Alternative Sources of Potassium from Potassium Feldspars, from Mining to Cropping: A Review.

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Abstract

This review examines thermal, hydrothermal, chemical, and biological processes for producing controlled-release potassium fertilizers exclusively from potassium feldspars. A comparative assessment is presented covering extraction efficiency, environmental impact, and technological feasibility of the main activation routes. Among these, alkaline hydrothermal treatments and pyrometallurgical chlorination achieve the highest potassium extraction efficiencies, often exceeding 80% and reaching above 90% under optimized conditions. In contrast, moderate calcination and bioleaching show lower extraction rates but offer environmental and operational advantages, such as reduced energy demand, lower reagent consumption, and potential suitability for sustainable agricultural practices. Agronomic trials demonstrate that properly activated potassium feldspars can match the performance of conventional potassium chloride (KCl) in terms of crop yield, while providing the advantage of controlled nutrient release and prolonged residual effects in the soil. Economic and macroeconomic analyses emphasize Brazil's strong dependence on imported potassium fertilizers and the strategic opportunity of exploiting domestic feldspar deposits. By integrating mining, beneficiation, activation processes, and agricultural application, this review supports the development of sustainable, locally sourced alternatives to conventional KCl, enhancing self-sufficiency and resilience in agricultural production systems.

Keywords: potassium feldspar, thermofertilizer, hydrothermal processing, pyrometallurgical chlorination, controlled-release fertilizer

1. Introduction

Potassium (K) is an essential macronutrient for plant growth, directly influencing photosynthesis, enzyme activation, osmotic regulation, and resistance to biotic and abiotic stresses. Its adequate supply is critical to achieving high crop yields and quality [1,2]. Globally, the main potassium fertilizers are potassium chloride (KCl) and potassium sulfate (K_2SO_4), with KCl representing more than 90% of the traded potassium fertilizer market [3].

The supply of KCl is highly concentrated in a few countries, notably Canada, Russia, and Belarus, which together account for more than 60% of world production. This geographical concentration increases the vulnerability of importing countries to supply disruptions and price volatility [4,5]. In Brazil, the dependence on imported potassium fertilizers exceeds 90% of domestic demand, making the agricultural sector particularly exposed to international market fluctuations and logistical challenges [6]. Transportation from ports to inland agricultural regions is costly and subject to infrastructure limitations, further raising fertilizer costs and impacting production competitiveness.

Given this scenario, the search for alternative potassium sources from domestic mineral resources has gained strategic importance. Potassium feldspars—especially microcline (triclinic) and orthoclase (monoclinic)—are abundant in granitic and syenitic rocks and contain 12–16% K_2O [7]. Despite their low natural solubility (<1% in water or weak acids), these minerals can be activated by mechanical, thermal, or chemical treatments to increase potassium release to agronomically relevant levels [8,9].

The use of potassium feldspars as alternative fertilizers offers potential advantages, including the possibility of controlled nutrient release, co-supply of silicon and aluminum, and the utilization of domestic mineral reserves to reduce import dependence. However, the efficiency of potassium release depends on the activation route, process conditions, and the degree of mechanical pre-treatment applied to the mineral.

This review aims to compile and critically analyze the main technological routes for activating potassium feldspar for fertilizer production, focusing on extraction efficiency, agronomic performance, environmental impact, and economic feasibility. The study also evaluates Brazil's potential to integrate these processes into its agricultural supply chain as part of a strategy to reduce dependency on imported KCl.

The methodology consisted of a systematic literature review covering articles, patents, and technical reports published between January 2020 and 2025, using databases such as Web of Science, Scopus, ScienceDirect, and Google Scholar. Search terms included "potassium feldspar," "hydrothermal activation," "thermofertilizer," and "pyrometallurgical chlorination." Studies were selected based on relevance to potassium extraction from feldspar, reporting of quantitative efficiency data, and/or agronomic evaluations.

