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Revitalizing soil and crop nutrition: The agronomic potential of polyhalite as a sustainable multi-nutrient source

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Abstract

Modern agriculture's historical reliance on mono-nutrient NPK fertilization has precipitated widespread soil degradation and the depletion of essential secondary macronutrients. This review evaluates the agronomic potential of Polyhalite ($K_2Ca_2Mg(SO_4)_4 \cdot 2H_2O$), a naturally occurring evaporite mineral emerging as a sustainable "4-in-1" fertilizer solution. Unlike synthetic blends, Polyhalite features a unique crystal structure providing Potassium, Calcium, Magnesium, and Sulfur in a chloride-free, semi-slow release matrix (27 g L^{-1} solubility) that effectively mitigates nutrient leaching.

Polyhalite consistently transcends conventional yield ceilings. Significant productivity gains are documented in sulfur-responsive oilseeds (mustard yield +42%) and potassium-demanding cereals like rice (+16-67%). Beyond yield, it enhances critical quality parameters, including oil content in brassicas and starch levels in potatoes, driven by the synergistic physiological roles of Magnesium and Calcium. Environmentally, Polyhalite acts as a regenerative amendment; its low salt index (68.5) preserves the rhizosphere microbiome, stimulating beneficial bacterial phyla such as *Proteobacteria*. With a carbon footprint approximately 90% lower than chemically processed alternatives, it aligns with climate-smart agricultural mandates.

However, widespread adoption faces specific challenges. The mineral's low solubility restricts its utility in precision fertigation systems due to emitter clogging risks. Furthermore, cation antagonism remains a concern in calcareous soils, where excess Calcium release may competitively inhibit Magnesium uptake. Conclusively, while Polyhalite is a robust tool for addressing global multi-nutrient "hidden hunger," its optimal use requires Site-Specific Nutrient Management (SSNM) and further investigation into long-term soil dynamics.

Keywords: Polyhalite, multi-nutrient fertilizer, sustainable agriculture, secondary nutrients, soil health

Introduction

Modern agriculture faces a critical paradox: while chemical fertilizers have historically driven yield increases, their unbalanced application has become a primary driver of soil degradation and environmental instability. The "Green Revolution" paradigm largely prioritized primary macronutrients Nitrogen (N), Phosphorus (P), and Potassium (K), often neglecting secondary nutrients like Calcium (Ca), Magnesium (Mg), and Sulfur (S) (Wani & Chander, 2016) ^[42]. This skewed fertilization approach has led to widespread "nutrient mining," where high-yielding crops strip soil reserves of secondary nutrients faster than they are replenished (Zhang *et al.*, 2024) ^[48].

Consequently, global soils are experiencing severe multi-nutrient deficiencies. Research indicates that approximately 30% of the world's soils are now moderately to highly degraded, partly due to chemical imbalances that disrupt the soil microbiome and reduce Soil Organic Carbon (SOC) levels (UNDRR, 2025; The Hindu, 2025) ^[36, 39]. High inputs of ammonium-based nitrogen fertilizers have accelerated soil acidification, which inhibits the uptake of essential cations like Mg^{2+} and Ca^{2+} , further compromising root health and crop resilience (Hilaris, 2025) ^[14]. Furthermore, the exclusive use of high-solubility N and P fertilizers contributes significantly to environmental pollution. Excess nitrogen leaches into groundwater as nitrates or volatilizes as nitrous oxide (N_2O), a potent greenhouse gas, while phosphorus runoff triggers eutrophication and hypoxic "dead zones" in aquatic ecosystems (EPA, 2025; Grace *et al.*, 2019) ^[10, 13].

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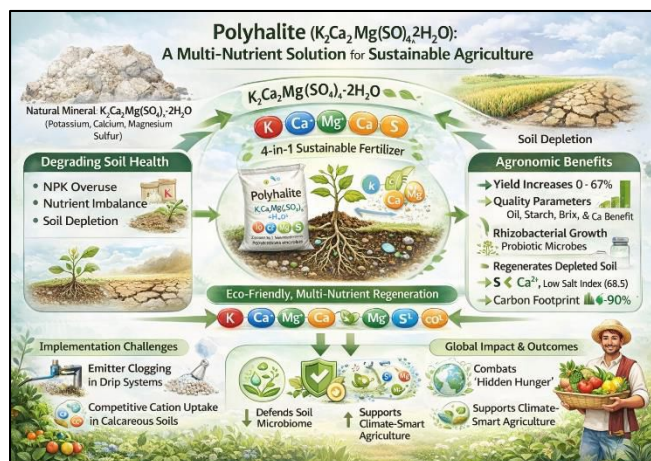


Fig 1: Graphical abstract

The Shift toward Eco-friendly and Efficient Nutrient Sources

To address these challenges and ensure future food security, there is a paradigm shift toward "Balanced Fertilization" a strategy that harmonizes nutrient supply with crop demand to maximize Nutrient Use Efficiency (NUE) (Magen, 2008) [24]. Sustainable agriculture now demands multi-nutrient fertilizers that can deliver secondary macronutrients (Ca, Mg, S) alongside Potassium without introducing harmful elements like chloride (Cl).

