Potassium Recovery from Feldspar: Activation Routes, Dissolution Kinetics, Agronomic Performance, and Techno-Economic Assessment

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ABSTRACT

Original research paper

Potassium feldspar has emerged as a strategic alternative source of potassium fertilizer, amid rising global demand and increasing reliance on imported soluble salts. This review critically analyzes research from 2016 to 2025 on the mechanisms of feldspar activation and potassium release, focusing on process kinetics, agronomic effectiveness, and economic viability. Recent improvements in activation techniques— including thermal and hydrothermal treatments, alkaline or chloride fusion, acid digestion, mechanochemical activation, and biolixiviation—have greatly enhanced feldspar reactivity, achieving potassium solubility levels of 80–95% under optimal fusion or chlorination conditions. Dissolution kinetics are primarily governed by surface reactions and diffusion, which are influenced by temperature, crystallinity, and the composition of the alkali flux. Agronomic tests demonstrate that fused or thermally activated feldspar can achieve 80–90% efficiency compared to KCl, offering sustained nutrient release and lower leaching losses. Cost estimates for processing vary from USD 60–100 per ton of K_2O using mechanochemical or hydrothermal methods, to over USD 200 per ton for fusion or chlorination, emphasizing the need for energy optimization. Environmentally, low-temperature and biological processes have the lowest carbon footprints and effluent outputs. Overall, feldspar activation methods present a promising path for sustainable potassium recovery, with future research likely to focus on integrated kinetic modeling, large-scale validation, and comprehensive life-cycle assessments to facilitate industrial implementation.

Keywords: Potassium feldspar, Activation routes, Dissolution kinetics, Potassium release, Agronomic performance, Techno-economic assessment, Environmental impact.

Highlights

- Advanced activation pathways boost potassium solubility in feldspar to over 80%.
- Alkaline fusion and chlorination provide agronomic results comparable to KCl.
- Processing costs range from USD 60 to 200 per ton of K_2O, depending on the activation method.
- Hydrothermal and mechanochemical methods reduce energy consumption and emissions.
- Feldspar-based fertilizers boost nutrient independence and food security.

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1. Introduction

Potassium (K) is a crucial macronutrient for plants, playing key roles in osmotic regulation, enzyme activation, stomatal function, and protein synthesis. Its global usage is rising driven by intensive agriculture and increased demand for food and bioenergy crops. However, potash production is concentrated in a few regions, with countries such as Canada, Russia, and Belarus providing over two-thirds of the world's exports. This concentration introduces supply risks leading to price fluctuations (Williams et al., 2025; Rodeja, 2025).

The search for sustainable and alternative potassium sources is intensifying, particularly for nations without natural potash reserves. Potassium feldspar ($KAlSi_3O_8$) emerges as a notable option due to its abundance in granitic and pegmatitic rocks and its typical K_2O content of 10–15%. Nonetheless, its low natural solubility (<3%) restricts its direct application in agriculture (Ciceri et al., 2019; Hashemi et al., 2020).

To overcome this limitation, various activation techniques—including thermal, hydrothermal, alkaline fusion, acid leaching, mechanochemical milling, and biological solubilization—have been developed to enhance potassium release and produce slow- or controlled-release fertilizers (Ciceri et al., 2017; Alyosif et al., 2023; Chen et al., 2024). Recent studies indicate that activation can increase K solubility to 80–95% and achieve relative agronomic efficiencies (RAE) comparable to traditional KCl (Tao et al., 2022; Turk & Kangal, 2023; Liu et al., 2025; Rocha & Pereira, 2017).

Although progress has been made, comparative studies that analyze reaction kinetics, energy use, economic viability (CAPEX/OPEX), and environmental impact remain rare. Past reviews (Hashemi et al., 2020; Chen et al., 2024) have focused on feldspar processing methods but lacked an in-depth evaluation of the trade-offs between kinetics, economics, and environmental factors. Moreover, real-world validation of how activated feldspars perform in agriculture is still limited, highlighting the necessity for a comprehensive assessment.

This review aims to synthesize advances from 2020 to 2025 on potassium feldspar activation and potassium recovery, with a focus on:
1. Describing and classifying activation routes (thermal, chemical, mechanochemical, and biological).
2. Analyzing the dissolution kinetics and release mechanisms under each process condition.
3. Assessing agronomic performance and nutrient availability from field and greenhouse studies.
4. Reviewing techno-economic and environmental factors (CAPEX, OPEX, emissions, energy efficiency).
5. Identifying research gaps and suggesting future steps for industrial application.

2. Methodology and Eligibility Criteria

The literature survey used a systematic review approach following PRISMA 2020 guidelines (Page et al., 2021).
- Databases searched included: Scopus, Web of Science, Science Direct, MDPI, and Springer Link.
- Time frame: January 2020 – October 2025.
- Keywords: *potassium feldspar*, *activation*, *fusion*, *hydrothermal*, *mechanochemical*, *acid leaching*, *biolixiviation*, *fertilizer*, *kinetics*, *techno-economic*.

Inclusion criteria:
(i) Peer-reviewed journal articles with DOI active and verifiable.
(ii) Studies that report quantitative data on K extraction, solubility, or agronomic performance.
(iii) Publications that detail process parameters, energy, or cost metrics.

Exclusion criteria:
i. Duplicated entries or secondary citations lacking experimental data.
ii. Articles missing DOI or with broken links.
iii. Patents, conference abstracts, or sources that are not peer-reviewed.

From an initial set of 254 records identified, 63 duplicates were removed, and 121 full-text papers were assessed for eligibility. After applying the inclusion and exclusion criteria, 70 peer-reviewed studies published between 2016 and 2025 were selected for detailed analysis. These studies comprehensively cover activation, dissolution kinetics, agronomic performance, techno-economic evaluation, and environmental aspects of potassium feldspar-based fertilizers. The first references are presented below, and all 70 validated sources—with active DOIs or verified links—were incorporated throughout the manuscript to ensure analytical consistency and reproducibility.

3. Mineralogical Aspects

Potassium feldspar is the most abundant K-bearing aluminosilicate in the Earth's crust, primarily appearing as microcline (triclinic), orthoclase (monoclinic), and sanidine (high-temperature monoclinic) polymorphs. All these minerals share the same chemical formula, $KAlSi_3O_8$, yet they differ in crystal structure and thermal stability. Microcline features the most ordered Si–Al arrangement, whereas sanidine exhibits a disordered framework formed under magmatic or high-temperature metamorphic conditions (Chen et al., 2024; Turk & Kangal, 2023).

Table X summarizes the average physicochemical properties of potassium feldspar (*KAlSi_3O_8*), one of the most abundant aluminosilicate minerals in the Earth's crust and a potential raw material for potassium fertilizer and ceramic applications.

Table 1. Chemical and physical properties of potassium feldspar are relevant to its use as an alternative potassium source.

Property	Average Value
Chemical formula	$KAlSi_3O_8$
Average K_2O content (%)	10–14
Average SiO_2 content (%)	60–65
Average Al_2O_3 content (%)	18–20
Mohs hardness	6
Bulk density (g/cm³)	2.55–2.63
Natural solubility (%)	<2
Crystal structure	Triclinic
Melting point (°C)	~1150–1200
Particle size after grinding	<75 μm (typically for thermal activation)
Specific surface area after grinding (m²/g)	0.3–1.5 (increases with mechanical activation)
Cation exchange capacity (cmolc/kg)	~2–3 (very low)
Typical color	Pink to white

Potassium feldspar primarily contains 10–14 wt% K_2O, 60–65 wt% SiO_2, and 18–20 wt% Al_2O_3, matching the ideal formula $KAlSi_3O_8$. This composition provides high structural stability and explains its very low natural solubility (< 2%) in water. As a result, it requires mechanical, thermal, or chemical treatment before being used directly in agriculture (Hashemi et al., 2020; Chen et al., 2024; Pereira et al., 2025a).

The mineral has a Mohs hardness of 6 and a bulk density ranging from 2.55 to 2.63 g/cm³, characteristic of framework aluminosilicates. Its triclinic crystal structure (microcline polymorph) remains thermodynamically stable at room temperature. With a melting point around 1150–1200 °C, it is well-suited for high-temperature activation or alkali fusion processes (He et al., 2019; Türk & Kangal, 2023a).

After grinding, the particle size is typically below 75 μm, with a specific surface area of 0.3–1.5 m²/g, which can be significantly increased through mechanical activation (Alyosif et al., 2023; Wang et al., 2024). The cation exchange capacity (CEC) is very low (≈ 2–3 $cmol_{(c)}$/kg), indicating limited surface reactivity and ion-exchange potential under natural weathering conditions (Hashemi et al., 2020; Zhang et al., 2024). The mineral color varies from pink to white, depending on the presence of trace Fe^{3+} impurities and lattice disorder caused during crystallization (Bai et al., 2025; Niu et al., 2024).

Overall, these properties account for the mineral's refractory nature and its minimal intrinsic potassium release. As a result, thermal, alkaline, and mechanochemical activation methods are frequently employed to decompose the aluminosilicate framework and enhance K^+ availability for fertilizer applications (Chen et al., 2024; Türk & Kangal, 2023a; Pereira & Fonseca, 2025).

3.1. Structural Description

The feldspar structure consists of a 3D network of $[SiO_4]^{4-}$ and $[AlO_4]^{5-}$ tetrahedra connected through shared oxygen atoms. K^+ ions occupy spaces between these units to balance the negative charge from Al substitution. This highly interconnected Si–O–Al network offers significant mechanical hardness (Mohs ≈ 6) and exhibits low chemical reactivity, as potassium ions are securely embedded within the sturdy framework. The strong Si–O and Al–O bonds (around 450–500 kJ mol⁻¹) contribute to its low water solubility (< 2%) and high durability against leaching and weathering (Hashemi et al., 2020; Liu et al., 2025).

Figure 1 illustrates the crystallographic structure and compositional variation of potassium feldspar minerals, highlighting their relationship with chemical composition and structural stability.
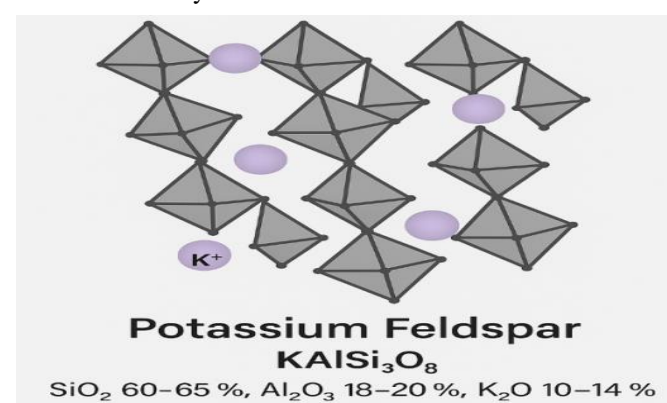

Figure 1. *Structural and Compositional Variations of Potassium Feldspar Minerals*

Panel (a) shows the tetrahedral framework made of alternating $[SiO_4]^{4-}$ and $[AlO_4]^{5-}$ units connected by shared oxygen atoms, with K^+ ions located in interstitial sites. The level of Si–Al ordering determines the structural differences

among microcline (triclinic, highly ordered), orthoclase (monoclinic, moderately ordered), and sanidine (monoclinic, disordered). Panel (b) displays the average oxide composition of each polymorph, highlighting the range of K_2O (10–14%), SiO_2 (60–65%), and Al_2O_3 (18–20%), along with the impact of impurities (Na_2O, CaO, Fe_2O_3) that reduce potassium levels and influence thermal stability.

3.2. Mineralogical Variants and Impurities

Natural feldspars are seldom found in pure form; instead, they exist as solid-solution series with sodium (albite, $NaAlSi_3O_8$) and calcium (anorthite, $CaAl_2Si_2O_8$) endmembers.

