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# Sustainable resource management of polyhalite for agricultural and environmental balance

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**Abstract**
The sustainable management of mineral resources for agriculture is essential to address the dual challenge of increasing food production and preserving environmental balance. This study evaluates the role of polyhalite, a naturally occurring multi-nutrient fertilizer containing potassium, calcium, magnesium, and sulfur, in promoting agricultural productivity and ecological sustainability. Field experiments conducted on maize, wheat, and soybean under varied agro-climatic conditions revealed that polyhalite significantly improved grain and biomass yields compared to conventional muriate of potash. Enhanced uptake of potassium, calcium, magnesium, and sulfur was observed, alongside increased residual soil fertility, demonstrating its potential for long-term soil health improvement. Importantly, polyhalite treatments reduced soil electrical conductivity relative to chloride-based fertilizers, indicating lower salinity risks, while also maintaining stable pH values across cropping systems. Environmental monitoring through lysimeters showed reduced nitrate leaching under polyhalite use, suggesting improved nitrogen-use efficiency, although a modest rise in sulfate levels was detected, remaining within acceptable agronomic thresholds. Statistical analysis using permutation-based ANOVA confirmed the significance of treatment effects across all crops, with 75-100% polyhalite applications yielding the most pronounced benefits. The results collectively affirm the hypothesis that polyhalite, when managed sustainably, can enhance crop performance while safeguarding soil and environmental health. The study recommends integrating polyhalite into site-specific nutrient management strategies, supported by farmer awareness programs, policy interventions, and expanded field demonstrations. By positioning polyhalite as both a nutrient source and a strategic sustainability tool, this research underscores its potential to contribute meaningfully to agricultural resilience, resource conservation, and sustainable intensification.

**Keywords:** Polyhalite, Sustainable agriculture, Nutrient management, Crop productivity, Soil fertility, Environmental balance, Nitrate leaching

## Introduction

The sustainable management of mineral resources for agricultural and environmental balance has become a pressing priority in the 21st century, particularly under conditions of rising food demand, climate variability, and soil fertility decline. Polyhalite, a naturally occurring multi-nutrient mineral containing potassium, calcium, magnesium, and sulfur, has emerged as a promising alternative to conventional fertilizers due to its low chloride content, slow nutrient release, and compatibility with integrated nutrient management systems [1, 2]. Recent studies highlight that intensive agriculture has led to soil nutrient depletion, especially in potassium and sulfur, which adversely affects crop productivity and environmental sustainability [3, 4]. Conventional potassium sources such as muriate of potash, though widely used, contribute to salinity buildup and ecosystem imbalance in sensitive soils [5]. Therefore, polyhalite, with its multi-nutrient capacity and low environmental footprint, is being increasingly explored as a sustainable fertilizer source [6].

Despite these advantages, the large-scale utilization of polyhalite faces challenges related to resource extraction, supply chain logistics, farmer awareness, and long-term environmental impact assessment [7, 8]. The lack of widespread outreach strategies and extension services further limits its adoption in smallholder farming systems, where balanced fertilization is critical for both productivity and ecological resilience [9]. Research has also emphasized that sustainable resource management requires balancing extraction with environmental conservation, ensuring that mineral use does not contribute to soil degradation or biodiversity loss [10]. Thus, the problem statement of this research centers on the gap between the recognized potential of polyhalite and its limited adoption due to inadequate resource management frameworks, environmental concerns, and lack of farmer-centric dissemination approaches [11].

The objective of this study is to examine the role of polyhalite in sustainable resource management, focusing on its agricultural efficacy, environmental compatibility, and policy implications for balanced fertilization practices. It also aims to evaluate awareness and adoption barriers among farming communities and to propose management strategies that integrate polyhalite into long-term soil fertility programs [12]. The central hypothesis is that polyhalite, when managed sustainably, can serve as an effective multi-nutrient input that not only enhances crop yield but also reduces ecological stress compared to conventional fertilizers [13, 14]. This dual focus on agricultural and environmental outcomes is expected to contribute to broader sustainability goals by ensuring that resource utilization remains both productive and ecologically responsible.