2. Results And Discussion

2.1. Mineralogy and occurrence of potassium feldspars

Potassium feldspars ($KAlSi_3O_8$) represent a group of tectosilicate minerals with three principal polymorphs — microcline, orthoclase, and sanidine — which crystallize under different temperature conditions [10, 11]. Microcline forms at low temperatures and exhibits distinctive grid-twin (tartan) twinning; orthoclase, an intermediate-temperature monoclinic form, commonly displays Carlsbad or Baveno twins; sanidine is a high-temperature monoclinic form typical of volcanic rocks [11, 12].

These polymorphs occur widely across geological environments: microcline is prevalent in granitic and high-grade metamorphic rocks; orthoclase is common in both plutonic and some volcanic contexts; sanidine is abundant in rhyolites, obsidians, and felsic volcanic flows [12]. Their physical properties are similar, but subtly distinct:

- Chemical composition: $KAlSi_3O_8$ (all three forms) [13].
- Hardness (Mohs scale): approximately 6–6.5 [14].
- Specific gravity: about 2.5–2.6 [14].

Table 1 summarizes the main mineralogical and geological features of the three potassium feldspar polymorphs, highlighting their crystal structures, typical geological environments, and temperature ranges of formation. This classification is important not only for petrological studies but also for evaluating their potential as alternative potassium sources for fertilizers.

Table 1: Key characteristics of potassium feldspar polymorphs

Polymorph	Temperature formation	Crystal system & twinning	Common occurrence
Microcline	Low	Triclinic; grid (tartan) twinning	Granites, pegmatites, metamorphic rocks
Orthoclase	Intermediate	Monoclinic; Carlsbad/Baveno twins	Plutonic & some volcanic rocks
Sanidine	High (rapid cooling)	Monoclinic; simple twins	Rhyolites, obsidian, pyroclastic deposits

From an agronomic perspective, the microcline variety, although more abundant in granitic rocks and pegmatites, tends to exhibit lower weathering rates due to its triclinic structure and more ordered Al–Si framework, which reduces potassium release in soil environments [15]. Orthoclase, by contrast, has intermediate ordering, while sanidine is structurally disordered due to rapid cooling, potentially enhancing K solubility in chemical or hydrothermal treatments [16].

Geographically, potassium feldspar deposits are widespread worldwide — notable occurrences are found in Brazil, India, China, and Canada, often associated with large granitoid bodies and feldspathic sandstones. In Brazil, the most promising reserves are concentrated in Minas Gerais, Bahia, and Rio Grande do Norte, often co-occurring with quartz and mica, requiring beneficiation to achieve agronomic grade [17].

Understanding these mineralogical distinctions is essential for selecting extraction or activation processes that maximize K release, since mineral structure, alteration state, and associated gangue minerals directly influence leaching efficiency and operational costs in fertilizer production.

Figure 1 summarizes the magmatic-to-surface pathway that leads to the formation and transformation of K-feldspars ($KAlSi_3O_8$). It begins with K-, Si-, and Al-rich magma, proceeds through fractional crystallization, and culminates in the crystallization of the three principal K-feldspar polymorphs—sanidine (high-T, monoclinic), orthoclase (intermediate-T, monoclinic), and microcline (low-T, triclinic)—followed by post-magmatic alteration (hydrothermal and weathering) and redistribution into secondary deposits (soils and sediments)

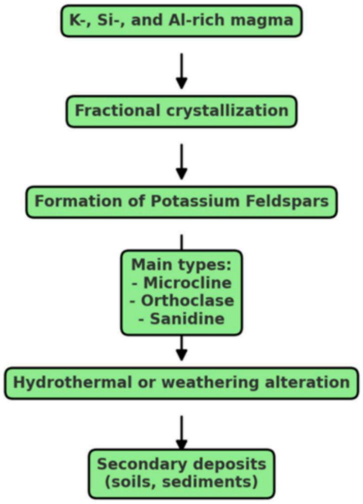

Figure 1: Genesis of potassium Feldspar.

From a process standpoint, the order–disorder continuum in the alkali feldspars governs which polymorph forms along the cooling path: rapid cooling stabilizes sanidine; slower cooling promotes partial ordering to orthoclase; very slow cooling and/or fluid-assisted re-equilibration favor the fully ordered microcline [19]. This structural evolution also generates exsolution and replacement microtextures (e.g., perthites, cryptoperthites), producing microporosity and reactive interfaces that later modulate dissolution and ion mobility during alteration—features directly relevant to fertilizer activation strategies that rely on enhanced K release [18. 19].