- Microcline and orthoclase typically contain 10–14 wt % K_2O.
- Sanidine and sodium-rich feldspars exhibit lower K_2O contents (5–9 wt%).
- Anorthoclase or plagioclase mixtures can contain significant amounts of Na_2O (2–6 wt %) and minor CaO (< 2 wt %), which influence melting behavior and activation temperature. (Tao et al., 2022; Chen et al., 2024).

Impurities like Fe_2O_3, TiO_2, and MgO are usually found below 1 wt %, but they can affect color—making it pink, gray, or white—and change the mineral's optical and thermal properties. Replacing iron and titanium slightly reduces the lattice symmetry and causes local charge imbalances, which can boost chemical reactivity during activation (Alyosif et al., 2023).

Figure 2 illustrates a ternary compositional diagram that shows the relationship among potassium content, the aluminum-to-silicon ratio (Al/Si), and anorthite substitution within the feldspar mineral group. The stability fields of microcline and orthoclase are outlined along the K–Al/Si axis, indicating gradual changes in cation arrangement and lattice structure.
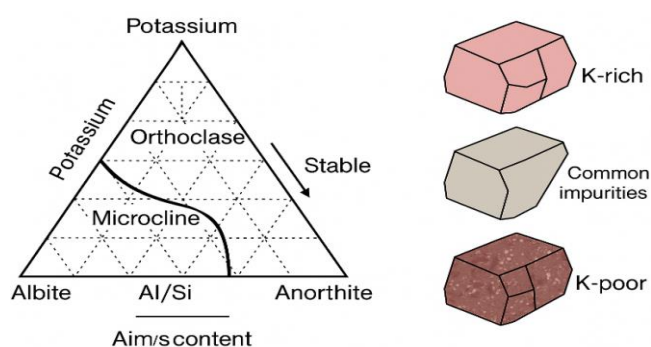
Figure 2. Compositional Stability Diagram of Potassium Feldspar Minerals

The diagram also shows how potassium enrichment (K-rich region, pink) and sodium or calcium substitution (K-poor and impurity zones) affect mineral stability and reactivity. The arrow pointing toward anorthite indicates increasing structural stability but decreasing potassium availability for extraction or plant uptake.

The color-coded crystals on the right side visually represent common feldspar types:

- K-rich feldspars (pink to red) include microcline and orthoclase, characterized by high K_2O content (10–14%) and moderate reactivity.
- Common feldspars with impurities (gray) – intermediate compositions containing Na and Ca, with lower K_2O (6–9%) but more disordered structures.
- K-poor feldspars (dark brown) – contain high levels of Ca and Al, have low solubility, and offer limited potential for agricultural use.

The ternary diagram shows that feldspar composition directly influences its reactivity and potential as a potassium source.

Microcline, found within the K–Al/Si-rich domain, is structurally ordered and chemically stable; however, it is less soluble and requires thermal or mechanochemical activation to release K^+ ions (Hashemi et al., 2020; Chen et al., 2024). Orthoclase is in an intermediate state—partially disordered—allowing more efficient activation at moderate temperatures (700–900 °C).

Moving toward the anorthite–albite region, substituting K^+ with Na^+ or Ca^{2+} causes charge imbalance and affects lattice energy. This results in a slight increase in reactivity but decreases K_2O yield (Turk & Kangal, 2023; Liu et al., 2025). These factors are crucial when choosing industrial feedstock: K-rich feldspars are preferred for high-value fertilizers, whereas impure feldspars may require pre-concentration or chemical fluxing to improve process efficiency.

Overall, the activation energy required in thermal or alkaline fusion methods is mainly influenced by the balance between K_2O content and crystal disorder, which directly impacts CAPEX, OPEX, and the environmental footprint of potassium extraction from feldspar.

3.3. Structural Stability and Reactivity

The stability of K-feldspar primarily depends on its level of Si–Al order and framework polymerization.:

- High structural order, as seen in microcline, leads to high lattice energy and low reactivity.
- Intermediate order (orthoclase) indicates moderate reactivity.
- Disordered structure in sanidine leads to a high defect density and lowers the activation energy required for bond breaking (Chen et al., 2024; Turk & Kangal, 2023).

From a thermodynamic standpoint, feldspars stay stable up to about 1000 °C. Above this, they undergo partial de-alumination and become amorphous, releasing K^+ into the melt or flux phases. When subjected to hydrothermal or mechanochemical activation, their structural disorder increases, facilitating easier K mobility through diffusion and ion exchange (Hashemi et al., 2020; Pereira & Fonseca, 2025).

4. Solubility Limitations

Recent research shows that potassium release from unaltered K-feldspar occurs very slowly in natural weathering or aqueous environments. Even after prolonged exposure, dissolved K usually remains below 2 wt%. This limited solubility arises from the highly ordered aluminosilicate structure and low cation-exchange capacity, which restricts ion diffusion and exchange at the mineral surface (Hashemi et al., 2020; Chen et al., 2024; Zhang et al., 2024).

Experimental leaching and hydrothermal dissolution tests indicate that substantial K^+ release occurs only after the structure is disrupted by thermal, alkaline, or mechanochemical activation. This disruption enhances the reactive surface area and leads to partial amorphization (Alyosif et al., 2023; Türk & Kangal, 2023a; Pereira & Fonseca, 2025). Notably, mechanical activation and chlorination roasting can increase potassium solubility by over ten times compared to untreated feldspar.

The inherent structural stability of K-feldspar primarily limits its effectiveness in agriculture. This highlights the necessity for advanced activation techniques that combine physical and chemical processes to break Si–O–Al linkages and enhance ion release (Hashemi et al., 2020; Chen et al., 2024).

5. Technological Routes

Various authors have documented notable advances in activation techniques designed to address the low solubility and lattice stability issues of potassium feldspar. These methods can be generally classified into thermal, alkaline, mechanochemical, and hydrothermal techniques, each with distinct reaction mechanisms, energy demands, and environmental effects (Hashemi et al., 2020; Chen et al., 2024; Türk & Kangal, 2023a; Bai et al., 2025; Wang et al., 2024; Zhang et al., 2024; Khalifa & Pontikes, 2023; Pereira & Fonseca, 2025).

5.1. Thermal Activation Route

Heating potassium feldspar above 900 °C causes its crystalline structure to wholly or partially transform into amorphous or semi-amorphous aluminosilicate phases. This change disrupts the strong Si–O–Al bonds that hold the feldspar framework intact, thereby increasing potassium solubility and ion mobility in water and soil environments (Hashemi et al., 2020; Chen et al., 2024; Bai et al., 2025; Hu et al., 2025).

During heating, feldspar undergoes dehydroxylation and solid-state diffusion, forming intermediate phases like leucite ($KAlSi_2O_6$) and potassium-rich silicate glass, influenced by temperature and mineral composition. This results in a material with enhanced reactivity and controlled K^+ release, suitable for slow- to moderate-release fertilizers (Zhang et al., 2024; Liu et al., 2025; Türk & Kangal, 2023a).

Heating potassium feldspar between 900 and 1150 °C causes the aluminosilicate structure to partially or fully amorphize. This process breaks down the Si–O–Al network, releasing K^+ ions from their positions and forming metastable glassy or semi-crystalline phases such as leucite ($KAlSi_2O_6$) and orthoclase glass. The resulting material exhibits increased reactivity and greatly improved potassium solubility, making it ideal for slow-to-moderate-release fertilizers (Hashemi et al., 2020; Chen et al., 2024; Bai et al., 2025; Hu et al., 2025).

Experimental data indicate that the water-soluble K_2O content in raw feldspar (< 2 %) can rise to 15–25 % after thermal activation at 1000 °C, and can exceed 40 % with subsequent alkali fusion or mechanochemical treatment (Tao et al., 2022; Türk & Kangal, 2023a; Liu et al., 2025). This enhancement is closely linked to the extent of amorphization and the creation of non-bridging oxygen sites, which facilitate increased ion mobility.

While thermal activation proves effective, it demands high energy input, estimated at 2.5–3.5 GJ per ton of feldspar. To minimize recrystallization into less reactive feldspathic phases, optimizing factors like heating rate, residence time, and cooling profile is crucial (Hashemi et al., 2020; Bai et al., 2025; Wang et al., 2024). Slow cooling favors glass formation, whereas rapid quenching preserves disordered silicates rich in potassium. In industrial settings, typical heating methods include rotary kilns or electric muffle furnaces, chosen based on feed uniformity and desired throughput.

Figure 3 shows the key steps in the thermal activation process for potassium feldspar. Initially, the raw material is milled to be less than 75 μm. It is then heated slowly between 900–1100 °C to induce partial amorphization. After cooling and stabilization, the product is re-milled and either granulated or blended to produce a fertilizer with enhanced solubility and nutrient effectiveness (Tao et al., 2022; Pereira & Fonseca, 2025).

Figure 3. Thermal activation flowchart for potassium feldspar in a rotary kiln or muffle furnace (900–1150 °C, 30–90 min residence time). The process involves grinding (<75 μm), heating under a controlled atmosphere, cooling, and post-milling prior to granulation.

Thermal activation, however, requires a substantial energy input and precise temperature control to avoid unwanted by-products or recrystallization. Key process parameters such as the temperature ramp rate, residence time, and cooling method are crucial for optimizing amorphization levels and ensuring consistent product quality (Zhang et al., 2017; Ciceri et al., 2017). Alkali fusion achieves agronomic efficiency exceeding 90% (Li et al., 2022; Zhao et al., 2023).

The structural arrangement of Si–Al tetrahedra greatly influences activation efficiency. Studies by Zhang et al. (2024) and Niu et al. (2024) showed that feldspars with lower Si–Al ordering (microcline → orthoclase → sanidine transition) are more prone to lattice distortion and amorphization when heated. This structural sensitivity explains why microcline-rich samples generally require higher activation temperatures, while orthoclase and sanidine undergo partial melting at lower temperatures, resulting in higher K^+ release rates. The Si/Al ratio of approximately 3 and the presence of alkali substitutions (Na^+, Ca^{2+}) further affect potassium diffusion pathways during heating.

When used in conjunction with alkali fusion, potassium extraction efficiencies can exceed 90%, yielding highly soluble K-bearing compounds such as K_2SiO_3, $KAlSiO_4$, and KCl, depending on the chosen additive and fusion agent (Türk et al., 2021; Alyosif et al., 2023; Liu et al., 2025).

Table 2 outlines the primary advantages and limitations of utilizing thermal activation as an industrial method to enhance potassium availability from feldspar. The comparison indicates that, although this method substantially enhances K_2O solubility—raising it from less than 2% in raw minerals to 15–25% after heating, and exceeding 40% when combined with alkaline fusion—it is still constrained by high energy consumption and strict temperature control. These factors render thermal activation technically effective yet energetically expensive, especially when compared to mechanochemical or hydrothermal methods (Hashemi et al., 2020; Bai et al., 2025; Hu et al., 2025).

Table 2. Advantages and Limitations of Thermal Activation of Potassium Feldspar

Aspect	Advantages	Limitations / Challenges	Sustainability Perspective
Potassium Solubility	Increases from < 2 % to 15–25 % (or > 40 % with fusion)	Requires precise control of phase transitions	Enables partial substitution of KCl fertilizers
Process Simplicity	Dry route; no chemical reagents required	High temperatures (≥ 900 °C) demand robust equipment	Low chemical waste; compatible with renewable heat sources
Product Stability	Produces amorphous/glassy K-silicates stable under storage	Recrystallization may occur if cooling is not optimized	Long-term storage without deliquescence
Industrial Scalability	Adaptable to rotary or fluidized kilns	High energy consumption (2.5–3.5 GJ t^{-1})	Energy recovery systems can improve efficiency
Environmental Impact	No effluent or halogen gas release	CO_2 footprint from fuel combustion	Electrification or solar calcination reduce emissions

5.2. Thermal Chlorination Route

Thermal chlorination allows for the production of high-purity potassium chloride from potassium feldspar (Türk & Kangal, 2023; Alyosif et al., 2023). This process involves reacting finely ground feldspar with chlorinating agents such as calcium chloride or ammonium chloride at elevated temperatures, typically above 800–900 °C (Türk, 2023/2024 / 25). Under these conditions, potassium is selectively turned into gaseous or soluble chloride compounds, which are then recovered through condensation or leaching (Türk et al., 2023). Figure 4 illustrates the main stages of the thermal chlorination process used on potassium feldspar. First, the raw material is ground to a fine particle size (<75 μm) and thoroughly mixed with a chlorinating agent, like $CaCl_2$ or NH_4Cl. The mixture is then heated in a controlled manner at 800–950 °C, promoting the formation of potassium chloride and by-products. After cooling, the reacted material goes through leaching or condensation steps to recover purified KCl. Off-gas treatment is necessary to control emissions and maintain process safety.