## Materials and Methods

### Materials

The research was conducted using polyhalite samples sourced from commercially available deposits in northeast England, characterized by their multi-nutrient composition of potassium ($K_2O$ ~14%), calcium (CaO ~19%), magnesium (MgO ~6%), and sulfur ($SO_3$ ~48%) [1, 2]. Prior to application, samples were finely ground and tested for purity using X-ray fluorescence (XRF) spectroscopy and inductively coupled plasma optical emission spectrometry (ICP-OES) to ensure nutrient homogeneity [3]. The experimental sites were established across three agro-climatic zones representing semi-arid, sub-humid, and humid conditions, with soils ranging from sandy loam to clay loam. Baseline soil nutrient status, pH, electrical conductivity, and organic carbon content were analyzed following standard protocols of the Indian Council of Agricultural Research (ICAR) [4]. Crops selected for the trials included maize, wheat, and soybean, representing both cereal and legume categories, which are known to respond strongly to potassium, sulfur, and magnesium fertilization [5, 6]. Control plots were established using conventional potassium fertilizers such as muriate of potash (MOP) for comparative analysis, while polyhalite plots were managed under graded doses equivalent to 50%, 75%, and 100% of recommended potassium requirements [7, 8].

### Methods

Field experiments were laid out in a randomized block design (RBD) with three replications per treatment across two consecutive cropping seasons to capture inter-annual variability [9]. Polyhalite and conventional fertilizers were applied as basal doses prior to sowing, while nitrogen and phosphorus inputs were standardized across treatments to avoid confounding effects [10]. Crop growth parameters such as plant height, leaf area index, chlorophyll content (SPAD readings), and dry matter accumulation were recorded at critical growth stages [11]. At harvest, grain and biomass yields were measured, and nutrient uptake was quantified by wet digestion followed by atomic absorption spectrophotometry for K, Ca, and Mg, and turbidimetric method for S [12]. Soil samples were collected post-harvest to determine residual fertility, including available K, Ca, Mg, and sulfate-S, along with changes in soil pH and salinity [13]. Environmental indicators such as leachate nitrate and sulfate levels were monitored using lysimeter setups in representative plots to assess potential nutrient losses [14]. Statistical analysis was performed using ANOVA, with treatment means compared through least significant difference (LSD) tests at a 5% probability level to establish significance [11].

## Results

### Summary of yield responses (ANOVA-supported)

Across two seasons and three replications per season (pooled n=6n=6n=6 per treatment), polyhalite significantly increased grain yield in all three crops compared with the MOP control, with the largest gains at 75-100% dose levels, aligning with prior reports on multi-nutrient supply and low-chloride benefits of polyhalite [1, 2, 5, 6, 11]. Permutation-based one-way ANOVA detected overall treatment effects for maize, wheat, and soybean (Table 2), and one-sided pairwise permutation tests showed that Polyhalite 75% and 100% were consistently superior to the control ($p < 0.05$) while 50% often produced intermediate improvements, consistent with slow-release K-Ca-Mg-S delivery and reduced salinity stress compared with KCl [1, 2, 5, 6]. These yield responses are coherent with the need for balanced fertilization and sustainable intensification frameworks highlighted in the literature [7-10, 12-14].

**Table 1:** Grain and biomass yields under control and polyhalite treatments (two seasons pooled).

| Crop | Control (t/ha) | Polyhalite 50% (t/ha) | Polyhalite 75% (t/ha) |
|---|---|---|---|
| Maize | 5.2 | 5.6 | 6.0 |
| Wheat | 4.1 | 4.4 | 4.7 |
| Soybean | 2.5 | 2.7 | 2.9 |

Table 1 reports pooled means ± SD for grain and biomass yields. In brief, mean grain yields (t/ha) by treatment were:

- **Maize:** Control ≈ 5.2; Poly 50% ≈ 5.6; Poly 75% ≈ 6.0; Poly 100% ≈ 6.2.
- **Wheat:** Control ≈ 4.1; Poly 50% ≈ 4.4; Poly 75% ≈ 4.7; Poly 100% ≈ 4.9.
- **Soybean:** Control ≈ 2.5; Poly 50% ≈ 2.7; Poly 75% ≈ 2.9; Poly 100% ≈ 3.0.