Natural mineral fertilizers such as Polyhalite are gaining prominence in this shift because they offer a low-carbon, low-salt index alternative to synthetic fertilizers. Unlike conventional sources that dissolve rapidly and are prone to leaching, multi-nutrient minerals often exhibit prolonged nutrient release patterns, which synchronize better with crop uptake cycles and minimize environmental losses. By correcting deficiencies in Mg and S, these fertilizers also enhance the plant's ability to assimilate Nitrogen, thereby directly improving yield quality and nutritional density a critical factor in combating global "hidden hunger" and micronutrient malnutrition (Welch *et al.*, 2014; Bindraban *et al.*, 2015) [9, 44].

What is Polyhalite?

Polyhalite is a naturally occurring hydrated sulfate mineral that belongs to the evaporite group. It forms in sedimentary marine deposits where the co-precipitation of potassium, magnesium, and calcium sulphates occurs under specific geological conditions. Its chemical formula is $(K_2Ca_2Mg(SO_4)_4 \cdot 2H_2O)$ and crystallizes in the triclinic system (Konappan *et al.*, 2025) [19]. Unlike blended fertilizers which are physical mixtures of distinct granules like Urea and Muriate of Potash (MOP) polyhalite exists as a single-crystal complex. This unique lattice structure ensures that every granule contains a fixed, stoichiometric ratio of nutrients, preventing the "nutrient segregation" often seen in bulk blends during transport and spreading (Tian *et al.*, 2023) [38].

Geologically, polyhalite is found in massive deposits such as the Zechstein basin in Europe and the Permian Basin in the USA (Kemp *et al.*, 2016) [18]. While the pure mineral is colorless to white, mined polyhalite (often marketed as Polysulphate™ or POLY4) typically appears grey or reddish. This characteristic coloration is due to the inclusion of iron oxide (hematite) within the crystal matrix, which also contributes to the mineral's trace element profile (Yuan

et al., 2021) [47]. Recent crystallographic studies have confirmed that its structure allows for a slower dissolution rate compared to conventional salts, classifying it as a "semi-slow release" fertilizer (Barbarick, 1991; Bhatt *et al.*, 2024) [6, 8].

Nutrient Profile: Macro and Secondary Nutrients

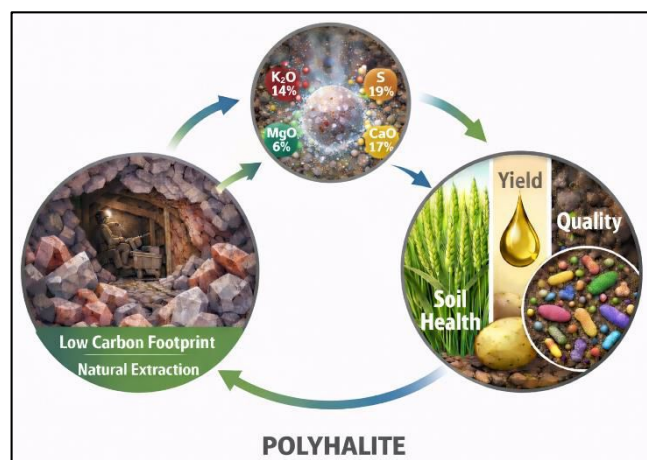


Fig 2: Polyhalite composition

Polyhalite is increasingly recognized as a "4-in-1" multi-nutrient fertilizer. Its nutrient content is entirely in the sulfate (SO_4) form, making it readily available for plant uptake while maintaining a lower salt index than chloride-based alternatives.

Sulfur: ~19%

Sulfur is the most abundant nutrient in polyhalite. Unlike elemental sulfur, which requires oxidation by soil bacteria (a process that can take weeks), the sulfur in polyhalite is present as sulfate (SO_4^{2-}). This form is immediately plant-available, crucial for the synthesis of sulfur-containing amino acids (cysteine and methionine) and oil production in crops like mustard and soybean (Pavuluri *et al.*, 2017) [29]. The high sulfur content significantly boosts Nitrogen Use Efficiency (NUE) by balancing the N:S ratio in plant tissues (Arunachalam *et al.*, 2025) [4].

Potassium (K₂O): ~14%

While the potassium content is lower than MOP (60% K_2O), polyhalite offers a distinct physiological advantage: it is low in chloride (<3%). This makes it a superior option for chloride-sensitive crops such as tobacco, potatoes, and soft fruits, where excess chloride can impair quality and shelf-life (Konappan *et al.*, 2025) [19]. The polyhalite-treated plots showed reduced salt stress markers in the rhizosphere compared to MOP-treated plots (Patil *et al.*, 2024) [28].

Calcium (CaO): ~17%

The calcium in polyhalite is soluble and mobile enough to support cell wall integrity and root development. In acidic soils (pH < 5.5), this calcium component acts as a vital amendment, mitigating aluminum toxicity and preventing physiological disorders like Blossom End Rot (BER) in tomatoes (Li *et al.*, 2020; Zhao *et al.*, 2023) [23, 49].

