POLYHALITE: A CHLORIDE-FREE MULTI-NUTRIENT FERTILIZER FOR ENHANCING SOIL FERTILITY AND SUSTAINABLE CROP PRODUCTION

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ABSTRACT:
The secondary macronutrients calcium(Ca), magnesium (Mg) and sulphur (S) are being increasingly depleted from agricultural soils due to the excessive use of nitrogen, phosphorus and potassium (NPK) fertilizers. This led to multiple nutrient deficiencies limiting both crop yield and soil fertility. Polyhalite ($K_2Ca_2Mg(SO_4)_4{\cdot}2H_2O$) is a naturally occurring marine evaporite mineral found 1,200 m below the England's North Sea Coast and has become a promising multi-nutrient fertilizer alternative to conventional potassic fertilizers such as muriate of potash (MOP) and sulphate of potash (SOP) and delivering potassium (14% K_2O), calcium (17% CaO), magnesium (6% MgO) and sulphur (48% SO_3) in one chloride-free application. Along with the impact on soil health and environmental sustainability, this review includes mineralogical origin, dissolution dynamics and agronomic performance of polyhalite in cereals, legumes, oilseeds, horticultural and tuber crops. Its slow-release dissolution enhances nutrient use efficiency and reduces leaching losses. It has a carbon footprint of just 0.034kg CO_2e kg^{-1}, far below MOP and sulphate of potash, and is globally certified organic; a multi-nutrient fertiliser scientifically validated for environmentally responsible, sustainable crop production. field evidence shows yield increases of 20-30% for cereals, 7.5-29% for legumes and 6-14% horticultural crops.

KEYWORDS: Multi-nutrient fertilizer, Chloride-free potassium source, Slow-release mineral, Soil fertility, Nutrient use efficiency, Sustainable agriculture, Crop productivity.

1. INTRODUCTION

The growing interest in sustainable agricultural production has highlighted the need for fertilizers that not only increase crop productivity but also maintain soil health and are economically viable. The overuse of primary nutrients has made this need more critical, as it has led to widespread deficiencies in several essential secondary and micronutrients (Pingali et al., 2012). The Green Revolution led to a huge leap in agricultural productivity through the mass adoption of high-yielding crop varieties, the expansion of irrigation facilities, and increased use of chemical fertilizers. As a result, global cereal production nearly doubled between 1960 and 1985 (Nelson et al., 2019). The pursuit of higher crop yields has encouraged the extensive use of chemical fertilizers, supplying the major plant nutrients nitrogen (N), phosphorus (P) and potassium (K). Despite their contribution to increased productivity, continuous and indiscriminate application of these fertilizers has resulted in nutrient imbalance, reducing the long-term sustainability of soil fertility (Dhaliwal et al., 2019; Pingali et al., 2012). These fertilizers primarily focus on one or two nutrients and often ignore other essential nutrients required for balanced plant growth. As a result, many soils have gradually become deficient in important secondary nutrients, primarily calcium (Ca), magnesium (Mg) and sulphur (S) (Bhatt et al., 2019; Rusu et al., 2024). Deficiency of these plant nutrients has adverse effects on soil health and interferes with several physiological processes. Magnesium plays a vital role as a structural component of chlorophyll during photosynthesis, especially (Grzebisz et al., 2023; Sun et al., 2024). Therefore, insufficient nutrient availability limits the growth of plants, causing a reduction in biomass production, loss of yield and deterioration of crop quality (Akinoglu 2025).

In addition, long-term nutrient depletion in unbalanced soils reduces the inherent fertility of the soil, accelerates salinization and acidification and threatens the sustainability of agriculture. These challenges are more evident in post Green Revolution India, where the adoption of HYVs has aggravated micronutrient deficiencies (Singh 2008; Shukla et al., 2021). To overcome these difficulties by increasing the need to adopt multi-nutrient fertilizers that can supply several vital nutrients at the same time (Vale and Girotto, 2022). Polyhalite is a naturally occurring marine evaporite mineral having the chemical formula $K_2Ca_2Mg\,(SO_4)_4.2H_2O$. It acts as a multi-nutrient fertilizer, providing potassium (14% K2O), calcium (17% CaO), magnesium (6% MgO), and sulfur (48% SO3) in balanced proportions (Yermiyahu et al., 2017; Sirus

Mineral, 2016; Gokul et al., 2023). Besides these four main nutrients, it also contains eight micronutrients that include boron, copper, iron, manganese, molybdenum, selenium, strontium and zinc (Singh et al., 2023).