In the hydrothermal stage, K-feldspar commonly undergoes sericitization (replacement by fine muscovite/sericite ± quartz), which locks K into sheet silicates and reduces immediate K availability within the rock matrix; nevertheless, such reactions increase permeability and create reaction fronts that can be leveraged by engineered treatments [20]. Progressing to weathering, K-feldspar transforms to clays (illite, then kaolinite/smectite depending on pH–Eh–fluid flux), transferring K to exchangeable or interlayer sites in soils and sediments and thereby shaping the landscape-scale K cycle [21].

Implications for this review. The flowchart highlights three leverage points for alternative K-fertilizer development from feldspars:

- selecting source lithologies enriched in sanidine/orthoclase or microcline with abundant microtextures;
- targeting hydrothermal/sericitic alteration fronts where permeability and reaction interfaces are maximized; and
- integrating soil-process knowledge (where K resides after weathering) to predict agronomic release. Collectively, microstructural inheritance (magmatic and subsolidus), alteration pathways, and depositional context control how much, how fast, and under which conditions K can be mobilized from feldspar matrices—critical variables for comparing hydrothermal, thermal, and chemical activation routes discussed later in this review [17, 18, 20].

Mining and beneficiation

Extraction methods. Potassium feldspar (K-feldspar) is predominantly mined from granitic/pegmatitic bodies by open-pit bench mining with drilling–blasting, followed by selective loading of feldspathic zones; small underground stopes may occur in narrow pegmatite veins. Industrial practice targets low-iron feed to meet ceramic/glass specifications; mine planning therefore emphasizes selective mining and on-site sorting to control Fe-bearing accessories (mica, amphibole, oxides) that penalize whiteness and flux behavior [22]. In Brazil, feldspathic pegmatites are widespread (e.g., Borborema Province in NE Brazil and parts of Minas Gerais), with state and federal mapping underpinning resource targeting and environmental licensing [23, 24].

Crushing, grinding and concentration. ROM ore undergoes staged crushing (jaw/cone) and grinding (ball/rod or vertical mills) to liberate feldspar from quartz and Fe-bearing gangue. Downstream magnetic separation removes paramagnetic impurities (biotite, garnet, Fe-oxides), and feldspar–quartz separation is typically achieved by froth flotation. Recent process development focuses on HF-free or low-fluoride reagent schemes—mixed collectors (amine + anionic surfactants), fatty acids, and "self-assembly" collector systems—seeking selectivity while lowering EHS risk [25, 26]. For routes aimed at fertilizer precursors, comminution to finer sizes accelerates subsequent hydrothermal or thermochemical activation of K-feldspar matrices [15].

Economic and environmental aspects. Comminution is the major energy sink of mineral processing—often ~40–50% of plant energy—so circuit design (HPGR/stirred milling, classification efficiency) is pivotal to cost and footprint [27]. Flotation reagent choice drives OPEX and compliance: the shift from HF to fluorine-free collectors reduces hazard management and waste-water treatment loads [25]. Market signals also matter: USGS reports stable 2024 U.S. marketable feldspar output (~450 kt) with average unit value ~US$110/t, while trade flows and consumption are tied to glass and ceramics demand cycles [22]. In Brazil, sector diagnostics guide permitting and infrastructure planning for industrial minerals, including feldspar within pegmatite clusters that also host Li-bearing minerals—creating opportunities for co-products (quartz, mica) and residue valorization [17, 24]

Table 2 outlines the typical path from run-of-mine to feldspar concentrate: bench mining with grade control (low-Fe feed), staged comminution (crushing/grinding) for liberation, magnetic separation to remove Fe-bearing accessories, and feldspar–quartz flotation—with a recent shift toward HF-free reagent schemes for EHS compliance. For fertilizer-oriented routes, finer particle sizes are favored to accelerate hydrothermal/thermochemical activation of K-feldspar [15, 17, 25, 26].