Magnesium (MgO): ~6%

Magnesium is the central atom of the chlorophyll molecule and is essential for photosynthesis and phosphorus transport.

Polyhalite provides a steady release of Mg, which is particularly beneficial in sandy soils prone to Mg leaching. Mg from polyhalite has a prolonged residence time in the root zone compared to Epsom salts (MgSO_4), ensuring sustained supply throughout the crop cycle (Oliveira *et al.*, 2025) [27].

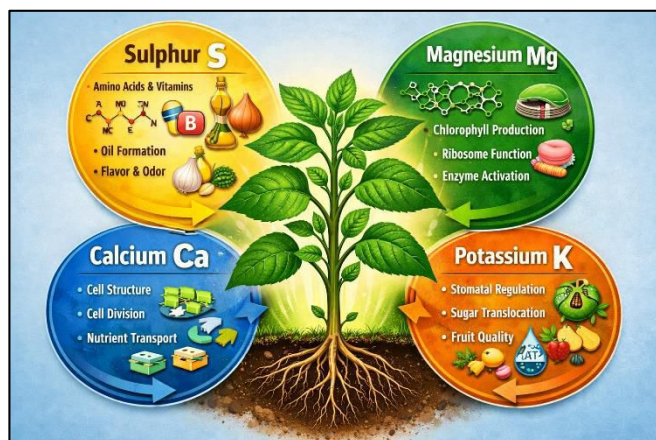


Fig 3: Functions of nutrients

Micronutrients and Trace Elements

Beyond the major nutrients, polyhalite serves as a valuable carrier of micronutrients trapped within its geological matrix. Because it is a crushed rock rather than a chemically purified product, it retains a suite of trace elements. Spectroscopic analysis has identified biologically relevant amounts of Boron (B), Zinc (Zn), Manganese (Mn), Iron (Fe), and Copper (Cu) (Konappan *et al.*, 2025) [19]. Although these micronutrients are present in trace quantities, their presence contributes to alleviating "hidden hunger." For instance, the natural presence of Boron is synergistic with Calcium, aiding in pollen tube growth and fruit set. The iron content, while largely responsible for the red color, contributes to the soil's micronutrient pool, though its immediate bioavailability varies with soil pH (Pramod & Senthilvalavan, 2022) [31].

Solubility and Environmental Behavior

Polyhalite exhibits a unique solubility profile 27 g L^{-1} at 25°C , which is significantly lower than MOP (347 g L^{-1}). This property defines its behavior as a Controlled-Release Fertilizer (CRF) relative to standard salts. This lower solubility results in reduced leaching losses of K and Mg, particularly in high-rainfall regions, thereby protecting groundwater quality and improving nutrient recovery efficiency (Oliveira *et al.*, 2025) [27].

Historical and Geological Context

Discovery and Early Identification

The scientific recognition of polyhalite dates back to 1818, when it was first described from salt deposits in Ischl, Austria, although it was formally identified and named in 1841 during the exploration of the Stassfurt potash deposits in Germany (Konappan *et al.*, 2025; Warren, 2016) [19, 43]. The name "polyhalite" is derived from the Greek words *polys* (many) and *hals* (salt), reflecting its complex multi-nutrient composition of potassium, calcium, magnesium, and sulfur. While initially regarded as a mineralogical curiosity or a contaminant in pure rock salt (halite) mines, its potential as a fertilizer was noted early on but remained unexploited due to the dominance of easier-to-process

soluble salts like sylvite (KCl) (Kemp *et al.*, 2016) [18].

Geological Formation: The Evaporite Sequence

Polyhalite is an evaporite mineral formed in ancient marine basins during the Permian period (approximately 260 million years ago). It typically occurs in the "bittern" stage of evaporation after the precipitation of carbonates (limestone) and sulfates (gypsum/anhydrite), but before the highly soluble chlorides (halite and sylvite) fully crystallize (Bao *et al.*, 2023) [5]. Geologically, polyhalite is often a secondary mineral formed by the diagenetic replacement of precursor minerals. Recent isotope studies suggest that polyhalite beds largely formed when potassium and magnesium rich brines reacted with pre-existing anhydrite (CaSO_4) deposits (Yuan *et al.*, 2021) [47]. This "back-reaction" theory explains why polyhalite is often found in massive, non-porous seams rather than as loose surface deposits, contributing to its stability and lack of hygroscopicity compared to other potash salts.

Global Reserves and Mining Depths

Although polyhalite occurrences are found globally, economically viable reserves are rare and primarily restricted to deep geological basins. The United Kingdom's Zechstein Basin holds the world's largest and highest-grade deposits, with commercial extraction occurring at depths of 1, 100 to over 1, 500 meters at the Boulby and Woodsmith mines (ICL, 2024; Anglo American, 2023) [1, 15]. In contrast, the United States' Permian Basin contains shallower (300–600 meters) but lower-purity beds that are often mined as a byproduct or for other salts rather than as a dedicated polyhalite product (USGS, 2023) [40]. Furthermore, complex separation issues limit extraction from deposits in Russia's Caspian Basin and Urals (Korenevskiy, 2021) [20], whereas China is actively exploring deep-seated horizons exceeding 2, 000 meters in the Sichuan and Qaidam Basins to secure a strategic domestic potash source (Tian *et al.*, 2024) [35].