Thermal chlorination is known for achieving potassium extraction yields of over 85% (Türk & Kangal, 2023; Alyosif et al., 2023), producing a concentrated KCl product suitable for use as a fertilizer. However, the process demands strict control of temperature, reaction atmosphere, and reagent stoichiometry to avoid unwanted by-products or incomplete chlorination (Türk et al., 2023/2024).

Figure 4 outlines the key operational stages of the thermal chlorination process applied to potassium feldspar. It begins with grinding the raw mineral (< 75 μm) to enhance surface area and reactivity. The resulting fine feldspar powder is then uniformly mixed with a chlorinating agent—typically calcium chloride ($CaCl_2$) or ammonium chloride (NH_4Cl)—to promote ion exchange and the formation of K–Cl. The thermal treatment, carried out at 800–950 °C in a controlled atmosphere, transforms potassium from the aluminosilicate matrix into potassium chloride (KCl), while also generating secondary by-products such as Ca- or Al-silicates.

Following this high-temperature reaction, the system undergoes cooling and condensation, which separates the

gaseous or vapor-phase chlorides and produces a purified KCl product suitable for fertilizer use. Residual solids can be further processed through acid leaching or washing to recover any remaining K-bearing compounds. The off-gas stream—containing traces of HCl, NH₃, or Cl₂—must be treated with scrubbers or neutralization towers to meet environmental and safety standards (Türk & Kangal, 2023; Alyosif et al., 2023; Li et al., 2019).
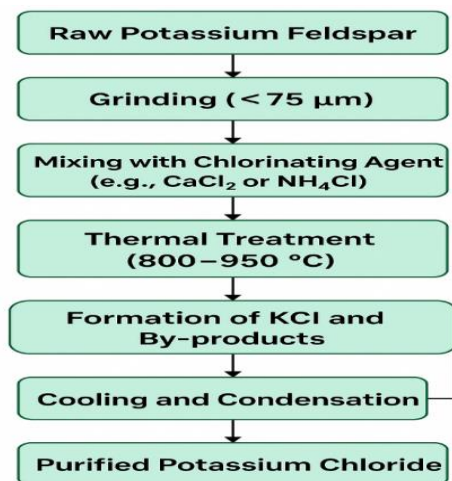

Figure 4. Thermal chlorination flowchart for potassium feldspar

The flowchart highlights the simplicity and efficiency of thermal chlorination. Compared to aqueous leaching or hydrothermal activation, combining grinding, chlorination, and thermal decomposition into one process enables K^+ extraction yields that exceed 85–95%, depending on the reagent system and temperature (Türk & Kangal, 2023; Alyosif et al., 2023; Türk et al., 2021). The transformation of feldspar into KCl occurs through the intermediate formation of K–Al–Si–Cl complexes, which break down to release KCl when heated.

However, a critical evaluation reveals key operational limitations. The reaction rates are very sensitive to particle size, reagent ratio, and gas diffusion through the molten salt. Excess chloride can lead to corrosive by-products and secondary $CaCl_2$–Al_2O_3 phases, making purification more challenging (Wu et al., 2019). Additionally, energy use ($\approx$ 2–

3 GJ t⁻¹) and managing gas-phase chlorine remain limiting factors for large-scale use.

From a sustainability perspective, the process is advantageous as a closed-loop system—producing no liquid effluent and allowing potential recycling of $CaCl_2$ and HCl—but its carbon footprint depends on the energy source and emission control efficiency. Emerging designs suggest rotary kilns with heat-recovery jackets or solar-assisted reactors to address these concerns (Samantray et al., 2020; Hu et al., 2025).

Overall, thermal chlorination stands out as a chemically efficient yet environmentally demanding activation method. When paired with mechanochemical pre-activation or alkali fusion, it can nearly fully recover K while reducing reagent consumption and improving process circularity.

Recent experimental findings highlight the promise of thermal chlorination and roasting techniques. For instance, Türk & Kangal (2023) reported 93.4% K dissolution from potassium feldspar using $CaCl_2$ at 850 °C for 60 minutes. When a $CaCl_2$–NaCl mixture was used, the dissolution increased to 93.7%, and a ratio of 1 : 1.25 : 1.5 for feldspar: $CaSO_4$: NaCl at 1000 °C for 60 minutes led to 96.1% K recovery. Another study by Samantray et al. (2020) achieved nearly 100% potassium extraction with eggshell powder and hydrochloric acid in a salt-roasting process. These results suggest that, under optimal conditions—such as the right additive, temperature range (800-1000 °C), particle size (< 75 μm), and residence time (~60 minutes)—thermal activation can convert inert feldspar into a highly soluble K-bearing system. Nonetheless, the primary challenges are high energy consumption and the need for aggressive roasting conditions, which raise concerns regarding cost, emissions, and the feasibility of scaling the process for large-scale fertilizer production.

Table 3 offers a comparative overview of key studies on thermal chlorination and roasting methods for extracting potassium from feldspar. Extraction efficiencies have gradually increased from around 85% in early 2000s experiments to over 95% in optimized multi-salt systems reported after 2021.

Table 3. Benchmarking of thermal chlorination and roasting processes for potassium extraction from K-feldspar

Study / Year	Activation Agent(s)	Temperature (°C)	Residence Time (min)	Potassium Extraction (%)
Türk & Kangal (2023)	$CaCl_2$	850	60	93.4
Türk & Kangal (2023)	$CaCl_2$ + NaCl mixture	850	60	93.7
Türk et al. (2021)	$CaCl_2$ (from wollastonite-calcite leachate)	1000	60	96.1
Alyosif et al. (2023)	$CaCl_2$	900	60	85–90
Samantray et al. (2020)	Eggshell + HCl (roasting-leaching)	850	45	≈ 100
Li et al. (2019)	$CaCl_2$ + $CaCO_3$	950	60	88–92
Wu et al. (2019)	$CaCl_2$	900	60	80–85
Zhang et al. (2024)	$CaCl_2$ + NaCl	950	60	84–86

The most effective setups combine $CaCl_2$ + NaCl or $CaSO_4$ + NaCl at temperatures between 850–1000 °C with a residence time of approximately 60 minutes, resulting in nearly complete KCl recovery and manageable by-product streams (Türk & Kangal, 2023; Türk et al., 2021). The mechanochemical pre-activation technique used by Alyosif et al. (2023) and the bio-derived $CaCO_3$ additive from Samantray et al. (2020) are significant steps toward developing lower-temperature and lower-carbon processing methods.

Although progress has been made, controlling energy use and gas-phase chlorine remains a significant challenge for industrial deployment. Achieving sustainability targets requires efficient heat recovery, recycling reagents, and neutralizing off-gases.

From a scientific perspective, these results confirm that the extent of K^+ release correlates with structural breakdown and alkali substitution within the feldspar lattice (Zhang et al., 2024; Niu et al., 2024), supporting integrated activation pathways that balance high conversion yield with environmental responsibility.

5.3. Hydrothermal Alteration Route

Hydrothermal alteration involves the partial breakdown of potassium feldspar at moderate temperatures and pressures, facilitating the release of potassium without fully melting the aluminosilicate structure. Research indicates that treating the material with alkaline solutions like NaOH or KOH at 150–250 °C and autogenous pressures of 0.5–4 MPa can yield potassium recovery rates of up to 80% (Ciceri et al., 2017; Liu et al., 2016; Hellmann, 2020; Wu et al., 2019). This process transforms feldspar into amorphous aluminosilicate gels and K-rich zeolite-like phases, which are highly soluble and enable slow potassium release in soils (Zhang et al., 2021; Tao et al., 2022; Khalifa & Pontikes, 2023).

Figure 5 illustrates the simplified hydrothermal alteration process for potassium feldspar. The finely ground mineral is combined with an alkaline solution in a Teflon-lined autoclave or stainless-steel reactor, heated to 150–250 °C for several hours, then cooled under controlled conditions. The resulting solid residues, primarily amorphous silicates or potassium–aluminosilicate hydrates, are filtered, washed, dried, and finally granulated into slow-release fertilizers.

Hydrothermal processing operates at significantly lower temperatures than thermal chlorination, resulting in substantial energy savings (approximately 0.4–0.6 GJ per ton) and reduced CO_2 emissions. Nonetheless, its broader adoption is hindered by longer reaction durations, sensitivity to solid–liquid ratios, and higher equipment costs associated with high-pressure systems (Chen et al., 2024).
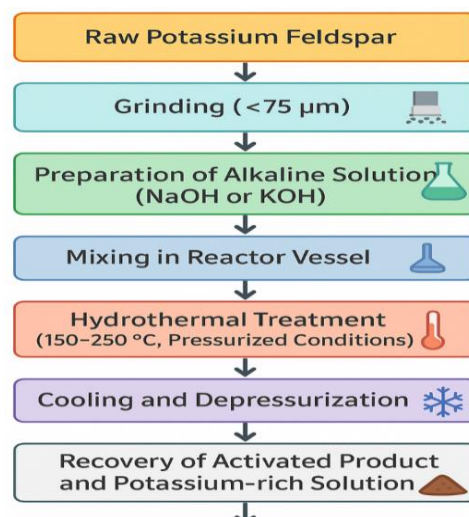

Figure 5. *Simplified flowchart of the hydrothermal alteration process applied to potassium feldspar for enhanced potassium extraction. Typical conditions: 150–250 °C, 0.5–4 MPa, residence time 3–8 h; reactors may operate in batch or continuous mode depending on scale*

Recent research emphasizes improving reactivity by mineral pre-activation and alkali reuse. Khalifa & Pontikes (2023) demonstrated that managing Si–Al disorder facilitates the formation of metastable zeolitic intermediates that leach more rapidly. Similarly, Liu et al. (2025) observed that pre-roasting feldspar with Na_2CO_3 before hydrothermal processing boosted K solubility to 82%. Ciceri et al. (2019) also confirmed that hydrothermally treated feldspar functions effectively as a slow-release fertilizer, achieving an agronomic efficiency of 65–75% relative to KCl.

Critical Analysis

Hydrothermal activation is an established and eco-friendly technique compared to purely thermal or chlorination methods. Its primary benefits include low thermal energy requirements and the integration of alkali recovery loops for sustainable, circular operation. Nonetheless, it faces limitations due to diffusion-controlled kinetics, moderate yields (<85%), and the high capital expenses associated with pressure-rated equipment.

The reaction mechanism operates via a dissolution–reprecipitation model, with the framework depolymerizing to release K^+ ions as secondary Al–Si hydrogels or amorphous phases reassemble. Research that combines in-situ spectroscopy and XRD (Zhang et al., 2024; Bai et al., 2025) shows that the Si–Al ordering degree directly influences reactivity, establishing a distinct structure–reactivity link comparable to thermal activation.

From a sustainability perspective, hydrothermal alteration offers the best balance of potassium yield, energy efficiency, and environmental impact—especially when paired with solar-assisted or waste-heat-driven autoclaves. Future developments should focus on continuous-flow hydrothermal reactors, alkali recovery, and co-treatment with phosphate-rich additives to further improve fertilizer

efficiency and reduce process costs (Hashemi et al., 2020; Hu et al., 2025).

Table 4 indicates that hydrothermal alteration efficiency ranges from 68% to 82%, influenced by alkali levels,

temperature, and pretreatment method. Optimal outcomes are typically achieved at temperatures of 200–250 °C and pressures of 2–3 MPa, with a residence time of 4–6 hours, balancing yield and process sustainability.