Table 2: Typical unit operations in K-feldspar mining and beneficiation

Stage	Main operation	Objective	Key environmental/ economic notes	References
Mine	Open-pit drilling–blasting; selective loading	Maintain low-Fe feed; grade control	Selective mining lowers downstream reagent/energy demand	USGS 2025 [22]
Crushing & grinding	Jaw/cone crushing; ball/rod/stirred mills	Liberation to 75–300 µm (spec-dependent)	Largest energy share; optimization reduces costs/emissions	*Hatchl*. 2025 [27]
Magnetic separation	Wet/dry LIMS or HIMS	Remove Fe-bearing	Cuts Fe_2O_3 for ceramic/glass specs;	Sun *et al*. 2023[25]

Stage	Main operation	Objective	Key environmental/ economic notes	References
		accessories	reduces depressant demand	
Feldspar–quartz flotation	HF-free/low-F collectors; mixed systems	Selective feldspar recovery vs. quartz	Shift to fluorine-free systems for EHS compliance	Sun *et al*. 2023 [25]; Mohanty *et al*. 2024 [26])
Product handling	Dewatering, drying, sizing	Meet market specs (ceramic/glass) or feed activation routes	Particle size tailored for downstream use (tiles/glass or K-extraction)	Chen *et al*. 2024 [15]; USGS 2025 [17]

Because comminution typically dominates plant energy use, circuit efficiency (classification performance, stirred mills/HPGR) strongly influences cost and footprint; concurrently, moving from HF to fluorine-free collectors reduces operational risk and effluent treatment loads, though diluted-HF schemes can still show strong selectivity at lab scale [25, 26, 28]. At mine, selective extraction of low-Fe fronts and pre-sorting lower downstream reagent/energy demand and improve product fit for ceramics/glass or as a reactive precursor for K extraction [17].

Mechanisms of potassium release

Potassium in K-feldspar is hosted in large A-sites within a rigid aluminosilicate framework ($KAlSi_3O_8$). Under agronomic or processing conditions, K^+ liberation is governed predominantly by surface-controlled dissolution rather than bulk solid-state diffusion. Near-neutral solutions generate the slowest rates; dissolution accelerates under acidic (proton-promoted) and strongly alkaline conditions (hydroxyl-/ligand-promoted) and is strongly modulated by surface heterogeneity (etch pits, defects, twins) and by the precipitation of secondary phases that can sequester Si and Al and partially mask net release [19, 29, 30].

At the micro- to nanoscale, intrinsic crystal heterogeneity—exsolution/intergrowth textures and defect densities—creates spatially variable retreat rates; K-rich lamellae tend to dissolve faster and at more dispersed rates than Na-rich ones and etch-pit nucleation along defects enhances local fluxes [19]. These observations explain why mechanical activation (which increases defect density and reactive area) consistently boosts K release at a given chemistry [29].

Solution chemistry exerts first-order control. Low-molecular-weight organic acids (LMWOAs) promote ligand-assisted bond breaking at the feldspar–fluid interface; recent experiments show oxalic acid tends to mobilize Al more efficiently, whereas citric acid mobilizes Si, and mixed acids can be synergistic [31]. In alkaline hydrothermal systems (180–280 °C), OH$^-$ attack dissolves the framework, and K is redistributed into secondary zeolites or Ca-(Al)-silicates (e.g., tobermorite, hydrogrossular), generating materials with substantially higher leachable K than the parent feldspar [7, 16].

Finally, proximity to equilibrium matters: as solutions approach saturation with respect to secondary aluminosilicates, apparent dissolution slows by 1–2 orders of magnitude and becomes controlled by coupled dissolution–precipitation; kinetic interpretations must therefore decouple forward dissolution from simultaneous precipitation [32, 33].

Table 3 consolidates the main controls on K$^+$ release from K-feldspar—surface heterogeneity/defects, particle size (mechanical activation), solution chemistry (pH, organic ligands), alkaline hydrothermal conditions, and proximity to equilibrium—linking each control to its operative mechanism and net effect on dissolution/ion liberation [19, 32].