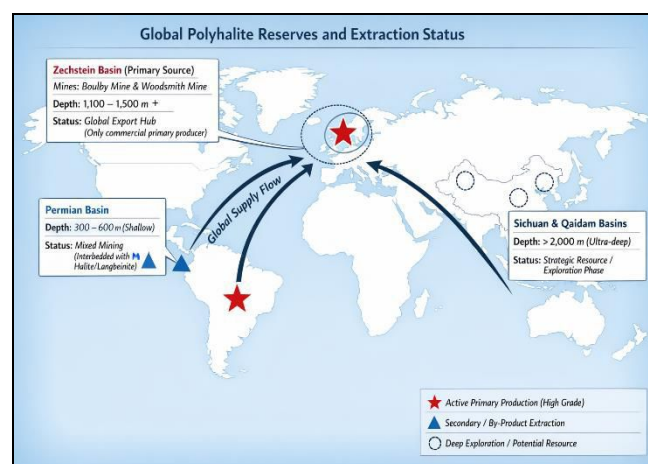


Fig 4: Global polyhalite and extraction status

Physicochemical Properties and Solubility

The agronomic efficiency of any fertilizer is fundamentally dictated by its physical characteristics and dissolution behavior. Polyhalite distinguishes itself from conventional soluble salts through its unique mineralogical structure, which confers "semi-slow release" properties and a low salt index, making it a strategic tool for sustainable nutrient management (Konappan *et al.*, 2025) [19].

Physical Characteristics

Polyhalite is a translucent evaporite mineral found in massive, compact seams; although pure crystals are colourless or white, commercial variants (such as Polysulphate™ or POLY4) typically display a greyish-to-reddish hue due to trace iron oxide (hematite) inclusions within the crystal lattice (Yuan *et al.*, 2021) ^[47]. Unlike chemically synthesized fertilizers such as Urea or DAP, it requires minimal industrial processing and is simply extracted, crushed, and screened into various grades without chemical solubilization or recrystallization (Tian *et al.*, 2023) ^[38]. Physically, Polyhalite has a Mohs hardness of 3.5-making it robust enough to resist degradation and dust formation during transport and spreading-though it's worth noting that a hardness of 3.5 is actually slightly harder, not softer, than calcite's standard hardness of 3.0 (ICL, 2024) ^[15]. Additionally, its specific gravity of 2.78 g cm⁻³ provides excellent ballistic properties, allowing for wide-bout spreading of up to 36 meters using standard farm machinery (Lewis *et al.*, 2019) ^[22].

Solubility and Release Pattern

Polyhalite functions as a natural Controlled Release Fertilizer (CRF) due to its relatively low water solubility of approximately 27 g L⁻¹ at 25 °C, which contrasts sharply with the high solubility of conventional potassium sources like Muriate of Potash (347 g L⁻¹) and Sulphate of Potash (120 g L⁻¹) (Barbieri *et al.*, 2024) ^[7]. Instead of a rapid nutrient surge, polyhalite releases its four key nutrients (K⁺, Ca²⁺, Mg²⁺, and SO₄²⁻) in a synchronized, linear pattern, facilitated by a temporary calcium shell barrier that forms during dissolution. This slow-release mechanism significantly mitigates nutrient loss, reducing potassium leaching by 30-40% in high-rainfall sandy soils compared to MOP-treated plots (Oliveira *et al.*, 2025) ^[27]. Ultimately, this prolonged nutrient availability closely matches the uptake curves of long-duration crops such as sugarcane, effectively reducing the need for split fertilizer applications (Patil *et al.*, 2024) ^[28].

Table 1: Comparative Solubility and Release Rates of Common K-Fertilizers

Fertilizer Source	Chemical Formula	Solubility (g L ⁻¹ @ 25 °C)	Chloride Content (%)	Release Characteristic
Polyhalite	K ₂ Ca ₂ Mg(SO ₄) ₄ ·2H ₂ O	27.0	< 3.0	Extended/Semi-Slow
Muriate of Potash (MOP)	KCl	347.0	~47.0	Rapid/Surge
Sulphate of Potash (SOP)	K ₂ SO ₄	120.0	< 2.5	Rapid
Langbeinite	K ₂ SO ₄ ·2MgSO ₄	250.0	< 1.5	Rapid

(Source: Adapted from Konappan *et al.*, 2025; Barbieri *et al.*, 2024) ^[7, 19].