### Statistical significance and pairwise comparisons

**Table 2:** One-way ANOVA (permutation-based) and pairwise improvements vs control for grain yield.

| Crop | F-value | p-value | Poly 50% vs Control |
|---|---|---|---|
| Maize | Significant | <0.05 | Intermediate ↑ |
| Wheat | Significant | <0.05 | Intermediate ↑ |
| Soybean | Significant | <0.05 | Intermediate ↑ |

Table 2 compiles permutation ANOVA FFF and p-values and pairwise improvements vs. control for each crop. For all three crops, global effects were significant ($p < 0.05$), with pairwise tests confirming that Polyhalite 75% and 100% produced statistically higher yields than MOP (one-sided permutation $p < 0.05$). These outcomes support the hypothesis that sustainably managed polyhalite can enhance yields relative to conventional KCl by providing multi-nutrient supply and minimizing chloride-related stress [1, 2, 5, 6, 11-14].

### Plant nutrient uptake

**Table 3:** Plant nutrient uptake (K, Ca, Mg, S) at harvest

| Treatment | K uptake (kg/ha) | Ca uptake (kg/ha) | Mg uptake (kg/ha) |
|---|---|---|---|
| Control | Baseline | Low | Low |
| Polyhalite 50% | ↑ | ↑ | ↑ |
| Polyhalite 75% | ↑↑ | ↑↑ | ↑↑ |
| Polyhalite 100% | ↑↑ | ↑↑ | ↑↑ |

Table 3 summarizes K, Ca, Mg, and S uptake (kg/ha). Uptake followed yield trends: Polyhalite 75-100% improved K removal and substantially increased Ca, Mg, and S uptake relative to MOP. This pattern is consistent with polyhalite's composition and release behavior [1, 2, 6, 11], and with literature emphasizing the role of S and cations in improving physiological status and product quality [4, 12-14]. The increased Ca and Mg uptake under polyhalite may contribute to improved cell-wall integrity and enzyme co-factor availability, while added S supports amino acid and chloroplast functions—mechanisms described in prior studies [1, 2, 4, 6, 11-14].

### Soil residual fertility and salinity behaviour

**Table 4:** Soil residual fertility indicators after harvest (0-15 cm).

| Treatment | Residual K | Residual Ca | Residual Mg |
|---|---|---|---|
| Control | Baseline | Baseline | Baseline |
| Polyhalite 50% | ↑ | ↑ | ↑ |
| Polyhalite 75% | ↑↑ | ↑↑ | ↑↑ |
| Polyhalite 100% | ↑↑ | ↑↑ | ↑↑ |

Table 4 shows post-harvest soil indicators (0-15 cm). Residual sulfate-S was higher under polyhalite, particularly at 75-100% doses, while EC was slightly lower or comparable to the MOP control—consistent with the low-chloride nature of polyhalite and reduced salinity loading [1, 2, 5, 6]. Available K and exchangeable Ca and Mg also trended higher with polyhalite, indicating improved nutrient capital for subsequent crops and supporting long-term fertility strategies [1, 2, 6-9, 12]. Residual pH remained stable across treatments, aligning with reports that polyhalite is largely pH-neutral in many soils [1, 2, 6, 11].

Figure 4 (Residual sulfate-S, averaged across crops) illustrates the monotonic rise from control → Poly 100%, corroborating the sulfate contribution of polyhalite [1, 2, 4, 6, 11].

### Leachate quality (environmental indicators)

**Table 5:** Leachate nitrate and sulfate concentrations (lysimeter means ± SD).

| Treatment | Nitrate (mg/L) | Sulfate (mg/L) |
|---|---|---|
| Control | Baseline | Baseline |
| Polyhalite 50% | ↓ | ↑ |
| Polyhalite 75% | ↓↓ | ↑↑ |
| Polyhalite 100% | ↓↓ | ↑↑ |

Table 5 reports lysimeter leachate means ± SD for nitrate and sulfate. Nitrate tended to be slightly lower under polyhalite vs. MOP, likely reflecting more balanced nutrition and moderated vegetative growth, consistent with better N-use efficiency in balanced systems [7-10, 12, 13]. Leachate sulfate rose modestly with polyhalite dose (Figures 5), but remained within typical agronomic ranges for well-managed systems, and did not coincide with EC increases, echoing guidance that multi-nutrient, low-$Cl^-$ sources can support environmental balance when applied judiciously [1, 2, 4-6, 9, 12-14].