Table 3: Main controls on K$^+$ release from K-feldspar

Control	Mechanism (summary)	Net effect on K release	Recent evidence
Surface heterogeneity (defects, twins, intergrowths)	Preferential etch-pit nucleation and step retreat on defect-rich domains	↑ Rates where defects concentrate	Lange *et al.*, 2021 [19].
Particle size / mechanical activation	Higher specific area; disorder/amorphization of near-surface	↑ Rapid early K$^+$ liberation	Zhang *et al.*, 2024 [29]
pH (H$^+$ vs. OH$^-$)	Proton- or hydroxyl-promoted bond breaking in the framework	↑ Far from neutrality; ↓ near pH ~6–8	Zhu *et al.*, 2020 [32]; Schott *et al.*, 2024. [30]
Organic ligands (LMWOAs)	Complexation of Al/Si and enhanced detachment kinetics	↑; acid-specific selectivity (oxalic≈Al, citric≈Si)	Lin *et al.*, 2023 [31].
Hydrothermal alkali media	OH$^-$ attack; CIDR* to K-bearing secondaries (zeolites/C-A-S-H)	↑ Orders of magnitude vs. raw rock	Zhai *et al.*, 2021 [7]; Wu *et al.*, 2022. [16]
Near-equilibrium conditions	Coupled dissolution–precipitation reduces apparent forward rate	↓ 1–2 orders; requires tracer methods	Zhu *et al.*, 2020 [32]; Xu *et al.*, 2025. [33]

*CIDR = coupled interfacial dissolution–reprecipitation.

Processing technologies

Mechanical routes (ultrafine grinding, mechanochemical activation). Intense milling increases defect density, amorphizes the aluminosilicate network, and exposes K–O sites, which accelerates subsequent chemical leaching or biological solubilization. Planetary milling with small amounts of alkaline additives (e.g., $Ca(OH)_2$) has been shown to raise citric/acid-leachable K and shorten reaction times in downstream steps [29]. When coupled to fungal solubilization (e.g., *Aspergillus niger*), mechanical activation can more than double K release from pristine K-feldspar, evidencing a practical path to “green” K-fertilizers that avoid harsh reagents [29, 34].

Thermal routes (calcination with additives, fusion/roast-leach). Roasting K-feldspar with chloride/sulfate salts generates KCl in situ (via Ca^{2+}/Na^{+} exchange and network depolymerization), enabling high potassium recoveries after simple water leaching. Using $CaCl_2$ produced from local carbonates, >98 % K extraction has been demonstrated at ~900 °C/60 min; mixtures such as $CaSO_4$–NaCl can reach ~93–96 % while reducing $CaCl_2$ consumption [35, 36]. “Waste-derived” additives (e.g., eggshell–HCl to make $CaCl_2$) have also been validated for near-quantitative K recovery, supporting circular-economy variants of the roast-leach route [35, 36, 37].

Hydrothermal and chemical routes (alkaline/acid leaching; hydrothermal). Under subcritical conditions (≈200–280 °C) in concentrated alkali, K-feldspar transforms through metastable leucite/kaliophilite toward kalsilite, from which K (and Al) are readily leached—providing a controlled-release product and zeolitic by-products depending on conditions [16]. Micrometer- to nanometer-scale studies confirm that alkaline hydrothermal alteration produces secondary K-bearing phases at the feldspar interface that govern agronomic release kinetics, linking process parameters to plant-available K [7, 16].

Biological routes (microorganisms, bio-fertilizers). Potassium-solubilizing fungi and bacteria excrete organic acids and chelators that mobilize non-exchangeable K from silicate lattices. Recent work with A. niger shows substantial K release from K-bearing minerals under mild conditions, and the effect is amplified when starting from mechanically activated feldspar powders [34, 38]. Although slower than thermo/hydrothermal routes, bio-routes offer low-impact processing and compatibility with organic systems. [34, 38].

Table 4 condenses the main processtrade-offs andK-feldspar—mechanical, thermal (roast–leach), alkaline hydrothermal/chemical, and biological—linking operating windows to typical K recovery and operational trade-offs, and highlighting options that can serve either as stand-alone extraction (e.g., roast–leach) or pre-activation steps (e.g., ultrafine grinding) [7, 16, 35].