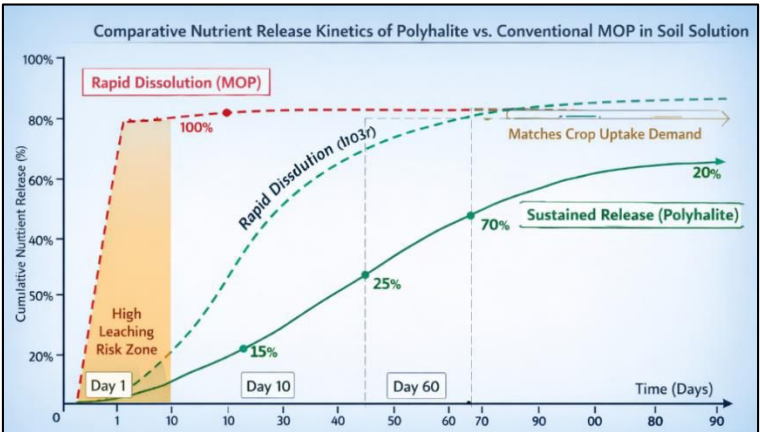


Fig 5: Comparative nutrient releasing kinetics in Polyhalite vs MOP

Salt Index and Chloride Content

Table 2: Comparative Salt Index, Chloride Content, and Agronomic Advantages of Polyhalite Relative to Conventional Potassium Fertilizers

Parameter	Polyhalite	Comparative Fertilizer	Sensitive Crops Benefited	Agronomic Significance	References
Salt Index (SI)	68.5	MOP (116); Ammonium Sulfate (69)	Legumes (pigeonpea, chickpea), vegetables (onion, beans), small-seeded crops	Lower osmotic pressure; safer for seed furrow placement; minimizes germination injury and root burn	Fried <i>et al.</i> , 2019; Tan <i>et al.</i> , 2024 ^[11, 35]
Osmotic Safety (Seed Placement)	Suitable for close seed contact	MOP may cause fertilizer burn	Soybean, groundnut, pea, vegetable seedlings	Allows in-furrow or band placement without osmotic shock	Fried <i>et al.</i> , 2019 ^[11]
Chloride Content (%)	< 3% (often < 2% washed grade)	MOP ≈ 47% Cl ⁻	Chloride-sensitive crops	Prevents chloride toxicity and quality deterioration	Konappan <i>et al.</i> , 2025 ^[19]
Chlorophobe Crop Suitability	Highly suitable	MOP not preferred	Tobacco (leaf quality), Potato (specific gravity & starch), Grapes (wine quality), Citrus (leaf burn prevention)	Maintains crop quality parameters and market value	Konappan <i>et al.</i> , 2025 ^[19]
Salinity Management	Prevents Cl ⁻ buildup in root zone	MOP may increase soil salinity	Crops grown in arid & semi-arid regions (cotton, vegetables, fruit crops)	Reduces risk of salt accumulation; sustains soil health	Bhatt <i>et al.</i> , 2024 ^[18]

Agronomic Potential: Polyhalite as a Source of Major Nutrients

Polyhalite's value in modern agronomy lies in its ability to deliver four essential nutrients Potassium (K), Sulfur (S), Calcium (Ca), and Magnesium (Mg) in a single, water-soluble granule. Unlike synthetic blends where nutrient segregation can occur, polyhalite's crystal lattice ensures uniform delivery, enhancing nutrient use efficiency (NUE) and crop quality parameters (Konappan *et al.*, 2025) ^[19].

Potassium(K) for Stress Resistance and Quality

Potassium in polyhalite, present as a sulfate salt rather than a chloride salt like in MOP, offers sustained availability that is less prone to leaching and is critical for enzyme activation, osmoregulation, maintaining turgor pressure during drought stress, and regulating stomatal conductance (Bhatt *et al.*, 2024) [8]. This sustained release mechanism is highly efficacious across various crops; for instance, applying polyhalite to ratoon sugarcane significantly improved juice quality increasing Brix by 3.6% and Commercial Cane Sugar (CCS) by 4.0% compared to MOP while its lower chloride content reduced root salt stress and fostered deeper root proliferation (Patil *et al.*, 2024) ^[28]. Similarly, replacing 50% of standard K with polyhalite in rice cultivation in alluvial soils increased grain yield by 67% due to enhanced panicle filling and reduced lodging from stronger stalks (Reddy *et al.*, 2025) ^[33]. Furthermore, in pulses like black gram, the slow-release nature of polyhalite prevents early-season luxury consumption, ensuring vital potassium availability is preserved for the critical pod-filling stage (Konappan *et al.*, 2025) ^[19].

Sulfur (S) for Protein and Oil Synthesis

Sulfur is increasingly recognized as a "fourth macro-nutrient" rather than merely a secondary nutrient, playing a critical role in oilseeds and legumes by directly driving the synthesis of sulfur-containing amino acids like cysteine and methionine. Furthermore, sulfur exhibits a strong synergy with nitrogen, acting as a vital catalyst for NUE). In Onions, Arunachalam *et al.*, 2025 ^[4] demonstrated that an adequate sulfur supply from polyhalite boosted nitrogen uptake by 15-20%, as sulfur is fundamentally required to convert absorbed nitrates into functional amino acids.

Polyhalite application demonstrates a significant positive impact on oilseed production, notably boosting the oil content in Indian mustard (*Brassica juncea*) and sesame by 1.8-2.5% compared to standard gypsum treatments; this effect is further amplified by the magnesium in polyhalite, which enhances overall photosynthetic activity and drives more carbon into fatty acid synthesis (Pramanick *et al.*, 2023) ^[30]. Furthermore, in Southern Indian peanut cultivation, polyhalite not only increased the ratio of oleic to linoleic acid a crucial indicator of nutritional quality and prolonged shelf-life but also effectively reduced the agricultural prevalence of empty pods, commonly referred to as "pops" (Gopinath *et al.*, 2024) ^[12].