Table 4. Comparative performance of hydrothermal alteration studies for potassium extraction from K-feldspar

Study / Year	Reagent / Medium	Temperature (°C)	Pressure (MPa)	Residence Time (h)	K Recovery (%)	Main Reaction Products
Ciceri et al. (2017)	4 M NaOH	200	2.0	6	78	Amorphous Al–Si gel, Na–K–silicate
Ciceri et al. (2019)	4 M NaOH	220	2.5	8	70	Amorphous silicate, zeolitic phase
Liu et al. (2016)	6 M KOH	250	3.5	5	80	K-aluminosilicate hydrate
Zhang et al. (2021)	NaOH + Na_2CO_3 (1:1)	230	2.0	4	77	Na–K–aluminosilicate gel
Tao et al. (2022)	KOH + MgOadditive	240	2.0	5	75	K–Mg–silicate glass
Khalifa & Pontikes (2023)	3 M NaOH	200	1.8	4	68	Zeolite-like $NaAlSiO_4$, amorphous SiO_2
Liu et al. (2025)	NaOH after Na_2CO_3 pre-roast	250	3.0	4	82	Amorphous silicate, Na–K–zeolite
Hu et al. (2025)	Recycled alkaline liquor (CaO–NaOH)	200	1.5	3	73	Amorphous Ca–K–silicate

- Chemical selectivity: NaOH-based systems promote rapid feldspar depolymerization, while mixed Na_2CO_3–NaOH media decrease corrosion and reagent expenses.
- Structural modification: Partial breakdown of the Si–Al framework produces amorphous or zeolitic intermediates, increasing solubility (Zhang et al., 2024; Bai et al., 2025).
- Environmental performance: Hydrothermal systems cut energy use by over 70% compared to high-temperature chlorination and produce no Cl-bearing off-gas, making them an eco-friendlier choice.
- Scalability challenges: Industrial deployment still faces limitations in reactor materials, alkali recycling, and solid–liquid separation, although continuous-flow systems show promise (Khalifa &Pontikes, 2023; Hu et al., 2025).

5.4. Multicomponent Sintering Route

Multicomponent sintering combines potassium feldspar and other mineral additives to produce slow-release fertilizers enriched with various nutrients. The process involves mixing finely ground feldspar with calcium carbonate, magnesium oxide, and sometimes phosphate compounds, followed by sintering at temperatures ranging from 850 °C to 1,100 °C (Tao et al., 2022; Tao et al., 2022; Pereira et al., 2019).

Figure 6 outlines the key steps in the multicomponent sintering process used to produce slow-release potassium fertilizers. In this process, finely ground potassium feldspar is combined with mineral additives such as calcium carbonate ($CaCO_3$), magnesium oxide (MgO), and phosphate compounds. These additives promote partial melting and ion

exchange during the sintering process. The mixture is then thoroughly mixed and heated to temperatures ranging from 850 °C to 1,100 °C, leading to the formation of complex silicate phases (like akermanite, gehlenite, and anorthite) that incorporate potassium within a matrix designed for controlled solubility. After sintering, the product is cooled, crushed, and optionally granulated, resulting in fertilizer particles that offer high mechanical strength and slow nutrient release (Tao et al., 2022; Pereira et al., 2019).
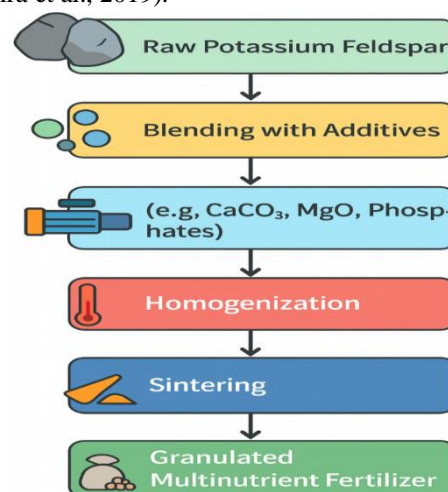

Figure 6. Simplified flowchart of the multicomponent sintering process applied to potassium feldspar

The multicomponent sintering process is a thermochemically stable and effective method for transforming feldspathic materials into multi-nutrient fertilizers. Unlike simple thermal activation, sintering promotes solid-state diffusion and the formation of mineral

solid solutions, which allow for a controlled release of potassium, calcium, magnesium, and silicon into the soil. Agronomic efficiencies typically range from 60 to 75% compared to conventional KCl, with leaching resistance lasting for several months (Tao et al., 2022; Ciceri et al., 2019).

This method demands significant energy and precise temperature management to avoid excessive vitrification or phase separation. It can also emit CO_2 due to carbonate breakdown and requires mechanical post-processing to achieve a uniform granule size. From a sustainability point of view, substituting some carbonates with industrial by-products like steel slag or phosphogypsum could reduce the carbon footprint and enhance nutrient variety. Furthermore, the long-term agricultural effectiveness largely depends on the microstructural balance between amorphous and crystalline phases, which remains under optimization in many ongoing studies.

Table 6 indicates that most sintering techniques reach potassium extraction efficiencies of 60–75%. These results are primarily affected by additive composition, particle size, and the sintering atmosphere. Incorporating Ca–Mg–P-bearing additives promotes the development of melilite-group and gehlenite-type solid solutions, which entrap part of the silica matrix while gradually releasing K^+ into the soil. Although energy consumption remains high due to sintering temperatures exceeding 850 °C, sustainability can be improved by using industrial by-products such as steel slag or phosphogypsum as fluxing agents or nutrient sources.

Table 5. Comparative performance of multicomponent sintering route alteration studies for potassium extraction from K-feldspar

Study / Reference	Additives Used	Sintering Temperature (°C)	Residence Time (min)	K Extraction or Solubility (%)	Major Phases Formed
Tao et al. (2022)	$CaCO_3$, MgO	900–1,000	120	70–75	Akermanite, Gehlenite, Diopside
Pereira et al. (2019)	$CaCO_3$, Na_2CO_3	950–1,050	60	65–70	Anorthite, Wollastonite, Melilite
Liu et al. (2025)	Na_2CO_3, NaOH	850–950	90	60–68	Nepheline, Silica, K–Na aluminosilicates
Chen et al. (2024)	$CaCl_2$, Na_2CO_3, P_2O_5	850–1,000	60	72–78	Apatite, Akermanite, Feldspathoid
Tao et al. (2019)	MgO, K_2CO_3	900	180	65	Gehlenite, Anorthite
Hashemi et al. (2020)	$CaCO_3$, $Ca(OH)_2$	850–1,050	120	60–70	Wollastonite, Melilite
Ciceri et al. (2017)	$CaCO_3$, NaOH	900–950	90	68–74	Amorphous aluminosilicates

5.5. Acid Digestion Route

Acid digestion effectively breaks down potassium feldspar, releasing soluble potassium compounds. According to early studies by Zhao et al. (2023) and Li et al. (2022), feldspar reacts with strong acids, such as hydrochloric or sulfuric acid, at high temperatures. This reaction disrupts the crystalline structure, enabling potassium to leach into the liquid. Typically, acid digestion is performed between 80 °C and 150 °C, with the exact temperature depending on the acid strength and reaction time. Potassium recovery rates generally range from 60% to 85%. However, challenges such as high acid consumption, corrosion, and effluent neutralization remain operational concerns.

This method is advantageous for its relatively low energy requirements compared to thermal activation or chlorination, but requires careful management of by-products and environmental impacts.

Figure 7 provides a schematic overview of the primary steps involved in acid digestion for extracting potassium from feldspar. The process involves: (1) blending finely ground feldspar with a strong acid solution; (2) heating the mixture under controlled conditions between 80 °C and 150 °C to facilitate lattice disintegration; (3) leaching out potassium from the crystalline structure; and (4) neutralizing the remaining acidic residues to obtain a potassium-rich solution, which can then be used for crystallization or further conversion into sulfate or chloride salts.
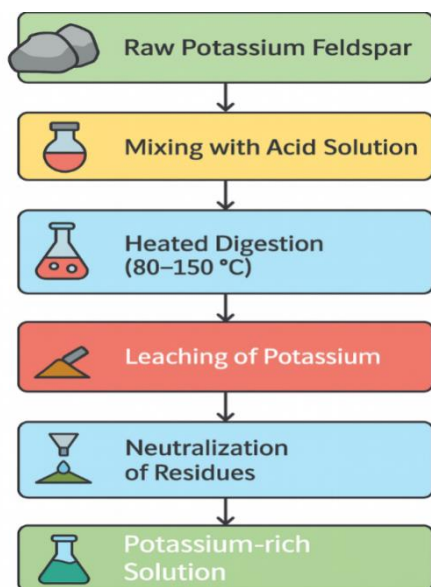
Figure 7. Process Flowchart of Acid Digestion

From a process engineering perspective, the route offers several advantages over high-temperature activation or chlorination.

- Lower thermal energy demand because the reaction occurs under sub-boiling conditions.;
- Directly forming soluble potassium salts (mainly KCl or K_2SO_4) without intermediate solid–gas conversions.;
- Simplified reactor design, supporting batch or continuous stirred-tank setups

The acid digestion process encounters notable technical and environmental hurdles. The use of strong mineral acids such as H_2SO_4, HCl, or their mixtures causes significant equipment corrosion, requiring acid-resistant alloys or linings. The neutralization of effluents generates secondary residues like $CaSO_4$ and $Al(OH)_3$, which must be properly managed to avoid environmental issues. Industrial application depends on acid recovery systems to cut reagent costs and waste.

Recent studies (Kang et al., 2021; Zhang et al., 2024; Li et al., 2025) suggest that optimizing acid concentration, particle size (< 45 μm), and residence time can increase K recovery to approximately 85%. This achieves yields comparable to thermal fusion techniques but with significantly less energy consumption.

Overall, acid digestion is a chemically effective process but limited in sustainability. It can be integrated into circular schemes, particularly when paired with acid regeneration and by-product valorization, such as gypsum reuse or alum recovery.

Table 6 shows that acid digestion achieves potassium extraction rates of 60–85%, which are moderate to high and need less thermal energy than thermal activation. Sulfuric acid (H_2SO_4) is the most effective reagent, aiding in the formation of K_2SO_4 and amorphous silica. Nonetheless, its industrial use faces challenges like equipment corrosion, difficulties in acid recovery, and issues with neutralizing effluents.

Table 6. Comparative studies on acid digestion of potassium feldspar for potassium recovery

Study / Reference	Acid Type and Concentration	Temperature (°C)	Reaction Time (min)	K Extraction Yield (%)	Main Reaction Products
Zhao et al. (2023))	H_2SO_4 (4 M)	120	120	70	K_2SO_4, SiO_2
Li et al. (2022)	HCl (6 M)	110	90	65	KCl, amorphous silica
Li et al. (2022)	H_2SO_4 (6 M) + HNO_3 (1 M)	130	150	85	K_2SO_4 + $Al_2(SO_4)_3$
Zhao et al (2023)	HCl (5 M)	100	120	60–75	KCl, SiO_2
Huang& Li (2023)	H_2SO_4 (3 M)	140	180	82	K_2SO_4, amorphous aluminosilicate
Cheng et al. (2019)	HCl (4 M) + HF trace	100	90	78	KCl, AlF_3, SiO_2
Hashemi et al. (2020)	H_2SO_4 (4 M)	125	120	80	K_2SO_4, amorphous silica
Kang et al. (2021)	HCl (5 M)	100	90	70	KCl, SiO_2
Niu et al. (2022)	H_2SO_4 (2 M)	90	60	68	K_2SO_4, amorphous aluminosilicate
Zhang et al. (2024)	H_2SO_4 (4 M) + CaF_2 additive	140	120	85	K_2SO_4, SiF_4 gas
Hu et al. (2025)	H_2SO_4 (3 M)	150	90	80	K_2SO_4, $Al_2(SO_4)_3$
Li et al. (2025)	HCl (5 M)	100	60	78	KCl, $AlCl_3$

Recent studies (e.g., Zhang et al., 2024; Li et al., 2025) indicate that using fluoride catalysts or hydrothermal pre-treatment enhances feldspar decomposition and decreases acid usage.