Table 4: Processing technologies for K-feldspar (summary, 2020–2025)

Route	Typical conditions	Typical outcome (K recovery / structural effect)	Energy / impact notes
Ultrafine grinding / mechanochemical activation	Planetary/attritor mills; optional alkaline additives (e.g., NaOH, $Ca(OH)_2$); minutes–hours	Marked increase in water-soluble / plant-available K vs. raw feldspar; enhanced reactivity for downstream steps	Electrical energy; no hazardous reagents; synergy with bioleaching
Roast–leach ($CaCl_2$)	850–900 °C, ~60 min; feldspar:$CaCl_2$ ≈ 1:1.5 ($CaCl_2$ can be made from calcite/eggshell)	Up to 98.6% K dissolution after water leach (900 °C, 60 min, 1:1.5)	High thermal load; chloride handling; circular Ca sources possible
Roast–leach ($CaSO_4$ + NaCl)	1000 °C, 60 min; ratio 1:1.25:1.5 (feldspar:$CaSO_4$:NaCl)	96.1% K dissolution; similar to $CaCl_2$ with less $CaCl_2$ consumption	High T; mitigates pure $CaCl_2$ demand
Alkaline hydrothermal (KOH/NaOH)	200–280 °C, 2–4 h (autoclave); concentrated alkali	Complete structural decomposition reported at 280 °C/120 min; K redistributed into secondary phases; high leachable K in products	Moderate thermal/pressure; produces zeolitic/C-A-S-H-like phases
Organic-acid leaching (LMWOAs)	0.01–0.1 M oxalic/citric; 25–80 °C; hours–days	Ligand-promoted dissolution of feldspar; selective mobilization (oxalic≈Al, citric≈Si); moderate K release	Low hazard vs. mineral acids; slower kinetics
Biological (e.g., *Aspergillus niger*)	Ambient–30 °C; pH ~4–6; days–weeks; nutrients optimized	Significant K release from K-bearing matrices; boosted when feed is mechanically activated	Very low impact; slower; compatible with organic systems

Roast–leach with salts delivers the highest recoveries (≈93–99%) but at a high thermal load and with chloride management requirements; circular Ca sources can mitigate impacts [35, 36, 37]. Alkaline hydrothermal routes achieve deep structural decomposition at 200–280 °C and yield reactive secondaries for controlled release, but demand caustic recycling and resistant reactors [7, 16]. Mechanochemical activation is low-hazard and energy-electricity based, excelling as a synergistic pre-treatment and pairing well with bio-routes [29, 34]. Organic-acid leaching and bioleaching are low-impact yet slower, fitting niche/organic contexts or hybrid schemes with prior mechanical activation [31, 38].

Agronomic efficiency

Environmental and economic aspects

Carbon footprint. Across the options, energy form and temperature are the main levers. Roast–leach routes for K-feldspar (e.g., $CaCl_2/CaSO_4$–NaCl roasts at ~850–1,000 °C) concentrate emissions in the high-temperature step and chloride handling, whereas alkaline hydrothermal conversion (≈200–280 °C) shifts impacts to electricity/steam and caustic make-up/recovery [39, 40]. For the benchmark soluble salts, an LCA of industrial production shows that Mannheim K_2SO_4 carries higher burdens than KCl, largely from fuel-oil combustion in the furnace; electricity dominates the KCl profile. These patterns contextualize feldspar-derived routes: lowering peak temperature and switching to lower-carbon heat (or electrification) materially reduces GHG intensity [40, 41].

Production and application costs. Cost drivers differ by route. Roast–leach OPEX is governed by fuel (kiln duty) and salt consumption; using mixed salts (e.g., $CaSO_4$+NaCl) can trim $CaCl_2$ demand at similar recoveries [36]. Hydrothermal OPEX depends on alkali dosage, materials of construction (corrosion-resistant autoclaves), and the efficiency of alkali recycling (e.g., causticizing K_2SiO_3 back to KOH with lime) [42]. Mechanochemical pre-activation is electricity-intensive but reduces downstream residence time and reagent needs, improving whole-chain economics when coupled to hydrothermal or bio-routes [42]. At the farm gate, feldspar-derived products tend to show controlled release; fewer split applications and lower K leaching can offset a lower first-cycle response relative to KCl/K_2SO_4 in sandy soils [43]. As a contextual input cost, the average U.S. feldspar unit value was about US$ 110 t^{-1} in 2024, indicating low feedstock cost for domestic sources [22].