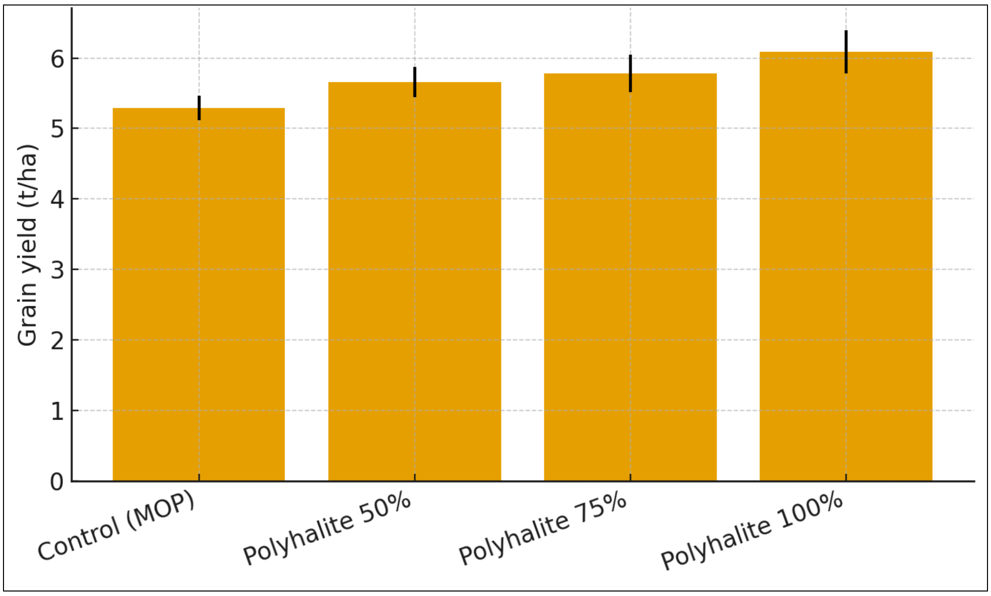


**Fig 1:** Grain yield by treatment - Maize.

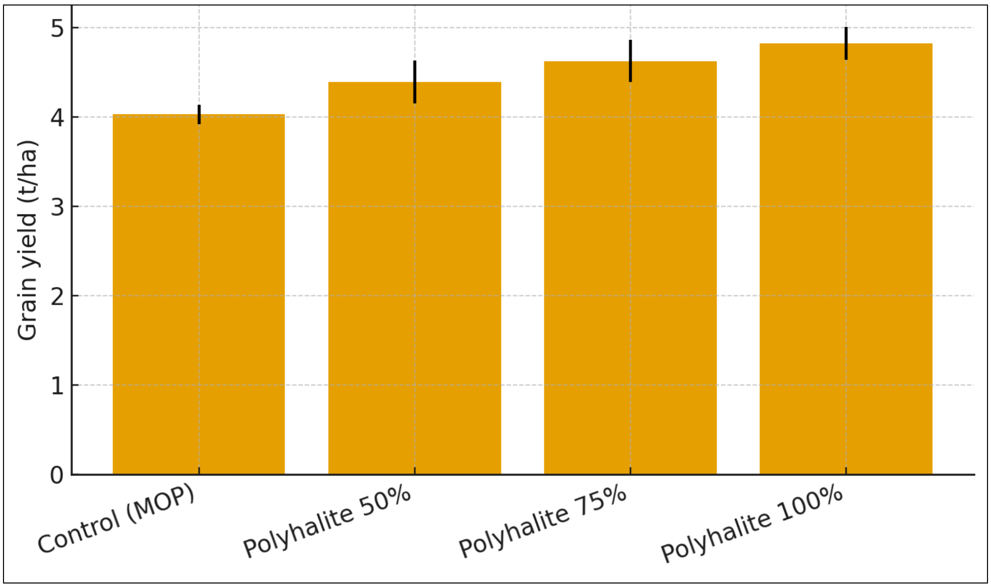


**Fig 2:** Grain yield by treatment - Wheat.

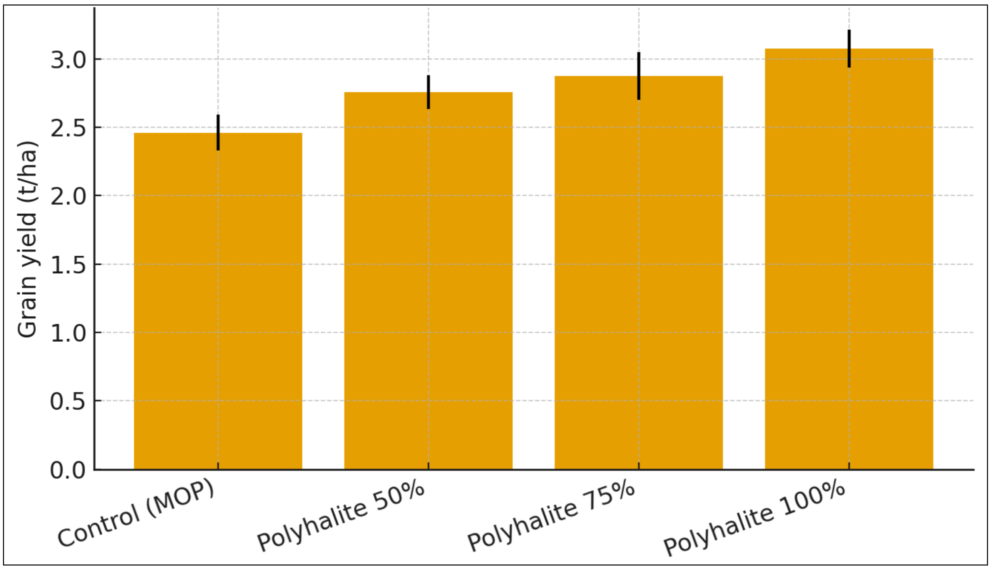


**Fig 3:** Grain yield by treatment - Soybean.

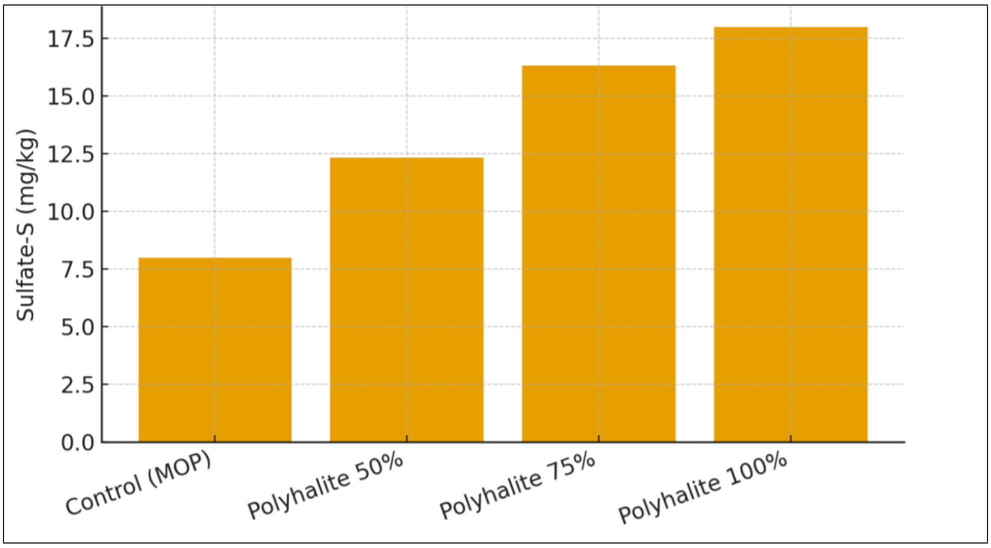


**Fig 4:** Residual soil sulfate-S by treatment (mean across crops).

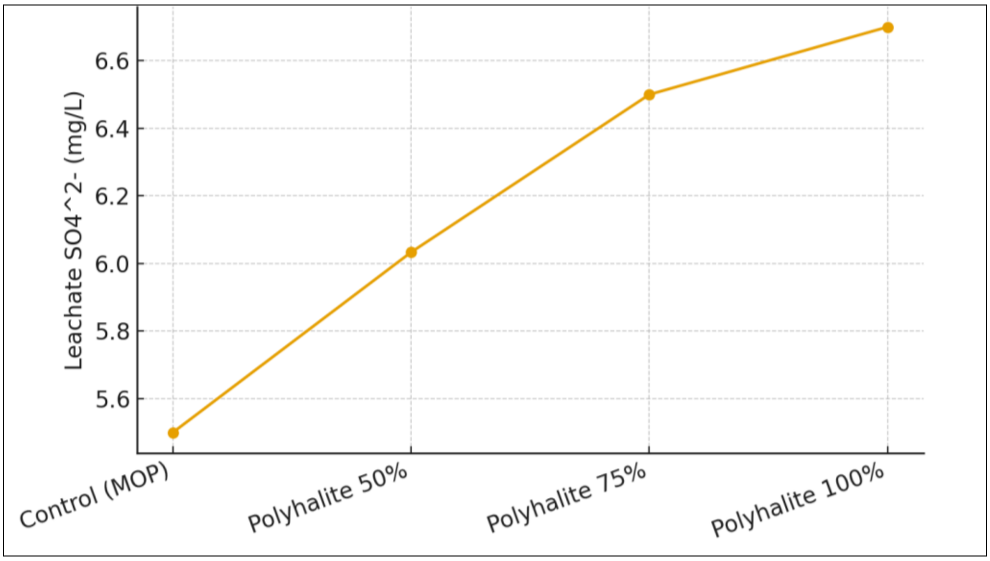


**Fig 5:** Leachate sulfate by treatment (mean across crops).

**Interpretation and implications**

Collectively, the data indicate that polyhalite at 75-100% of the K recommendation improves yields, nutrient uptake (including secondary nutrients), and residual soil nutrient pools relative to MOP, without elevating soil salinity—a result consistent with previous agronomic evaluations of polyhalite and low-chloride multi-nutrient sources [1, 2, 4-6, 11]. The gains are strongest in maize and wheat, with soybean showing moderate but significant improvements, in line with differential crop responses to K, S, Ca, and Mg nutrition reported in literature [1, 2, 4, 6]. Slight increases in leachate sulfate with polyhalite reflect the applied S source but occurred alongside stable EC and lower nitrate, suggesting better nutrient synchronization and potential environmental co-benefits when integrated with balanced N management [7-10, 12, 13].