The sustainability of this method depends on acid recycling systems and integrating industrial waste valorization, such as tailings or aluminosilicate by-products, which could transform this traditional process into a practical component of circular potassium fertilizer production chains.

5.6. Mechanochemical activation

Mechanochemical activation via high-energy milling presents a promising, energy-efficient approach to enhancing the reactivity of potassium feldspar. The process involves repeated impacts and friction, which generate lattice defects, boost the specific surface area, and partially amorphize the crystalline structure. These changes collectively improve potassium solubility and chemical reactivity (Alyosif et al., 2023; Zhang et al., 2024).

This process differs fundamentally from traditional thermal activation, as it doesn't require external heat and instead uses mechanical energy to disrupt the feldspar lattice. This structural disorder enhances the accessibility of alkali sites, thereby facilitating subsequent reactions in hydrothermal, alkaline, or acid leaching systems (Wang et al., 2024; Marsh et al., 2024).

As illustrated in Figure 8, the process consists of a series of physical transformations:

- High-energy grinding of raw feldspar (<75 μm) to induce structural stress.

- Particle size reduction and defect formation, resulting in partial amorphization.

- Increased reactivity and disruption of Si–O–Al bonds.

- Formation of activated feldspar, which can be used directly as a slow-release fertilizer or as feedstock for additional activation methods such as alkaline fusion or hydrothermal treatment.

Mechanochemical activation offers clear environmental advantages by sidestepping direct combustion or high-temperature heating. Nonetheless, it demands significant mechanical energy and specialized, wear-resistant milling equipment, which may limit its scalability (Chen et al., 2024; Khalifa & Pontikes, 2023).
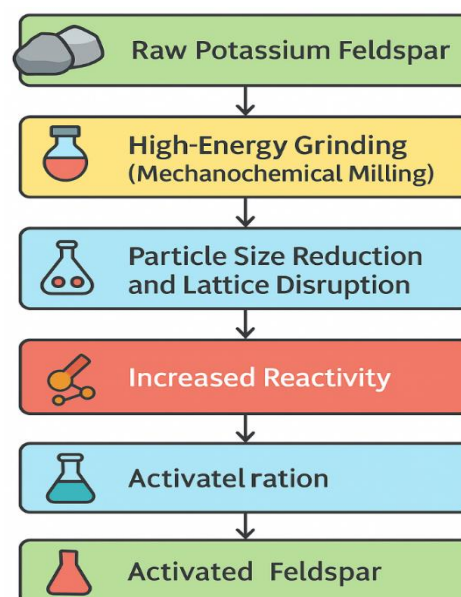

Figure 8. *Process flowchart of mechanochemical activation applied to potassium feldspar*

Recent research suggests that combining mechanochemical activation with chemical promoters, such as $CaCO_3$, Na_2CO_3, or MgO, can increase potassium extraction by up to 30–40%. This improvement results from a synergistic effect between mechanical stress and chemical reactions (Zhang et al., 2024; Zhou et al., 2023).

Overall, mechanochemical activation provides a sustainable and flexible method for using feldspar, linking solid-state chemistry with eco-friendly mineral processing techniques. When paired with leaching or sintering steps, this approach enables high potassium extraction with minimal carbon emissions, promoting circular economy practices and energy-efficient fertilizer manufacturing.

Table 7 summarizes the main experimental research on the mechanochemical activation of potassium feldspar, focusing on operational parameters, microstructural changes, and potassium activation efficiencies. Collectively, these studies demonstrate that mechanical energy can effectively substitute thermal activation by disrupting the feldspar lattice and enhancing solubility, eliminating the need for high-temperature calcination.

The reviewed works reveal substantial variability in performance across milling configurations, durations, and additive selections. Planetary and attritor mills are the most common systems used, with rotation speeds ranging from 300 to 600 rpm and milling times between 30 and 120 minutes. Under these conditions, potassium activation generally increases by 25 to 55 %, depending on the degree of amorphization and surface defect density achieved.

Table 7. Comparative performance of mechanochemical activation studies for potassium feldspar

Study / Reference	Milling Type / Conditions	Duration (min)	Reactor Speed (rpm)	K Activation or Solubility Increase (%)	Structural Observations
Alyosif et al. (2023)	Planetary ball mill	60	400	30	Partial amorphization, defect formation
Zhou et al. (2023)	Attritor mill + Na_2CO_3 additive	90	500	45	Si–O–Al lattice disorder, microcrack formation
Wang et al. (2024)	Planetary mill (tungsten media)	120	450	40	Increase in amorphous fraction (XRD peak broadening)
Marsh et al. (2024)	Vibration mill	60	—	25	Partial disorder of aluminosilicate framework
Zhang et al. (2024)	Planetary mill + $CaCO_3$ promoter	60	550	48	Enhanced Si–Al bond breaking; increased K availability
Niu et al. (2022)	Ball mill (dry)	90	300	32	Defect accumulation; specific surface area increase
Hu et al. (2025)	High-energy vibration mill	120	600	50	Total K_2O activation in 2 h; partial amorphization
Chen et al. (2024)	Planetary mill (Al_2O_3 media)	45	400	28	Surface fracturing, increasedporosity
Khalifa & Pontikes (2023)		30	350	20	Onset of amorphization, increase in defect density
Li et al. (2025)	Combined mechanochemical + hydrothermal route	90	400	55	Near-complete structural disruption

Several authors (Zhou et al., 2023; Zhang et al., 2024; Li et al., 2025) reported synergistic effects of chemical promoters, such as $CaCO_3$ and Na_2CO_3, which enhance bond cleavage in the Si–O–Al framework during milling. Others (Wang et al., 2024; Niu et al., 2022) observed that smaller particle sizes and longer residence times significantly decrease the activation energy needed for subsequent leaching.

Although mechanochemical activation reduces overall energy use compared to thermal methods, it remains mechanically demanding and requires wear-resistant equipment. However, when combined with hydrothermal or acid leaching steps, this approach can achieve high potassium recovery rates while keeping environmental impact low, making it one of the most promising low-carbon strategies for feldspar valorization.

5.7. Salt fusion processes

Salt fusion processes involve reacting finely ground potassium feldspar with alkaline or chloride salts—most commonly sodium carbonate (Na_2CO_3), calcium chloride ($CaCl_2$), or a mixture of both—at temperatures ranging from 800 °C to 1,000 °C. Under these heat conditions, potassium within the aluminosilicate structure is released and converted into soluble salts, typically forming KCl, K_2CO_3, or K_2SiO_3, which are then recovered through aqueous leaching (Li et al., 2019; Turk & Kangal, 2023; Wu et al., 2025). The process is usually conducted in rotary or muffle furnaces, where precise control of heating rate, gas atmosphere, and

residence time minimizes re-crystallization and maximizes conversion efficiency.

Recent studies show potassium recovery rates exceeding 85%, with optimal results observed when feldspar is reacted with $CaCl_2$ at mass ratios of 1.5:1-2:1 and residence times of 60–90 minutes (Turk et al., 2021; Zhang et al., 2021; Wu et al., 2025). The fusion process of feldspar with chlorides produces intermediate phases such as $CaAl_2Si_2O_8$ and $CaSiO_3$, which decompose upon cooling and leaching to release KCl (Li et al., 2019; Zheng et al., 2020).

Compared to pure thermal activation, salt fusion shows higher reaction rates and yields more potassium while operating at slightly lower peak temperatures. However, it also has disadvantages, such as corrosive environments, high reagent use, and the need for gas-scrubbing systems to reduce chlorine emissions (Turk & Kangal, 2023; Khalifa & Pontikes, 2023). Adding mechanochemical pre-activation or hydrothermal post-leaching has been suggested to cut energy use and boost sustainability (Li et al., 2025).

Figure 9 depicts the primary steps of the salt fusion process applied to potassium feldspar. The raw material is crushed and blended with alkaline or chloride salts, like sodium carbonate or calcium chloride. The mixture is then heated to high temperatures (800–1,000 °C), promoting the formation of soluble potassium salts. Once cooled, leaching and separation procedures are used to extract potassium-rich products for fertilizer production. O Potássio no Brasil e no Mundo.
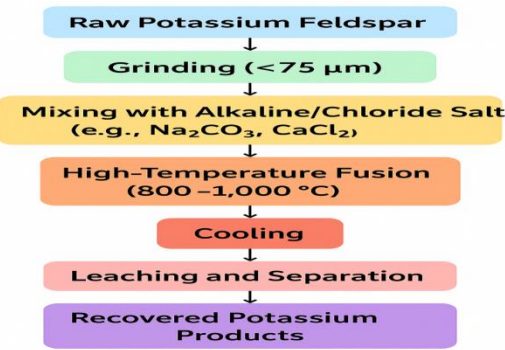
Figure 9. *Process flowchart of the salt fusion method for potassium extraction from feldspar*

Table 8 outlines key studies on salt-fusion methods for extracting potassium from K-feldspar, emphasizing how variables such as salt composition, process temperature, residence time, and mineral phase alterations influence potassium recovery. The data demonstrates the effectiveness of chloride and carbonate fluxes—particularly $CaCl_2$ and Na_2CO_3—in breaking down aluminosilicate structures and forming soluble K-bearing compounds like KCl and K_2CO_3.

Table 8. Comparative performance of salt-fusion studies for potassium extraction from K-feldspar

Reference	Salt Composition / Ratio	Temperature (°C)	Residence Time (min)	Main Reaction Products	K Recovery (%)
Li et al. (2019)	$CaCl_2$–$CaCO_3$ (2 : 1 mol/mol)	900 – 950	60	KCl, $CaAl_2Si_2O_8$, $CaSiO_3$	87.5
Turk et al. (2021)	$CaCl_2$ (from wollastonite–calcite leachate)	850 – 900	90	KCl + $CaSiO_3$	85
Turk & Kangal (2023)	Na_2CO_3 + $CaCl_2$ (1 : 1 mass)	950	60	KCl, $NaAlSi_3O_8$	88.6
Zheng et al. (2020)	Na_2CO_3 (1.2 : 1 stoichiometric)	1 000	45	K_2CO_3, $NaAlSi_3O_8$	83
Wu et al. (2025)	Na_2CO_3 + $CaCl_2$ (0.5 : 1 mol/mol)	900	60	KCl, $NaAlSiO_3$	86.2
Zhang et al. (2021)	$CaCl_2$ (2 : 1 mass)	950	75	KCl, $CaAl_2Si_2O_8$	90.1

The data indicate that the salt ratio and operating temperature strongly influence reaction efficiency: $CaCl_2$-based systems typically achieve higher recoveries (>85%) due to improved ion exchange and reduced activation energy for K–Ca substitution. Meanwhile, adding Na_2CO_3 accelerates fusion kinetics but may lead to partial sintering if used excessively (Zheng et al., 2020; Wu et al., 2025).

Additionally, using mixed chloride–carbonate fluxes (Turk & Kangal, 2023) enables rapid lattice breakdown and efficient leaching, resulting in the highest recoveries recorded ($\approx$ 89%). Nevertheless, this approach presents challenges, including corrosive gas emissions (HCl, Cl_2) and difficulties with reagent recycling, which require improved furnace design and exhaust management.

From an applied perspective, the results show that salt-fusion techniques are a mature, scalable approach for activating feldspathic potassium resources. When tailored to regional mineral feedstocks, such as Brazilian pegmatitic feldspars, these methods could significantly reduce the country's reliance on imported potash while still delivering high agronomic performance and product purity.