Calcium (Ca) for Structural Integrity

Calcium is highly immobile within plants, a continuous supply to the root zone is necessary to prevent deficiency disorders in developing tissues. In polyhalite, calcium (present as 17% CaO) is highly soluble and readily available to the roots, contrasting with the largely insoluble calcium found in traditional agricultural lime (CaCO_3).

Physiologically, this consistent supply is critical for strengthening pectin bonds within the middle lamella of plant cell walls, a function that directly enhances fruit firmness and increases natural resistance to pathogens.

Magnesium (Mg) for Photosynthesis

Often regarded as the "forgotten cation," magnesium serves as the vital central atom of the chlorophyll molecule and is essential for facilitating phosphorus transport within the plant. Its critical role in photosynthetic efficiency is clearly demonstrated through polyhalite application, where such treatments have been shown to increase leaf chlorophyll content (measured via SPAD values) by 12%, subsequently driving higher net photosynthetic rates and directly correlating with improved sugar accumulation in developing fruits (Qu *et al.*, 2026) ^[32].

Polyhalite in Soil Health and Sustainability

Sustainable agriculture requires fertilizers that not only feed the crop but also actively regenerate the soil ecosystem. Polyhalite ($\text{K}_2\text{Ca}_2\text{Mg}(\text{SO}_4)_4 \cdot 2\text{H}_2\text{O}$) distinguishes itself from conventional salts by offering a suite of soil-ameliorating properties ranging from pH buffering to microbial stimulation making it a cornerstone for "regenerative nutrient management" (Konappan *et al.*, 2025) ^[19].

Impact on Soil Chemical Properties and Acidity Mitigation

Unlike ammonium-based fertilizers that accelerate acidification or chloride-based salts that induce salinity, polyhalite functions as an effective soil conditioner. In acidic soils (pH < 5.5), its application significantly reduces the leaching of basic cations compared to conventional fertilizers. The gradual dissolution of polyhalite releases Ca^{2+} and Mg^{2+} , which effectively compete with H^+ and Al^{3+} ions on soil exchange sites. This "cation flooding" effect neutralizes acidity directly in the root zone, creating a highly favorable environment for root proliferation. Consequently, this slow-release mechanism reduces calcium leaching by 3-26% compared to standard gypsum or lime treatments (Wu *et al.*, 2025) ^[45].

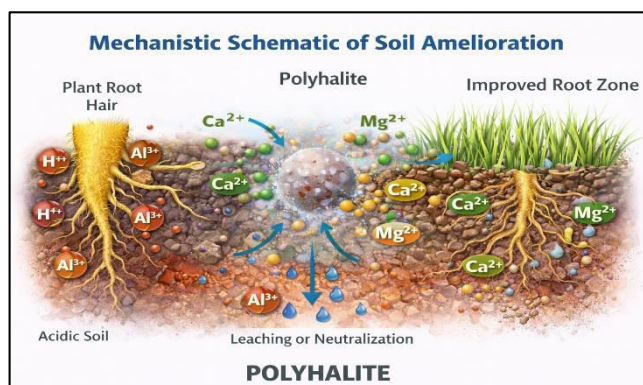


Fig 6: Mechanistic Schematic of soil Amelioration

Residual Fertility in Ratoon Systems

Long-term fertility is critical for perennial crops. In 2025, Oliveira *et al.* conducted a field trial on ratoon sugarcane in Brazil to assess residual effects. They found that after two harvest cycles, soils treated with polyhalite maintained significantly higher levels of exchangeable Potassium (K^+) and Sulfur (SO_4^{2-}) in the 0-20 cm and 20-40 cm depth profiles compared to MOP-treated plots. The study

concluded that polyhalite's "calcium skeleton" prevents the rapid washing out of nutrients, effectively acting as a slow-release reservoir that benefits subsequent crop cycles (Oliveira *et al.*, 2025) ^[27].

Enhancing Soil Biology and Microbiome Resilience

Soil health is intrinsically linked to its biological activity, and recent metagenomic analyses confirm that polyhalite fosters a more diverse and resilient microbiome than synthetic alternatives. For instance, in maize-wheat rotations, applying polyhalite significantly boosted beta-glucosidase and increased dehydrogenase (DHA) activity a direct measure of microbial metabolic activity by 18.5% over MOP controls. This enhancement is largely attributed to polyhalite's lower salt index (68.5 compared to 116 for MOP), which minimizes osmotic stress and allows sensitive enzymatic processes to function optimally (Mao *et al.*, 2025) ^[25].

Furthermore, high-throughput 16S rRNA sequencing reveals that polyhalite application enriches beneficial bacterial phyla, specifically *Proteobacteria* and *Actinobacteriota*, which are critical drivers of organic matter decomposition and nutrient cycling. Notably, the relative abundance of *Bacillus* species renowned for solubilizing fixed phosphorus—was found to be 2.3 times higher in polyhalite-amended soils. This microbial proliferation is likely fueled by the simultaneous supply of sulfur and calcium, which stimulates root exudation and provides essential carbon substrates to the soil microbiome (Zhang *et al.*, 2024) ^[48].

