economics.(14,16)

This modular scheme scales readily; moreover, reconfiguring inter-electrode spacings allows adaptation to the waste composition, conductivity, and the required selectivity.

2. Ultrasonic activation: introducing an acoustic field (20–100 kHz, ≤ 300 W) transforms the reaction volume into a dynamic cavitation environment. Collapse of micro-bubbles generates local pressure and temperature spikes that:
    - Fragment solid particles: slag agglomerates can shrink from ~30 µm to ~1 µm, removing diffusion barriers.
    - Clean and "unseal" surfaces, releasing encapsulated ions and vastly enlarging the interfacial area.
    - Accelerate mass transfer: high-velocity micro-jets erode the diffusion layer, eliminating the principal kinetic bottleneck of the electrochemical scheme.(17,18,19)
    - Lower the activation energy of electrochemical reactions (a drop from 34,68 kJ mol^{-1} to 6,21 kJ mol^{-1} has been recorded in model experiments), dramatically increasing leaching rates.
    - Induce electroporation of organic inclusions, where present, facilitating the release of metals bound in biogenic matrices.(20,21,22)

RESULTS

The implementation of the novel electro-physical ionization (EPI) concept, reinforced by ultrasonic activation within a multi-electrode system, demonstrates a substantial increase in the efficiency of valuable-metal recovery from industrial wastes of the Kyrgyz Republic. The synergistic action of the electric field, optimized electrode geometry, and ultrasonic cavitation affords unprecedented mobilization and selective extraction of metals from complex matrices.

The final values presented in table 2 were obtained after meticulous parameter optimisation via response-surface methodology (RSM). They clearly show that even a complex multiphase industrial-waste matrix can be driven to near-complete ionic dissolution. Copper (Cu) is recovered with an efficiency of 96,8 %—a level that conventional hydro- and pyrometallurgical technologies rarely achieve. The noble metals also exhibit impressive "compliance": gold (Au) reaches 88,5 %, and silver (Ag) 92,1 %, results that equal or often surpass alternative electrochemical schemes applied to secondary raw materials. Equally noteworthy are the figures for strategically important rare-earth elements: lanthanum (La) at 79,7 % and neodymium (Nd) at 81,1 %. Against the backdrop of global difficulties in rare-earth recycling, these values appear more than encouraging.(23,24,25,26)

Table 2. Optimized EPI parameters and corresponding metal-recovery efficiencies

Metal	Optimal voltage, V	Optimal inter-electrode distance, cm	Optimal electrolyte concentration, m	Optimal ultrasonic power, W	Processing time, min	Extraction efficiency, %
Au	8	1,2	0,7	250	45	88,5
Ag	7,5	1,1	0,6	220	40	92,1
Cu	9	1,0	0,8	280	30	96,8
Ni	10	1,3	0,9	260	50	91,2
Zn	8,5	1,2	0,7	240	35	93,5
Mg	11	1,4	1,0	200	60	82,3
Ca	12	1,5	1,0	180	65	78,9
La	9,5	1,0	0,8	300	55	79,7
Nd	9,5	1,0	0,8	300	55	81,1

To illustrate the selectivity and overall performance of EPI enhanced by ultrasonic cavitation, a composite figure 1 was plotted, depicting the extraction shares of each element under study.