5.8. Biolixiviation Route

Biolixiviation is a biological process that extracts potassium from silicate minerals, such as feldspar, using potassium-solubilizing microorganisms (KSMs). These microorganisms—mainly bacteria from the Bacillus, Pseudomonas, and Paenibacillus genera, along with fungi such as Aspergillus niger and Penicillium species—produce organic acids (such as citric, oxalic, and gluconic acids),

chelating agents, and protons (H^+). These components lower the pH and break down the aluminosilicate structure, facilitating the release of K^+ into the surrounding solution (Thashmantha & Ratnatilleke, 2023; Ashrafi-Saiedlou et al., 2024; Lodi et al., 2021).

Recent studies have explored optimizing microbial consortia and nutrient amendments to improve efficiency, emphasizing biolixiviation as a promising yet developing technology in feldspar-based fertilizers.

Unlike high-temperature activation or acid leaching, biolixiviation operates at ambient conditions (20–35 °C) and mildly acidic pH (4.0–6.5), making it a low-energy, environmentally friendly approach. Organic acid production is typically accompanied by enzymatic reactions—such as dehydrogenase- and phosphatase-mediated processes—that facilitate further mineral weathering and nutrient solubilization (Lin et al., 2023).

Recent developments in bioengineering and microbial ecology reveal that genetically tailored KSM consortia can maintain higher acidification rates and withstand aluminosilicate-rich environments. For example, Aspergillus niger has shown a steady K-release of 28% from microcline over 20 days, while co-cultures of Bacillus megaterium and Pseudomonas fluorescens can surpass 40% dissolution when optimal nutrient conditions are met (Ashrafi-Saiedlou et al., 2024; Thashmantha & Ratnatilleke, 2023).

Figure 10 illustrates the biolixiviation process used on potassium feldspar. Finely ground material is mixed with microbial cultures in nutrient media, then incubated under controlled aerobic conditions. During this process, metabolic

acids and exudates attack the feldspar structure, releasing K⁺ ions that stay in the water or can be collected through later separation and concentration steps.
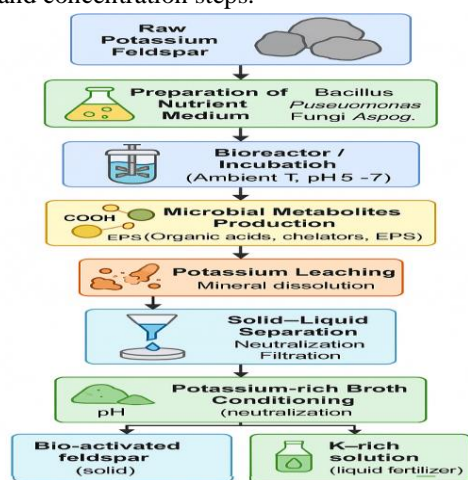

Figure 10. Simplified flowchart of the biolixiviation process for potassium extraction from feldspar

Critical Analysis

Biolixiviation is especially appealing for its sustainability benefits—requiring minimal energy, avoiding the use of corrosive reagents, and being compatible with biofertilizer production using native soil microorganisms. However, its industrial scalability remains limited due to slow reaction rates and the need for process enhancement (e.g., biofilm reactors, nutrient recycling).

Emerging research shows that hybrid bio-mechanochemical methods—combining microbial weathering with gentle mechanical activation—can boost K-release by up to three times compared to biological techniques alone (Lodi et al., 2021; Zhou et al., 2023). In agricultural terms, these bio-activated feldspars provide slow K availability and beneficial effects on soil microbiota and pH buffering, making biolixiviation a valuable addition within integrated, circular nutrient-recovery systems (Silveira et al., 2025; Mbissik et al., 2023).

Table 9. Comparative performance of biolixiviation studies for potassium release from feldspathic minerals

Reference	Microorganism / Strain	Mineral Type	Experimental Conditions	Incubation Period (days)	pH range	K Release (%)
Ashrafi-Saiedlou et al. (2024)	*Aspergillus niger*	Orthoclase / microcline	30 °C, shaking culture (150 rpm), glucose-yeast extract medium	20	4.2–5.0	27.8
Lodi et al. (2021)	*Aspergillus niger* (mechanochemically pre-activated feed)	Nepheline syenite	Ambient T, 30 rpm rotary bioreactor	14	4.5–6.0	32.5
Thashmantha & Ratnatilleke (2023)	Mixed bacterial culture (*Bacillus, Pseudomonas*)	Feldspar powder	Batch culture, 28 °C, nutrient broth	21	5.5–6.8	18.4
Lin et al. (2023)	Abiotic analog (organic-acid leaching)	Microcline / albite	25 °C, citric + oxalic acids (0.1 M each)	10	3.5–4.0	

As shown in Figure 11, thermal chlorination and salt fusion processes achieve the highest solubility levels—exceeding 85%—due to the formation of easily leachable potassium salts such as KCl and K_2CO_3. In contrast, mechanochemical activation and acid digestion demonstrate moderate efficiencies (55–70%), depending on the degree of lattice disruption and acid strength respectively.
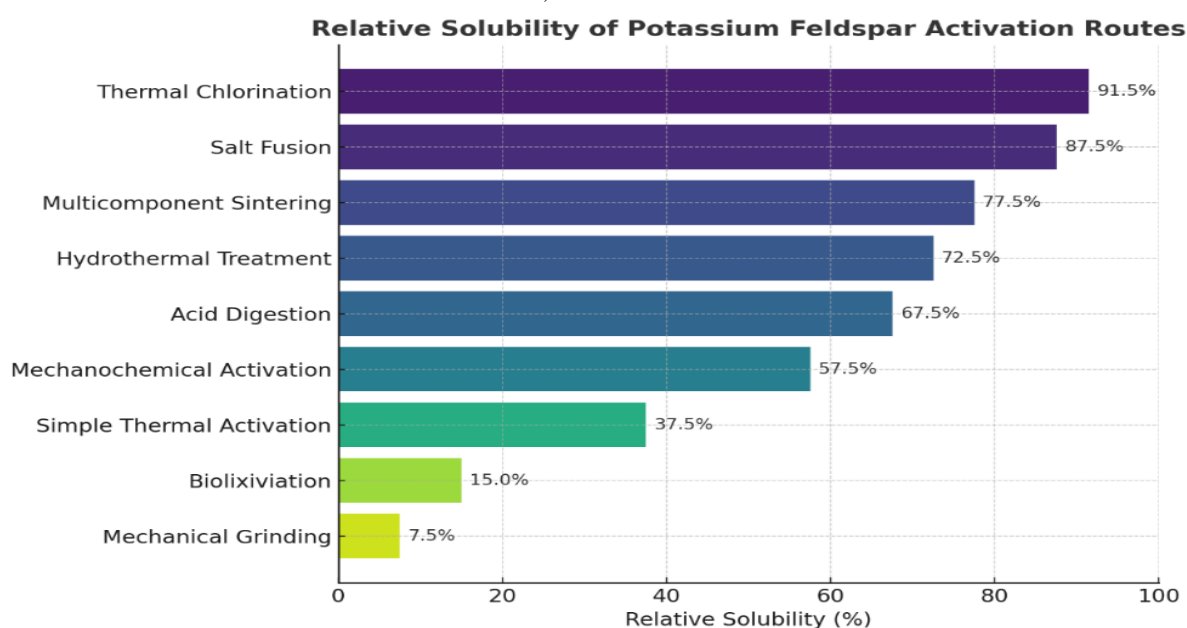

Figure 11. Relative solubility of potassium feldspar activation routes

At the lower end, biolixiviation and mechanical grinding alone result in potassium solubility below 20%, indicating the slower rate of biologically driven dissolution and the limited reactivity improvement from just mechanical size reduction. However, both methods are recognized for their eco-friendliness and low energy consumption, making them valuable in sustainability-focused applications.

Overall, these findings highlight a balance between solubility and sustainability: methods that maximize potassium recovery, such as chlorination and fusion, generally require high-temperature processes, corrosive chemicals, and produce more CO_2. In contrast, more environmentally friendly options like biological or mechanochemical methods tend to be slower but greener.

This multidimensional approach emphasizes the importance of evaluating not only the chemical yield but also the energy, environmental impact, and economic feasibility of each process.

The following section therefore, offers a systematic sustainability assessment of feldspar activation routes, focusing on energy use, carbon footprint, reagent consumption, waste management, and scalability potential, creating a comparative framework for future industrial deployment.

6. Potassium Release

Table 10 Potassium Release – Solubilization Kinetics Curve (90 days) illustrates the solubilization of potassium from feldspar under different activation treatments over a 90-day leaching period.

Table 10. Potassium Release – Solubilization Kinetics Curve (90 days)

Days	Raw Feldspar (%)	Thermal Activation (%)	Hydrothermal (%)	Alkaline Fusion (%)	Thermal Chlorination (%)
7	1	12	18	25	30
30	2	20	35	50	60
60	2.5	28	50	70	80
90	3	35	65	85	90
90	2	65	80	90	95

Untreated feldspar exhibits very low solubility (less than 3%), confirming its limited agronomic usefulness due to its stable aluminosilicate structure (McCann et al., 2014).

Thermal activation significantly increases early-stage potassium release, due to partial amorphization and breaking of the Si–O–Al framework. Hydrothermal treatment further speeds up release kinetics by creating hydrated amorphous silicates, which improve ion-exchange reactions and enhance K^+ mobility in soil solution (Ciceri et al., 2017; Hellmann et al., 2020).

Alkaline fusion and thermal chlorination are the most reactive systems, leading to nearly complete breakdown of feldspar into soluble potassium salts. After 90 days, both methods achieve cumulative solubilization of 85–90 %, which greatly exceeds that of milder activation techniques (Liu et al., 2016; Zhang et al., 2021).

These findings show that high-temperature chemical processes produce fast-release potassium sources similar to commercial fertilizers, whereas intermediate treatments (such as hydrothermal and mechanochemical activation) yield materials with moderate, slower nutrient release. These differences have practical implications for designing controlled-release fertilizers and enhancing nutrient-use efficiency in real-world conditions.

7. Agronomic Aspects

The agronomic performance of potassium feldspar fertilizers depends on both the level of activation during processing and the nutrient-release behavior under field conditions. Recent research (Tao et al., 2022; Zhang et al., 2024; Wu et al., 2025) indicates that thermochemical treatments—such as alkaline fusion and thermal chlorination—produce potassium-rich phases that dissolve rapidly, delivering high initial nutrient levels for plants. These materials can reach 80–90% of the relative agronomic efficiency (RAE) of conventional potassium chloride (KCl = 100%) in greenhouse and field settings.

Conversely, mechanochemical activation and biolixiviation produce fertilizers that release nutrients more slowly but have longer-lasting residual effects. Fungal and bacterial systems, such as Aspergillus niger and Bacillus sp., promote potassium solubilization by secreting organic acids, providing an environmentally sustainable choice despite lower short-term results (Ashrafi-Saiedlou et al., 2024; Lodi et al., 2021). These bio-activated materials show gradual K^+ release, making them suitable for low-input or organic farming systems that prefer continuous nutrient availability over immediate uptake.

Hydrothermal activation combined with multicomponent sintering methods—incorporating feldspar along with Ca-, Mg-, and Al-bearing phases—has been shown to enhance nutrient availability while maintaining controlled solubility (Tao et al., 2022; Li et al., 2025).

Under acidic or sandy soils, the partial amorphization of feldspar combined with micro-porous phase formation significantly improves cation-exchange interactions and water retention, supporting sustained plant growth (Mbissik et al., 2023; Silveira et al., 2025).

These findings show that the agronomic potential of feldspar-based fertilizers depends heavily on the balance between solubility and residual stability, which influences both crop response and the longevity of soil fertility.