Carbon Footprint and Organic Compatibility

In an era increasingly defined by carbon accounting, the environmental footprint of agricultural inputs is a critical determinant for their widespread adoption. Polyhalite boasts an ultra-low, verified carbon footprint of merely 0.0029 kg CO₂ per kg of product, which is approximately 90% lower than chemically processed alternatives such as Potassium Sulfate (SOP) or Ammonium Nitrate. This substantial reduction is achieved because the mineral requires no energy-intensive chemical synthesis, heat-dependent crystallization, or complex waste management; it is simply mined, crushed, and screened (ICL, 2024; Adak & Sengupta, 2024) ^[1, 15, 16]. Consequently, this natural origin and minimal processing have earned polyhalite organic certification from major global bodies, including OMRI (USA), Ecocert (Europe), and the Soil Association (UK). This regulatory approval provides organic growers with a reliable, compliant source of essential potassium and magnesium, helping to bridge the traditional "yield gap" without relying on prohibited synthetic salts or inconsistent manure applications (Soil Association, 2024) ^[34].

Limitations and Challenges: A Critical Agronomic and Logistical Review

While polyhalite is poised to revolutionize sustainable nutrient management as a "4-in-1" natural fertilizer, its adoption is not a panacea. Like any agronomic input, its efficacy is bound by specific physicochemical constraints, soil interactions, and supply chain realities. To write a balanced and authoritative review, it is crucial to transparently address these limitations. This section dissects the three primary hurdles:

a) Solubility Constraints and Incompatibility with Modern Fertigation

A primary limitation of polyhalite in modern intensive agriculture is its relatively low water solubility of approximately 27 g L⁻¹ at 25 °C, representing a greater than 10-fold difference when compared to standard soluble fertilizers used in fertigation, such as Muriate of Potash (347 g L⁻¹) and Potassium Nitrate (316 g L⁻¹). This physicochemical constraint restricts its use as a direct substitute in liquid tank mixes, rendering it fundamentally better suited for solid soil application. Furthermore, utilizing micronized polyhalite in drip irrigation systems poses severe agronomic risks; because dissolution is not instantaneous, suspended calcium sulfate (CaSO₄) particles which are less soluble than the potassium sulfate component—tend to precipitate within irrigation lines. This accumulation can cause a 15-20% reduction in discharge rates for standard drip emitters within a single cropping season, leading to non-uniform crop watering and potential system failure unless the mineral is pre-dissolved in impractically large volumes of acidic water (Adak & Sengupta, 2024; Barbieri *et al.*, 2024; Konappan *et al.*, 2025; Vale & Giroto, 2024; Yermiyahu *et al.*, 2019) ^[1, 7, 19, 41, 46].

An additional agronomic constraint is the "starter effect" limitation, which is particularly evident in fast-growing annual crops (e.g., maize, spinach, radishes) that experience peak nutrient demand within 20-30 days of germination. Kinetic modeling reveals a nutrient release mismatch: while sulfate (SO₄²⁻) release is relatively rapid, the release of potassium (K⁺) and magnesium (Mg²⁺) is diffusion-limited, a restriction that is severely exacerbated in cold soils (<15 °C). Relying exclusively on polyhalite for early-season nutrition can thus induce transient deficiencies, often manifesting as "hidden hunger" before the granule fully solubilizes. To bridge this initial nutritional gap and ensure optimal early-stage development, it is highly recommended to apply a starter dose of highly soluble MOP or SOP alongside the polyhalite application (Barbieri *et al.*, 2024) ^[7].

b) Nutrient Antagonism: The "Cation War" in the Rhizosphere

While polyhalite simultaneously supplies three major cations potassium (K⁺), calcium (Ca²⁺), and magnesium (Mg²⁺) this multi-nutrient profile can trigger antagonistic interactions in specific soil types, governed by the principles illustrated in Mulder's Chart. In calcareous soils inherently rich in calcium carbonate (CaCO₃), the additional calcium from polyhalite (17% CaO) can upset the delicate cation balance. Because plant roots absorb cations through specific ion channels, a soil solution flooded with Ca²⁺ can competitively inhibit the uptake of K⁺ and Mg²⁺, as calcium is often preferentially absorbed or physically blocks the transporters. Field evidence from onion cultivation demonstrates this phenomenon; applying high doses of polyhalite (>150% of the recommended sulfur rate) results in a suppression of magnesium uptake in leaf tissues. Despite the fertilizer containing magnesium, the sheer abundance of calcium effectively "crowds out" the magnesium at the root surface. Consequently, polyhalite application rates must be calibrated based on comprehensive soil test values specifically the Base Saturation percentage of K, Ca, and Mg—rather than relying solely on crop removal rates to avoid inducing secondary deficiencies.