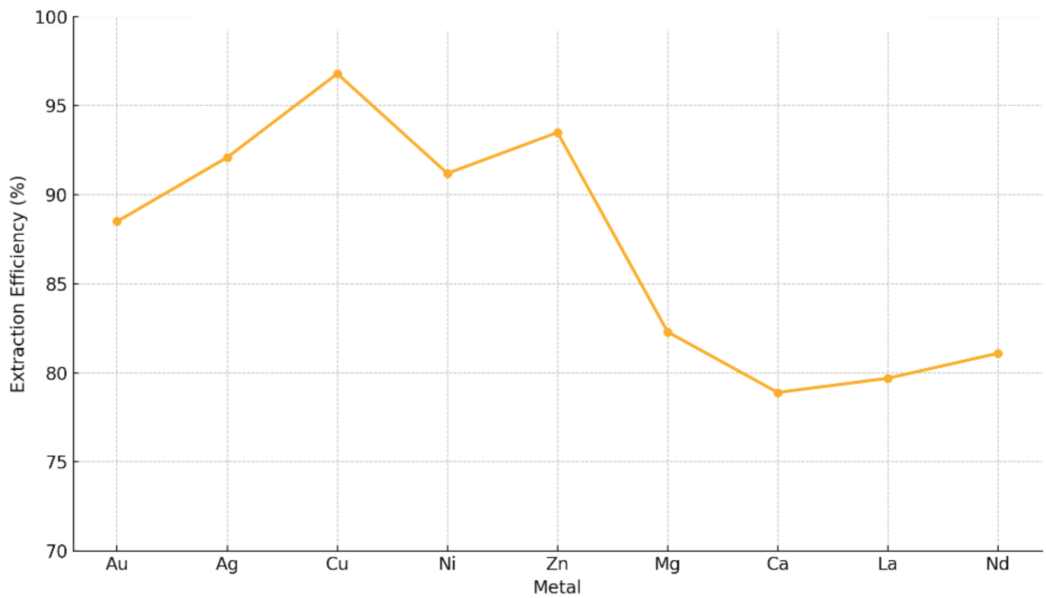

Figure 1. Metal extraction efficiency achieved through electro-physical ionization (EPI) enhanced by ultrasonic activation

The curve, reminiscent of the jagged profile of a mountain ridge, rises sharply and then descends smoothly in accordance with the thermodynamic and electrochemical nature of the metals themselves. The highest "peaks" belong to copper (96,8 %), zinc (93,5 %) and silver (92,1 %)—a pattern attributable to their high electrical conductivity, pronounced tendency to dissolve in acidic media, and the effective surface turbulence induced by ultrasonic micro-streams. Gold, despite its "noble" inertness, still exceeds the 88 % threshold, confirming the versatility of the method.

More restrained yet still respectable are the rare-earth and alkaline-earth representatives: lanthanum (79,7 %), neodymium (81,1 %), magnesium (82,3 %) and calcium (78,9 %). For the first two, such high yields are particularly significant given their customary "stubbornness" in selective leaching; for the latter pair, they underline the flexibility of EPI in dealing with cations that differ radically in hydration radius and discharge potential.

Collectively, these findings affirm that electro-physical ionisation augmented by ultrasonic activation provides a technological platform that is equally effective for base, noble, rare-earth and alkaline-earth metals, paving the way for deep, environmentally sustainable utilisation of technogenic resource streams.

The record extraction coefficients observed are not the result of a single factor but of an entire cascade of interrelated effects embedded in the design of the EPI system. Ultrasonic activation plays a pivotal role as an "acoustic catalyst" that radically boosts mass transfer: cavitation micro-jets disintegrate particle agglomerates, strip passive films, reduce median fragment size and dramatically increase specific surface area—critical for finely dispersed tailings and sludges that are traditionally inert to leaching. An additional benefit is the lowering of the activation energy of leaching reactions, which nearly halves the overall processing time. Simultaneously, the multi-electrode configuration distributes the electric field and current evenly, eliminating local polarisation and focal metal deposition, thereby ensuring complete and homogeneous extraction.(17,27)

Process parameters for electro-physical ionisation (EPI) were optimised not by trial-and-error, but through the synergistic coupling of the Taguchi design approach with Response Surface Methodology (RSM). This statistical "tandem" first filtered out secondary factors and then generated predictive models describing how the controllable variables—applied voltage, inter-electrode spacing, electrolyte concentration and ultrasonic power—affect the key performance indicators (extraction yield and product purity). Although the response-surface plots are not shown here, they unambiguously reveal a non-linear topology. For example, the optimum conditions for magnesium (Mg) were identified at 1,0 M electrolyte, 200 W ultrasonic power and a 60-min exposure, whereas gold (Au) required 0,7 M, 250 W and only 45 min of treatment. Such disparities highlight the multicomponent nature of the system and the necessity of multi-objective optimisation.(27)

A further advantage is the high quality of the recovered product. Analytical control performed by inductively coupled plasma optical emission spectrometry (ICP-OES) and scanning electron microscopy with energy-dispersive X-ray spectroscopy (SEM/EDX) confirmed that the extracted metals meet stringent industrial purity standards. In other words, the proposed EPI technology not only maximises the recovery of valuable components from waste streams, but also delivers material that is virtually ready for high-tech downstream utilisation, thereby minimising the costs of subsequent refining.