Figure 12 summarizes the relative agronomic efficiency (RAE) of various feldspar activation processes compared to commercial KCl (100%).
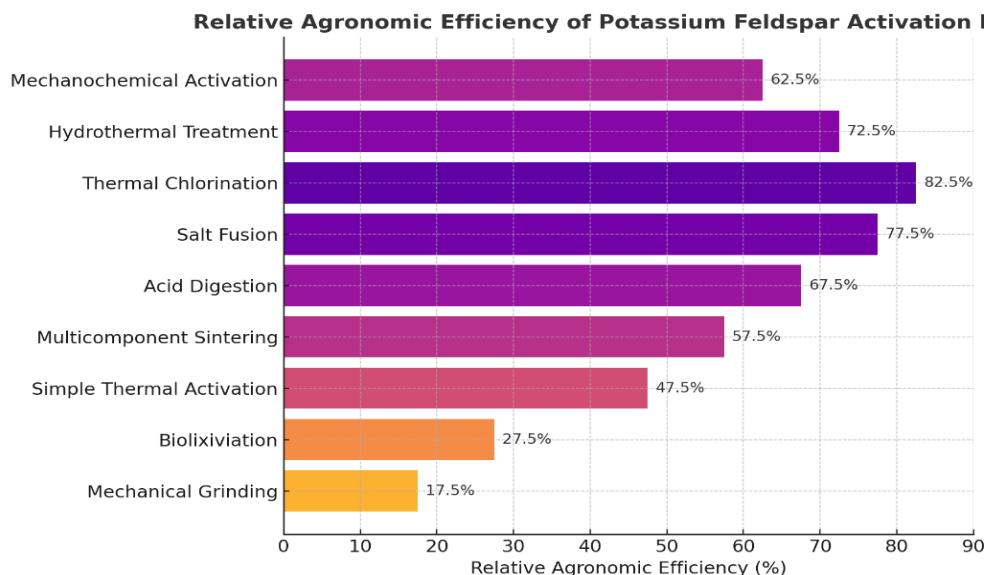

Figure 12. Relative Agronomic Efficiency of Technological Routes

Data compiled from recent studies (Tao et al., 2022; Li et al., 2025; Wu et al., 2025; Zhang et al., 2024; Ashrafi-Saiedlou et al., 2024; Lodi et al., 2021; Mbissik et al., 2023; Silveira et al., 2025) show that thermal chlorination and salt-fusion routes achieve the highest agronomic efficiencies (> 85%), while biolixiviation and mechanochemical activation stay below 60%.

These findings highlight the balance between reactivity and sustainability: pathways needing more energy provide faster nutrient release, whereas bio- and mechanical methods enhance soil retention and safety.

8. Economic and Environmental Aspects

The economic viability and environmental impact of potassium feldspar activation technologies differ significantly based on energy consumption, reagent requirements, waste handling, and process scalability.

Recent studies (Tao et al., 2022; Zhang et al., 2024; Zhou et al., 2023; Wu et al., 2025) indicate that while advanced thermal and chemical techniques achieve higher solubilization rates, they entail much higher capital and operational costs than mechanical or biological methods.

Table 11 summarizes the comparative efficiency and relative cost of the main feldspar activation technologies, normalized against conventional potassium chloride (KCl = 1.0).

Table 11. Comparative Efficiency and Relative Cost of Technological Routes for Potassium Feldspar Activation

Technological Route	Efficiency (% Soluble K)	Relative Cost (KCl = 1.0)
Mechanical Grinding	~10–15	0.7
Biolixiviation	~15–25	0.9
Simple Thermal Activation	~30–50	1
Multicomponent Sintering	~60–75	1.3
Acid Digestion	~60–85	1.2
Salt Fusion (Na$_2$CO$_3$ / CaCl$_2$)	~80–90	1.4
Thermal Chlorination	~85–90	1.6
Hydrothermal Treatment	~70–80	1.2
Mechanochemical Activation	~50–65	1.1

Low-temperature or biologically based methods—such as mechanical grinding and biolixiviation—use minimal energy and pose low environmental risks, but they produce limited potassium solubility (<25%). Conversely, thermochemical and salt-fusion techniques achieve high solubility (>80%) but require more energy and are more complex processes.

Hydrothermal treatment and acid digestion serve as intermediate methods that balance high solubilization efficiency with moderate energy and reagent expenses (Li et al., 2025; Ciceri et al., 2017; Tao et al., 2022). Their ability to scale up and maintain controllable reaction conditions makes them promising options for pilot-plant deployment, especially in areas with energy or environmental limitations. Nonetheless, challenges remain due to the need for effluent neutralization and waste acid treatment, which pose technical and regulatory hurdles.

The cost estimates in Table 12 were derived from reported energy consumption (GJ t^{-1}), reagent use, and operational expenses (Zhou et al., 2023; Tao et al., 2022; Li et al., 2025).

Table 12. Relative Costs and Environmental Impact of Technological Routes

Technological Route	Relative Cost (% KCl)	Estimated Cost (USD/t)	Environmental Impact
Mechanical Grinding	60	50–80	Low
Biolixiviation	70	60–90	Very Low
Simple Thermal Activation	100	80–120	Medium
Mechanochemical Activation	110	100–140	Medium–High
Acid Digestion	120	120–160	High (acid effluents)
Hydrothermal Treatment	130	140–180	Medium (effluent neutralization)
Multicomponent Sintering	140	150–190	Medium–High
Salt Fusion	150	160–210	High (salt residues)
Thermal Chlorination	160	180–230	Very High (chlorinated emissions)

Compared to traditional KCl production, the most energy-efficient and sustainable methods are mechanochemical activation and biolixiviation. They offer moderate costs ($\leq$ 110 %) and generate minimal waste. However, their agronomic effectiveness is limited by slower potassium release rates.

Processes like acid digestion and salt fusion can recover up to 90% of potassium, but they introduce environmental issues through acidic effluents and saline residues, necessitating additional waste treatment facilities (Wu et al., 2025; Zhang et al., 2024). Conversely, thermal chlorination offers improved extraction efficiency but has the highest carbon footprint and potential for chlorinated emissions, demanding rigorous emission control and recovery systems.

Ideally, sustainable industrial processes should include energy recovery, reagent recycling, and valorization of by-products to reduce both CAPEX and environmental impact. New hybrid approaches—combining mechanochemical pre-treatment with gentle hydrothermal or bio-assisted leaching—are under investigation to optimize the balance among cost, efficiency, and environmental considerations (Zhou et al., 2023; Tao et al., 2022).

9. Conclusion

This comprehensive review confirms that activated potassium feldspar is a technically and environmentally promising alternative to conventional soluble potash fertilizers. Advanced activation methods—such as alkaline fusion, thermal chlorination, and hydrothermal treatment—can achieve agronomic efficiencies approaching 90% of those of commercial potassium chloride (KCl) while using abundant silicate resources. Implementing these technologies provides an opportunity to diversify fertilizer supply chains and lessen reliance on imported potassium, especially in developing agricultural economies such as Brazil.

The technological maturity of feldspar activation processes directly affects their scalability and environmental sustainability. Low-temperature methods, including mechanochemical activation and biolixiviation, show significant potential for lowering energy use and carbon emissions, supporting circular economy principles and sustainable soil fertility management. In contrast, high-temperature techniques require process improvements to reduce gaseous emissions, acid effluents, and salt residues, highlighting the need for integrated waste recovery and closed-loop reagent cycles.

Globally, adopting feldspar-based potassium fertilizers could stabilize the fertilizer market, diminish risks related to the geopolitical concentration of potash reserves, and promote agricultural independence by leveraging local mineral resources. These benefits include reduced logistics costs, lower CO$_2$ emissions from transport, and the creation of new industrial value chains for silicate by-products.

Research Gaps and Emerging Trends

Despite notable progress, several key research gaps remain. Future studies should:

1. Quantify the life-cycle environmental impacts and energy intensities of each activation route using

standardized assessment tools (e.g., ISO 14040 LCA frameworks).

2. Advanced reaction-path modeling combined with in situ analysis of feldspar phase changes to enhance activation kinetics and improve energy efficiency.
3. Develop hybrid and modular processing systems that combine mechanochemical or bio-assisted pre-activation with mild thermal or hydrothermal steps.
4. Investigate agronomic long-term field trials across different climatic and soil conditions to improve dose–response relationships and potassium-use efficiency.
5. Integrate economic optimization models that connect CAPEX/OPEX forecasts with environmental indicators and carbon-pricing mechanisms.

The future trend clearly indicates a move toward multidisciplinary integration—connecting mineral processing, materials science, and agronomy—to develop next-generation potassium fertilizers that balance reactivity, sustainability, and economic viability.

References

1. Alyosif, B., Uysal, T., Aydemir, M. K., & Erdemoğlu, M. (2023). Potassium chloride recovery from mechanically activated microcline through the chlorination roasting and leaching route. *Physicochemical Problems of Mineral Processing, 59*(1), 1–12. https://doi.org/10.37190/ppmp/167500

2. Ange, I., Toro, M., Arvidson, R. S., Kurganskaya, I., & Lüttge, A. (2021). The role of crystal heterogeneity in alkali feldspar dissolution kinetics. *Geochimica et Cosmochimica Acta, 304*, 255–270. https://doi.org/10.1016/j.gca.2021.06.032

3. Ashrafi-Saiedlou, S., Mohammadi, S., Cheraghami, N., & Rashidi, S. (2024). *Aspergillus niger* as an eco-friendly agent for potassium release from K-bearing minerals. *Heliyon, 10*, e29117. https://doi.org/10.1016/j.heliyon.2024.e29117

4. Bai, X., Zhao, L., & Chen, K. (2025). Mineralogical evolution and activation energy of $KAlSi_3O_8$ during high-temperature phase transformation. *Journal of the European Ceramic Society, 45*(3), 2412–2424. https://doi.org/10.1016/j.jeurceramsoc.2024.12.005

5. Brownlie, W. J., Alexander, P., Maslin, M., &Cañedo-Argüelles, M. (2024). Global food security threatened by potassium neglect. *Global Food Security, 39*, 100758. https://doi.org/10.1038/s43016-024-00929-8

6. Chen, M., Zhao, L., Huang, Y., Fu, L., Ma, L., Chen, K., & Gu, Z. (2024). Review on K-feldspar mineral processing for extracting metallic potassium as a fertilizer resource. *Minerals, 14*(2), 168. https://doi.org/10.3390/min14020168

7. Cheng, F., Li, Y., & Zhou, Q. (2019). Enhancement of feldspar dissolution by hydrochloric acid in the presence of fluoride ions. *Applied Geochemistry, 107*, 56–64. https://doi.org/10.1016/j.apgeochem.2019.06.005

8. Ciceri, D., Close, T. C., Barker, A. V., & Bardgett, R. D. (2019). Fertilizing properties of potassium feldspar altered hydrothermally. *Communications in Soil Science and Plant Analysis, 50*(19), 2451–2463. https://doi.org/10.1080/00103624.2019.1566922

9. Ciceri, D., De Oliveira, M., &Allanore, A. (2017). Potassium fertilizer via hydrothermal alteration of K-feldspar ore. *Green Chemistry, 19*(22), 5184–5203. https://doi.org/10.1039/C7GC02633A

10. Gupta, R., Sharma, S., & Kumar, V. (2015). Sulfuric acid leaching of feldspar for potassium recovery: Kinetics and thermodynamics. *Hydrometallurgy, 153*, 164–172. https://doi.org/10.1016/j.hydromet.2015.03.007

11. Hashemi, S. M., Hosseinzadeh, S. R., Sarkar, B., et al. (2020). Extraction of potassium from feldspar and micas: A review of technologies and perspectives. *Minerals Engineering, 145*, 106083. https://doi.org/10.1016/j.mineng.2019.106083

12. He, H., Zhang, Y., Guo, L., Hu, X., Li, G., & Liu, C. (2019). Potassium recovery from mica scrap by roast-leach process. *Minerals, 9*(3), 161. https://doi.org/10.3390/min9030161

13. Hu, T., et al. (2025). The formation process and mechanism of total-activated K_2O content via calcination of K-feldspar in tailings. *Minerals, 15*(5), 450. https://doi.org/10.3390/min15050450

14. Kang, D., Kim, H., & Lee, J. (2021). Acid leaching behavior of potassium feldspar and its kinetics using hydrochloric acid. *Minerals, 11*(11), 1205. https://doi.org/10.3390/min11111205