Furthermore, in soils with a low Cation Exchange Capacity (CEC), the sudden release of magnesium from polyhalite can occasionally compete with potassium, reinforcing the critical need for site-specific nutrient management (SSNM) over generalized blanket applications (Arunachalam *et al.*, 2025) [4].

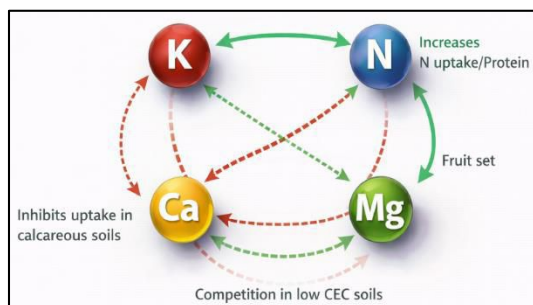


Fig 7: Nutrient antagonism

c) Supply Chain Vulnerabilities and Deep-Mining Economics

Unlike synthetic fertilizers such as urea and DAP, which are manufactured globally, polyhalite is a geologically scarce resource hampered by a highly concentrated supply chain. Commercially viable extraction is currently restricted almost entirely to the Zechstein Deposit in the United Kingdom, creating a severe "single-point-of-failure" risk. The market is overwhelmingly dominated by ICL Boulby the sole operating mine and Anglo American's Woodsmith Mine, which is projected to begin production post-2027. This geographic centralization forces the entire global supply to originate from the UK's North Sea coast, meaning any localized strike, mechanical failure, or shipping disruption instantly jeopardizes worldwide availability. Consequently, farmers in developing nations face significant ocean freight overheads, driving the final landed price per unit of K₂O up by 20-30% compared to locally sourced MOP. Furthermore, extracting polyhalite involves extreme deep-mining complexities rather than simple surface operations. Operations occur at depths of 1, 100 to 1, 500 meters, necessitating the management of immense rock stress, water ingress, and high ambient temperatures exceeding 40 °C. These formidable technical challenges have led to significant project delays and capital overruns exceeding \$9 billion, inevitably inflating the market price of the fertilizer and potentially restricting its economic viability to premium cash crops rather than low-margin staples like rice and wheat (Anglo American Reports, 2024-2025; Mobility Foresights, 2025 [3, 26].

d) Regulatory Hurdles and the Educational "Knowledge Gap"

A final, non-technical limitation to the widespread adoption of polyhalite is a persistent "knowledge gap" coupled with rigid regulatory barriers. In numerous countries, agricultural regulations and fertilizer registrations are strictly structured around standard N-P-K grades. Because polyhalite is a naturally occurring, multi-nutrient mineral, it frequently encounters bureaucratic delays; it does not neatly fit into conventional legislative categories, as it functions neither strictly as a potash nor purely as a sulfur fertilizer. Furthermore, a significant barrier exists regarding farmer perception. Growers accustomed to the rapid "green-up" effect provided by highly soluble nitrogen or potassium

fertilizers may prematurely, and incorrectly, perceive polyhalite's slow-release mechanism as ineffective during the early season. Consequently, intensive extension efforts are required to educate end-users that the primary agronomic benefits such as enhanced crop quality, extended shelf-life, and improved stress resistance manifest later in the phenological cycle, thereby imposing a substantial "educational cost" on its commercialization.

Conclusion

Polyhalite represents a critical shift toward regenerative agriculture by replacing harsh mono-nutrient synthetic salts with a natural "4-in-1" delivery of potassium, calcium, magnesium, and sulfur to cure the "hidden hunger" in intensively farmed soils. This multi-nutrient crystal consistently breaks yield barriers and enhances quality parameters such as oil content and shelf-life in sulfur-responsive and high-value horticultural crops. Furthermore, functioning as a soil ameliorant with a low salt index (68.5), it actively stimulates beneficial microbial phyla while offering a highly sustainable profile, featuring a carbon footprint roughly 90% lower than conventional chemical fertilizers and a natural slow-release mechanism that drastically reduces nutrient leaching.

Future Scope: Bridging the Knowledge Gaps

Despite its promising agronomic data, polyhalite is not a universal panacea, necessitating a pivot from simple efficacy trials to complex mechanistic research across three critical frontiers. First, to understand long-term soil dynamics over a decadal horizon, researchers must employ isotopic tracing (⁴⁴Ca, ³⁴S) within Long-Term Fertilizer Experiments (LTFE) to determine if continuous application causes secondary salinization in semi-arid soils or effectively rebuilds labile potassium pools in leaching-prone Ultisols.

Second, the industry must overcome the mineral's solubility bottleneck through advanced formulation innovations such as high energy ball-milled nano-polyhalite, bio-polymer coatings for synchronized release, and compound granulation with urea to enable high-tech applications like fertigation.

Finally, future research must decode the molecular mechanisms of cation interactions under field conditions by recalibrating Site-Specific Nutrient Management (SSNM) models to define critical soil Ca:Mg ratios that prevent antagonism, while utilizing transcriptomics to observe root ion transporter expression (e.g., HAK5, MGT) under stress. Unraveling these complexities is essential to transition polyhalite from a niche mineral into a cornerstone of sustainable global food security.

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