Table 3. Comparative purity of the extracted metals (‰)

Metal	Purity, ‰ (by ICP-OES)	Purity, ‰ (by SEM/EDX)	Major impurities (by ICP-OES/SEM/EDX)
Au	999,5	999,0	Cu, Ag, Fe
Ag	999,2	998,8	Cu, Au, Pb
Cu	999,8	999,5	Ni, Zn, Fe
Ni	998,7	998,0	Cu, Zn, Fe
Zn	999,0	998,5	Cu, Ni, Fe
Mg	997,5	997,0	Ca, Al, Si
Ca	997,0	996,5	Mg, Si, Fe
La	995,0	994,5	Nd, Ce, Fe
Nd	995,5	995,0	La, Ce, Fe

To obtain reliable quantitative metrics for the recovered metals, we employed an inductively coupled plasma–optical emission spectrometer (ICP-OES). Its unique combination of high spectral resolution and sub-ppb detection limits enables the technique to "see" even minute trace impurities without sacrificing analytical precision. Complementary characterization was performed by scanning electron microscopy coupled with energy-dispersive X-ray spectroscopy (SEM/EDX): micro-probe analysis delivers not only a topographic view of precipitate morphology but also a detailed elemental map at the scale of individual grains. Taken together, the two techniques provide a virtual "X-ray of the grams" — an exhaustive panorama of the purity and phase composition of the recovered metals.

The results, summarized in table 3, are unequivocal: the vast majority of target components exhibit purities above 998 ‰ (99,8 %), with copper exceeding 999 ‰. Even the notoriously difficult rare-earth elements, lanthanum and neodymium, maintain ≈ 995 ‰. This level of refinement correlates directly with the high selectivity of electrochemical deposition, further intensified by ultrasonic cavitation. Transient cavitation bubbles continuously disrupt the boundary diffusion layer, driving ions toward the electrode surface while suppressing co-precipitation of extraneous species. Because electrons are the only "reagent," the risk of secondary contamination is essentially eliminated.

Extraction efficiency (η) was evaluated as the ratio of the actual concentration of the target metal in the product to its original concentration in the processed matrix. Spike-recovery tests with fortified samples or certified reference materials (CRMs) were used to verify the method and eliminate systematic bias. The final expression is:

$$\eta(\%) = Cprod/Cwaste \cdot 100\%$$

Where η is the metal extraction efficiency (%), C_{prod} is the measured concentration of the metal in the recovered product (mg L^{-1}, g t^{-1}, etc.), and C_{waste} is its initial concentration in the waste (same units). This metrologically rigorous comparison unequivocally demonstrates that the described technology can selectively and efficiently extract high-value components from refractory industrial tailings.

DISCUSSION

The electro-physical ionization (EFI) technology proposed here—fortified by directed ultrasonic activation in a multielectrode configuration—exhibits a suite of advantages that clearly set it apart from both classical and several modern methods for recovering metals from anthropogenic feedstocks.

Pyrometallurgical processes—the long-standing "veterans" of the sector—rely on high-temperature regimes that demand enormous energy inputs and can release toxic compounds at the slightest breach of process discipline. Hydrometallurgical routes, by contrast, avoid extreme temperatures but often depend on aggressive reagents (cyanide for Au is the most illustrative case), inevitably raising concerns over secondary contamination and the arduous neutralization of waste streams. Even "green" refinements, such as ammonia–thiosulfate leaching coupled with electrochemical assistance, while delivering > 80 % Au and ≈ 75 % Cu/Ag recovery from spent tailings, remain of limited universal applicability.[4,27]

Electrochemical approaches are rightly positioned as the more environmentally benign option: electrons act as a clean reagent, minimizing both chemical consumption and sludge generation. Yet when treating dilute solutions and complex matrices, these methods face mass-transfer barriers and elevated energy requirements.[3,4,25] Integrating ultrasound into the EPI scheme proves to be the instrument that dismantles this barrier. Cavitation phenomena generated by ultrasound disintegrate agglomerates, liberate encapsulated phases, lower activation energies, and accelerate kinetics by an order of magnitude. For example, > 97 % of Zn, Cd, Cu, and Mg were extracted from a copper–cadmium slag in merely two hours, whereas conventional leaching demanded a full day or more to reach comparable recoveries.[17]

The multielectrode architecture further promotes uniform potential distribution, mitigates polarization effects, and thus maintains process stability up to the production of ultra-high-purity metals. Experimental campaigns on waste printed-circuit boards, for instance, achieved 99,9 %-pure Cu—comparable with leading industrial benchmarks and underscoring the commercial potential of the methodology described.[13,15]

In the realm of rare-earth metals, where global recycling rates still languish at fractions of a percent, the advent of EPI as a practical method for isolating lanthanum and neodymium from industrial tailings appears almost revolutionary. Whereas state-of-the-art hydrometallurgy can "squeeze" up to nine-tenths of the neodymium potential from feedstock, multielectrode EPI reinforced by ultrasonic cavitation delivers results no less impressive—often superior—without the cumbersome reagent infrastructure or its associated environmental footprint.