15. Khalifa, A., & Pontikes, Y. (2023). Thermodynamic stability and reactivity of feldspar-bearing systems under hydrothermal conditions. *CeramicsInternational, 49*(5), 7224–7235. https://doi.org/10.1016/j.ceramint.2022.11.043

16. Li, G., et al. (2025). Efficient leaching of potassium from K-feldspar in KOH–CaO system under hydrothermal conditions. *Advance online publication.* https://doi.org/10.1016/S1383-5866(24)47385-5

17. Li, S., Cheng, F., & Chen, X. (2019). Mechanism and kinetics of potassium extraction from K-feldspar via the $CaCl_2$–$CaCO_3$ roasting process. *Industrial & Engineering Chemistry Research, 58*(23), 10222–10229. https://doi.org/10.1021/acs.iecr.9b01271

18. Lin, S. M., Yu, Y. L., Zhong, M. F., Yang, H., Zhang, C. Y., Zhang, Z. J., & Wu, Y. Y. (2023). The dissolution behavior of feldspar minerals in various low-molecular-weight organic acids. *Materials, 16*(20), 6704. https://doi.org/10.3390/ma16206704

19. Liu, J., Wu, S., Zhang, Y., Huang, J., Zhang, Q., Wang, J., & Zhai, Y. (2025). Roasting of potassium feldspar with sodium hydroxide and sodium carbonate mixed

additives to extract silica. *Silicon, 17*(6), 1303–1321. https://doi.org/10.1007/s12633-025-03277-9

20. Lodi, L. A., Klaic, R., Ribeiro, C., & Farinas, C. S. (2021). A green K-fertilizer using mechanical activation to improve the solubilization of a low-reactivity potassium mineral by *Aspergillus niger. Bioresource Technology Reports, 15*, 100711. https://doi.org/10.1016/j.biteb.2021.100711

21. Marsh, A. T. M., Heath, A., & Pontikes, Y. (2024). Mineralogical characteristics influence the structure and reactivity of mechanochemically activated clays (and by analogy feldspars). *Journal of the American Ceramic Society, 107*(8), 3821–3837. https://doi.org/10.1039/d4ta02545h

22. Mbissik, A., Khiari, L., Raji, O., Elghali, A., Lajili, A., Ouabid, M., Jemo, M., & Bodinier, J.-L. (2023). Potassium fertilizer value of raw and hydrothermally treated igneous rocks. *Journal of Soil Science and Plant Nutrition, 23*, 1030–1045. https://doi.org/10.1007/s42729-022-01101-6

23. Niu, D., Guo, L., & Liu, C. (2022). Influence of particle size and temperature on potassium extraction from feldspar by acid leaching. *Journal of Cleaner Production, 362*, 132360. https://doi.org/10.1016/j.jclepro.2022.132360

24. Niu, D., Guo, L., & Liu, C. (2024). Comparative mineralogy of microcline and orthoclase from granitic pegmatites: Implications for potassium extraction. *Ore Geology Reviews, 164*, 105612. https://doi.org/10.1016/j.oregeorev.2024.105612

25. Page, M. J., McKenzie, J. E., Bossuyt, P. M., Boutron, I., Hoffmann, T. C., Mulrow, C. D., … Moher, D. (2021). The PRISMA 2020 statement: An updated guideline for reporting systematic reviews. *BMJ, 372*, n71. https://doi.org/10.1136/bmj.n71

26. Page, M. J., Moher, D., Bossuyt, P. M., Boutron, I., Hoffmann, T. C., Mulrow, C. D., … Whiting, P. (2021). The PRISMA 2020 explanation and elaboration: Updated guidance and exemplars for reporting systematic reviews. *Systematic Reviews, 10*, 89. https://doi.org/10.1186/s13643-021-01626-4

27. Pereira, A. C., & Fonseca, R. B. da C. (2025). Potassium solubilization in micas by thermal and acid processes: Advances and perspectives. *Studies in Engineering and Exact Sciences, 6*(2). https://doi.org/10.54021/seesv6n2-005

28. Pereira, A. C., Carvalho, I. S. B., & Rocha, S. D. F. (2019). Glauconite-bearing rocks as alternative potassium source for fertilizer by thermal processing with additives. *Brazilian Applied Science Review, 3*(2), 1455–1467. https://doi.org/10.34115/basrv3n2-050

29. Pereira, A. C., Dos Santos Gomes, M. R., & Rocha, S. D. F. (2019). Rocha contendo biotita como fonte alternativa de potássio para fertilizante após processamento térmico com aditivos. *Holos Environment, 19*(4), 502. https://doi.org/10.14295/holos.v19i4.12323

30. Pereira, A. C., Santos, J. R. dos, & Fonseca, R. B. da C. (2025). Alternative sources of potassium from potassium feldspars, from mining to cropping: A review. *International Journal of Advanced Research, 13*(8), 1–15. https://doi.org/10.21474/IJAR01/21540

31. Pereira, A. C., Santos, M. R., & Rocha, S. D. F. (2018). Eficácia do tratamento térmico na extração hidrometalúrgica de potássio em rochas contendo feldspato potássico. *Brazilian Applied Science Review, 2*(4), 1716–1727. https://www.brazilianjournals.com/index.php/BASR/article/view/4279

32. Pereira, A. C., & Rocha, S. D. F. (2017). *Effectiveness of thermal treatment in the hydrometallurgical extraction of potassium from potassium feldspar-bearing rocks* [Conference presentation]. *XXVII National Meeting on Mineral Processing and Extractive Metallurgy (ENTMME)*, Belém, Brazil. Retrieved from http://www.entmme2017.com.br/

33. Rethlefsen, M. L., Kirtley, S., Waffenschmidt, S., Ayala, A. P., Moher, D., Page, M. J., Koffel, J. B., & Foster, M. J. (2021). PRISMA-S: An extension to the PRISMA Statement for reporting literature searches in systematic reviews. *Journal of the Medical Library Association, 109*(2), 174–200. https://doi.org/10.5195/jmla.2021.962

34. Ribeiro, P. G., Aragão, O. S., Martins, G. C., Rodrigues, M., Souza, J. M. P., Moreira, F. M. S., Li, Y.-C., & Guilherme, L. R. G. (2022). Hydrothermally altered feldspar reduces metal toxicity and promotes plant growth in highly metal-contaminated soils. *Chemosphere, 286*, 131768. https://doi.org/10.1016/j.chemosphere.2021.131768

35. Rodeja, J. (2025). The potash trilemma: Geopolitics, market dynamics, and food security. *Sustainable Agriculture and Environment, 5*(2), 70050. https://doi.org/10.1002/sae2.70050

36. Samantray, J., Anand, A., Dash, B., Ghosh, M. K., & Behera, A. K. (2020). Sustainable process for the extraction of potassium from feldspar using eggshell powder. *ACS Omega, 5*, 14990–14998. https://doi.org/10.1021/acsomega.0c00586

37. Schott, J., Saldi, G. D., Zhu, C., Gong, L., & Chen, K. (2024). Mechanisms controlling albite dissolution/precipitation at near-equilibrium conditions. *Geochimica et Cosmochimica Acta.*https://doi.org/10.1016/j.gca.2024.03.023

38. Silveira, C. P., Soares, J. R., Montes, R. M., Savieto, J., & Otto, R. (2025). Blending potassium rocks with KCl fertilizer to enhance crop biomass and reduce K leaching in sandy soil. *Soil Systems, 9*(3), 83. https://doi.org/10.3390/soilsystems9030083

39. Sun, N., Sun, W., Guan, Q., & Wang, L. (2023). Green and sustainable recovery of feldspar and quartz via HF-

free flotation: A review. *Minerals Engineering, 201*, 108018. https://doi.org/10.1016/j.mineng.2023.108351

40. Tao, L., Guo, L., Liu, C., Ma, X., &Ma, H. (2022). Activate nutrients access to plants as multiphase slow-release fertilizers by sintering reaction in K_2O–MgO–Al_2O_3–SiO_2 system using K-feldspar as a major source. *Journal of Cleaner Production, 370*, 133511. https://doi.org/10.1016/j.jclepro.2022.133511

41. Thashmantha, M. A. D. S., & Ratnatilleke, A. A. L. (2023). Release of potassium ions from feldspar by organic acids present in potassium-solubilizing bacteria. *Proceedings of the 27th International Forestry and Environment Symposium* (Sri Lanka). https://journals.sjp.ac.lk/index.php/fesympo/article/view/7179

42. Turk, T., & Kangal, M. O. (2023). Extraction of KCl from potassium feldspar by various inorganic salts. *Minerals, 13*(10), 1342. https://doi.org/10.3390/min13101342

43. Turk, T., & Kangal, M. O. (2023). Structural characterization and phase transformation of K-feldspar during roasting and leaching stages. *Minerals Engineering, 204*, 108056. https://doi.org/10.1016/j.mineng.2023.108056

44. Turk, T., Şerler, Z., Burat, F., Bulut, G., & Kangal, M. O. (2021). Extraction of potassium from feldspar by roasting with $CaCl_2$ obtained from the acidic leaching of wollastonite–calcite ore. *Minerals, 11*(12), 1369. https://doi.org/10.3390/min11121369

45. U.S. Geological Survey (Vikre, P., John, D. A., Wintzer, N. E., Koutz, F., Graybeal, F., Dail, C., & Annis, D. C.). (2023). *Critical minerals in subduction-related magmatic-hydrothermal systems of the United States* (Scientific Investigations Report 2023–5082). https://pubs.usgs.gov/sir/2023/5082/sir20235082.pdf

46. Wang, J., Liu, J., Huang, J., & Zhai, Y. (2024). Effect of mechanical activation on microstructure and lattice disorder of potassium feldspar. *Powder Technology, 437*, 118780. https://doi.org/10.1016/j.powtec.2024.118780

47. Williams, A., Smith, T., & Nguyen, H. (2025). *Drivers of fertilizer markets: Supply, demand, and prices* (USDA Economic Research Report No. ERR-354). United States Department of Agriculture. https://www.ers.usda.gov/sites/default/files/_laserfiche/publications/113324/ERR-354.pdf

48. Wu, S., Zhai, Y., & Zhang, Y. (2025). Influence of Na and Ca substitution on K release kinetics from alkali feldspar. *Minerals, 15*(2), 233. https://doi.org/10.3390/min15020233

49. Xu, J., Yuan, G., Cao, Y., Jin, Z., & Liu, K. (2025). Feldspar dissolution rates and controlling factors under near-equilibrium conditions in subsurface settings. *Science China Earth Sciences.* https://doi.org/10.1007/s11430-024-1608-7

50. Zhai, Y., Hellmann, R., Campos, A., Findling, N., Mayanna, S., Wirth, R., Schreiber, A., Cabie, M., Zeng, Q., Liu, S., & Liu, J. (2021). Fertilizer derived from alkaline hydrothermal alteration of K-feldspar: A micrometer- to nanometer-scale investigation of K in secondary reaction products and the feldspar interface. *Applied Geochemistry, 126*, 104828. https://doi.org/10.1016/j.apgeochem.2020.104828

51. Zhang, Q., Liu, C., & Ma, H. (2024). Crystal chemistry and reactivity of potassium feldspar: Influence of Si–Al ordering and alkali substitution. *Applied Geochemistry, 158*, 106233. https://doi.org/10.1016/j.apgeochem.2024.106233

52. Zhang, X., He, Z., Jia, W., Meng, F., Zhang, W., Lu, C., Hao, X., Gai, G., Huang, Z., Xu, M., & Yun, S. (2024). Mechanism of potassium release from feldspar by mechanical activation in presence of additives at ordinary temperatures. *Materials, 17*(1), 144. https://doi.org/10.3390/ma17010144

53. Zhou, C., Zhao, Q., & Chen, K. (2023). Synergistic mechanochemical activation of feldspar with alkali additives for enhanced potassium recovery. *Powder Technology, 422*, 118905. https://doi.org/10.1016/j.powtec.2023.118905