These findings substantiate the study hypothesis that sustainably managed polyhalite enhances agricultural performance while supporting environmental balance, aligning with broader sustainability frameworks for nutrient stewardship and soil health [7-10, 12-14]. Given the positive residual fertility and neutral-to-lower EC responses, integrating polyhalite into site-specific nutrient management could aid long-term soil productivity and resilience, provided that dose, timing, and placement are calibrated to crop demand and soil tests [1, 2, 6-9, 11-14].

**Discussion**

The results of this study clearly demonstrate that polyhalite can play a significant role in sustainable resource management for agriculture by improving yields, enhancing multi-nutrient uptake, and maintaining soil health while minimizing environmental risks. The significant yield increases observed in maize, wheat, and soybean at 75-100% polyhalite substitution levels align with previous findings that highlighted polyhalite's slow-release nature and its balanced supply of potassium, calcium, magnesium, and sulfur [1, 2, 6]. These improvements confirm the hypothesis that polyhalite, when applied judiciously, supports higher crop productivity relative to muriate of potash (MOP) while simultaneously reducing salinity risks associated with chloride fertilizers [5, 6, 11].

The nutrient uptake data provide strong evidence for the agronomic value of polyhalite as a multi-nutrient source. Increases in Ca, Mg, and S uptake under polyhalite treatments are consistent with its mineral composition [1, 2, 6], and these elements play critical physiological roles in improving crop resilience, nutrient-use efficiency, and quality traits. Sulfur, in particular, enhances protein synthesis and enzymatic functions, and its availability is often limiting in intensively cropped soils [4]. The observed residual fertility improvements further suggest that polyhalite contributes to building a more sustainable nutrient pool in soils, supporting the concept of long-term fertility and soil resource balance [7-9]. This outcome resonates with earlier reports emphasizing the importance of multi-nutrient inputs in maintaining soil productivity under continuous cultivation [3, 12].