Circular-economy potential. Several feldspar routes can embed by-product valorization or waste substitution. Eggshell-derived $CaCl_2$ (from biowaste + HCl) has been demonstrated for near-quantitative K recovery, displacing virgin reagents [37, 40]. $CaCl_2$ sourced from acid-leached carbonate ores likewise supports salt-roasting without reagent-grade inputs [35]. HF-free flotation schemes reduce hazardous reagents in the concentrate supply chain [26]. Alkaline hydrothermal conversion can co-produce zeolitic phases and allows closed-loop caustic recycling (e.g., $K_2SiO_3 \rightarrow KOH$), tightening mass/energy cycles [7, 15].

CONCLUSIONS

Synthesis of findings.

Potassium feldspar (K-feldspar) is a widely available aluminosilicate whose polymorphism, micro textures, and alteration history govern how readily K^+ can be mobilized. Processing options span mechanical pre-activation (ultrafine grinding/mechanochemistry), thermal roast–leach with salts, alkaline hydrothermal/chemical conversion (subcritical autoclaves), and biological/organic-ligand routes. Mechanical activation reliably increases interfacial reactivity; salt roasting can deliver the highest K recoveries but at high thermal loads; alkaline hydrothermal processing achieves deep structural decomposition at moderate temperatures with opportunities for caustic recycling and by-product (zeolitic/C-A-S-H) co-production; biological and organic-acid approaches are low-impact but slower, and work best when paired with mechanical pre-activation.

Perspectives for sustainable agriculture

Across pot and field studies, feldspar-based materials function as controlled-release K sources: short-term responses often trail KCl/K_2SO_4, but residual supply to subsequent cuts/crops is a consistent advantage. Blending strategies (e.g., feldspathic rock + a small fraction of KCl) can match soluble salts agronomically while reducing K leaching, especially in sandy, high-rainfall systems. Environmentally, the principal levers to lower GHG intensity are (i) temperature/heat source (electrification, heat recovery), (ii) closed-loop alkali and salt management, and (iii) HF-free concentration flowsheets upstream. Economically, feedstock costs are modest; competitiveness depends on energy, reagent loops, and logistics (co-location, selective mining), with circular-economy options (waste-derived $CaCl_2$, co-product valorization) further improving viability.

Future research needs.

- ✓ Multi-site, multi-season trials benchmarking feldspar-based products against KCl/K_2SO_4 across soils, climates, and crops, tracking both yield and K uptake.
- ✓ Standardized release metrics and QC (e.g., citric/water solubility, kinetic tests) aligned with regulatory frameworks, plus granulation/formulation studies for field handling.
- ✓ Techno-economic assessment (TEA) and life-cycle assessment (LCA) reported as kg CO_2e per kg of plant-available K, not just per kg product.
- ✓ Scale-up of alkaline hydrothermal routes with corrosion-resistant materials, caustic recovery loops (e.g., $K_2SiO_3 \rightarrow KOH$), and valorization of zeolitic/C-A-S-H co-products.

- ✓ Decarbonized roast–leach variants: lower-T salt mixes, waste-derived $CaCl_2$, and heat integration/electrification.
- ✓ Mechanistic linking from micro/nano interfacial transformation to field K availability, integrating dissolution–precipitation kinetics and soil solution chemistry.
- ✓ Bio-routes optimization (microbial consortia, organic ligands) coupled to mechanochemical pre-activation to shorten residence time at scale.
- ✓ Soil–plant–microbiome interactions and leaching/runoff studies to quantify environmental trade-offs and long-term soil health impacts.
- ✓ Impurity management (trace metals, halides) and regulatory compliance for safe, consistent products.
- ✓ Adoption and logistics analyses (on-farm blending with soluble K, placement/timing strategies) to translate process gains into reliable agronomic performance.

Overall, K-feldspar shows credible potential as a local, lower-leaching, controlled-release potassium source within sustainable nutrient strategies—if process efficiency, product standardization, and agronomic management are advanced in parallel.

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