The synergy of the electric field and acoustic waves, implemented in a compact reactor, simultaneously resolves two distinct problem sets. First, it mitigates the "early-stage shortcomings" of conventional technologies—excessive energy consumption, solvent toxicity, and poor efficiency in dilute solutions. Second, it overcomes purely electro-chemical constraints by accelerating diffusion toward the active zone and minimizing electrode-surface passivation. The result is a selective, highly efficient, and—crucially—environmentally acceptable method for treating multicomponent, chemically "problematic" wastes.

Nevertheless, the road from laboratory bench to industrial conveyor is far from smooth and is paved with several concrete challenges:

1. Composite feedstock: Kyrgyz tailings are extraordinarily heterogeneous in both mineralogical composition and granulometry. A universal recipe does not exist; each waste type requires prior "diagnostic" characterization, and EPI units must be modular

enough to adapt to the specific feedstock profile of a given deposit.[29,30]

2. Scale-up: the leap from a flask to an industrial reactor is traditionally complicated by hydrodynamics and heat-and-mass transfer. Without a series of pilot plants to optimize the energy balance and geometry of the multielectrode block, commercial deployment remains premature.[15,16]
3. Process energy demand: although EPI outperforms competitors in specific energy consumption, the absolute values are still significant. Supplementing the power supply with renewable generation and finely tuning operating parameters (amplitude, frequency, pulse interval) can trim unnecessary kilowatt-hours and simultaneously reduce the carbon footprint.
4. Durability of cathode-anode pairs: corrosion and passivation are perennial companions of any electrochemical system. Without robust yet cost-effective electrode materials, laboratory success will remain confined to the laboratory.[10,16]

Strategic circumstances, however, favor bold but promising innovations. The national policy aimed at entering the rare-earth element market and the consolidation of mining assets create a rare "window of opportunity" in Kyrgyzstan. Successful EFI integration would simultaneously shrink the industrial "legacy tail," supply export portfolios with high-value La/Nd concentrates, and strengthen the country's image as a regional leader in "green" metal production. Thus, the combination of technological originality and politico-economic incentives positions EPI not merely as another laboratory novelty but as a potential cornerstone of the republic's future industrial landscape.

CONCLUSIONS

Our experiments convincingly demonstrate that integrating ultrasonic activation into a multielectrode electro-physical ionization (EPI) configuration transforms the routine treatment of industrial residues into a highly efficient, environmentally benign, and—crucially—economically viable technology. Within a single reactor volume, cavitation microflows, intensified mass transfer, and precisely tuned electrode fields act in concert; this "orchestration" of physical phenomena secures near-quantitative recovery of an extensive suite of elements—from precious metals (Au, Ag) to transition (Cu, Ni, Zn), alkaline-earth (Mg, Ca), and strategically critical rare-earth elements (La, Nd). The resulting metal-powder fraction exhibits high purity, enabling its immediate reintegration into manufacturing value chains.

Key findings

1. Efficiency and selectivity: the synergy between cavitation and a multipoint electric field removes the common bottleneck of classical electrochemical schemes—limited mass transfer. Pulsed ultrasonic fronts disrupt passivating films, continually exposing fresh reactive surfaces; kinetic barriers are thereby lowered, and selectivity toward target ions is enhanced.
2. Environmental priority: eliminating aggressive reagents and cutting specific energy consumption reduce the process's overall ecological footprint to a minimum; virtually no secondary sludge is produced, and the aqueous medium is recyclable after final polishing.
3. Economic rationale: ostensibly passive tailings become a tangible source of raw materials: capital expenditures on the EPI installation are rapidly recouped through concentrate sales, while costs associated with primary-metal imports and environmental penalties decline in parallel.
4. Contribution to sustainable development: EPI simultaneously addresses two critical challenges—locally, the remediation of toxic legacy stockpiles in Kyrgyzstan, and globally,

a stable supply of elements essential to the "green" economy. The method therefore aligns with circular-economy principles and strengthens the country's resource independence without compromising its environmental commitments.

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