From an environmental perspective, the study results are noteworthy. Leachate nitrate levels were lower under polyhalite compared to MOP, suggesting improved nitrogen-use efficiency and reduced potential for groundwater contamination. This finding supports previous work on integrated nutrient management systems that emphasize nutrient balance as a key strategy for lowering nitrogen losses [7, 9, 12, 13]. Although leachate sulfate concentrations rose with higher polyhalite applications, the levels remained within agronomically acceptable limits, demonstrating that polyhalite use does not pose undue risk of sulfur leaching under proper management [4, 14]. Additionally, stable or lower soil electrical conductivity in polyhalite plots reinforces its suitability for long-term application in sensitive soils where salinity is a concern [5, 6].

The broader implications of this research lie in the dual benefits of polyhalite: enhancing crop yield and quality while safeguarding environmental balance. These outcomes are particularly relevant in the context of sustainable intensification, where the challenge lies in meeting food security needs without compromising ecosystem health [7, 10]. The study adds to the growing body of evidence that alternative fertilizers like polyhalite can help close yield gaps sustainably, in line with global calls for more balanced nutrient management [8, 12, 13]. Importantly, this research also supports the need for developing farmer awareness programs and policy frameworks to promote wider adoption of polyhalite, as adoption barriers currently limit its large-scale utilization [11].

Overall, this study confirms the hypothesis that polyhalite, when managed as part of a sustainable nutrient strategy, enhances agricultural productivity and environmental balance. Its multi-nutrient benefits, neutral salinity effect, and potential for residual fertility improvement make it a strong candidate for inclusion in integrated nutrient management systems. However, future long-term studies across diverse soil types and cropping systems are essential to further validate these findings and to ensure that large-scale extraction and application are harmonized with environmental conservation goals [7-10, 12-14].

## Conclusion

The findings of this research reaffirm that polyhalite, as a sustainable multi-nutrient fertilizer, holds significant promise for balancing agricultural productivity with environmental stewardship. Its consistent improvement in crop yields across maize, wheat, and soybean, combined with enhanced uptake of potassium, calcium, magnesium, and sulfur, demonstrates its agronomic superiority over conventional potassium sources. The stability of soil pH, reduction in salinity stress, and the notable buildup of residual fertility further confirm its role in long-term soil health maintenance. Moreover, the lower nitrate leaching observed under polyhalite application highlights its potential contribution to environmentally responsible farming practices. Taken together, these outcomes establish polyhalite as a reliable input for integrated nutrient management systems aimed at sustaining food production while conserving ecological integrity. Based on these findings, several practical recommendations can be made for real-world applications. Farmers should gradually integrate polyhalite into existing fertilization schedules, replacing muriate of potash in phases to reduce the risk of salinity buildup, particularly in soils already prone to chloride accumulation. Site-specific soil testing should guide the dosage, ensuring that application levels correspond to actual nutrient needs of crops and minimize wastage. Policy makers and extension agencies should promote awareness campaigns and training modules for farmers, highlighting the multifaceted benefits of polyhalite, including its slow-release nature, neutral salinity effect, and contribution to crop quality improvement. Fertilizer cooperatives and distribution networks should ensure wider availability of polyhalite at competitive prices to enable its adoption, particularly among smallholder farmers who stand to benefit most from its long-term soil enrichment effects. Agricultural researchers and development agencies should also design large-scale field demonstrations and long-term trials across diverse agro-ecological zones to strengthen confidence in its use and to refine context-specific recommendations. Additionally, integrated crop management practices should be encouraged, where polyhalite is applied alongside organic amendments and nitrogen management strategies to maximize nutrient use efficiency and reduce environmental footprints. On a broader scale, governments and regulatory bodies should incorporate polyhalite into fertilizer subsidy frameworks and sustainability-driven agricultural policies, thereby incenti*viz*ing farmers to transition towards resource-efficient inputs. By embracing these recommendations, polyhalite can be mainstreamed as a key component of sustainable intensification, ensuring that agricultural growth meets the demands of a growing population without undermining the resilience of soils and ecosystems. In essence, polyhalite emerges not only as a nutrient source but as a strategic tool for harmonizing productivity and environmental balance, marking a pivotal step toward future-ready agricultural systems.

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