This fertiliser is suitable for chloride-sensitive crops due to its low chloride content, providing a safe and effective supply of nutrients (Konappan et al., 2025). It was formed geographically about 260 million years ago and is mined from about 1,200 m below the North Sea along the northeast coast of England. It is fit for direct use without any chemical processing (Gahlaut, ICL India, 2024). Its application minimizes the Ca and Mg deficiencies, enhances crop vigour and stabilize crop yield (Yermiyahu et al., 2017). Polyhalite improves nutrient availability by exchanging calcium, which helps the plant to uptake potassium more efficiently, and it also enhances yield and quality (Das et al., 2026). Polyhalite releases more nutrients gradually than conventional fertilizers (Vale and Girotto, 2022), which can improve the availability of nutrients over a longer period of time and also increase the fertilizer use efficiency. Furthermore, the nutrients provided by POLY-4 are relatively immobile in the soil, which helps to reduce leaching losses. Polyhalite has proven to be a multi-nutrient fertiliser in a wide range of crops, including cereals (Kumar et al., 2025), legumes (Karthikeyan et al., 2023) and oilseed crops (Pramanick et al., 2023) in several studies.

2. Origin, Mineralogy and Chemical Composition

The naturally occurring hydrated potassium, calcium, and magnesium sulfate mineral polyhalite ($K_2Ca_2Mg(SO_4)_4{\cdot}2H_2O$) is mostly found in evaporitic rock-salt formations and potash-bearing evaporite deposits (Cheng et al., 2026; Schorn et al., 2012; Kemp et al., 2026). It is widely found in ancient evaporite basins, especially those of Permian and Triassic age, where it frequently coexists with halite, anhydrite and other evaporite minerals that contain potassium and magnesium, such as carnallite, kieserite and sylvite (Peryt et al., 2005; Wang et al., 2024).

The genesis of polyhalite has been explained by two principal mechanisms: direct precipitation from highly concentrated saline brines and more commonly secondary (diagenetic) formation by replacing pre-existing gypsum or anhydrite with sulfate brines rich in potassium and magnesium (Richards et al., 2021; Yuan et al., 2021). Evidence from the Zechstein Basin of Poland and Russia, polyhalite is believed to have formed after the dehydration of syndepositional gypsum to anhydrite and then reacting with chemically evolved marine brines that were high in manganese and potassium. The sulfate was primarily obtained from marine sources, according to sulfur isotope evidence (Peryt et al., 2005). In the Sichuan Basin, primary sedimentary polyhalite associated with halite and secondary radiating polyhalite formed by the metasomatic replacement of gypsum have been reported. Seawater was the controlling factor in the primary formation of polyhalite, while meteoric water and terrigenous inputs contributed to the formation of some secondary deposits (Gong et al., 2021; Zhao et al., 2020). Further evidence from the basin suggests that polyhalite and halite were deposited under conditions involving the mixing of fresh water with concentrated seawater. In the next diagenetic stage, dense potassium- and magnesium-rich brines moved through the pore spaces and replaced the gypsum to form secondary polyhalite (Zhao et al., 2020). Evidence from the Qaidam Basin is more mixed. Some studies support gypsum salting out and transformation in the sedimentary stage to polyhalite, whilst other studies support formation by interaction of deeper Ca-rich brines and K-Mg rich sulfate brines, with temperature variations helping to control deposition (Yuan et al., 2021; Wang et al., 2024). The polyhalite is considered to be essentially a secondary fluid migration product in Alphine evaporites formed during diagenesis and deformation when fluids containing K, Mg and Ca migrated through Studies conducted in the Qaidum Basin have proposed multiple mechanisms for the formation of polyhalite. One hypothesis suggests that the mineral originated through gypsum salting out followed by its transformation during sediment deposition, whereas another attributes indicate that its formation to the interaction between potassium and magnesium rich sulfate brines and deeper calcium rich brines. Variations in temperature are also considered to have influenced the precipitation and accumulation of polyhalite (Yuan et al., 2021; Wang et al., 2024). In contrast, polyhalite occurring in Alphine evaporite deposits is generally regarded as a secondary mineral formed during diagenesis and tectonic deformation. This process involved the migration of potassium, magnesium and calcium-bearing fluids through mudstone, halite and sulfate-bearing strata, resulting in the replacement of pre-existing evaporite minerals (Leitner et al., 2013).

The texture of polyhalite gives useful information on its mode of formation. Long columnar, granular, acicular and pompom-like crystal morphologies are generally characteristic of primary depositional origins, while fibrous, radial, vein-filling, cavity filling and mylonitic textures are characteristic of secondary processes such as mineral replacement, recrystallisation and tectonic deformation (Schorn et al., 2012; Wang et al., 2024). Polyhalite generally retains significant geochemical signatures, but subsequent alteration by meteoric water infiltration, recrystallisation or thermal events can modify original mineral characteristics. Isotopic studies show that many deposits preserve the chemical signature of marine brines formed under evaporative conditions, which provides evidence of the depositional environment (Peryt et al., 2005; Bojar et al., 2019). The overall polyhalite formation process is given in Figure 1.

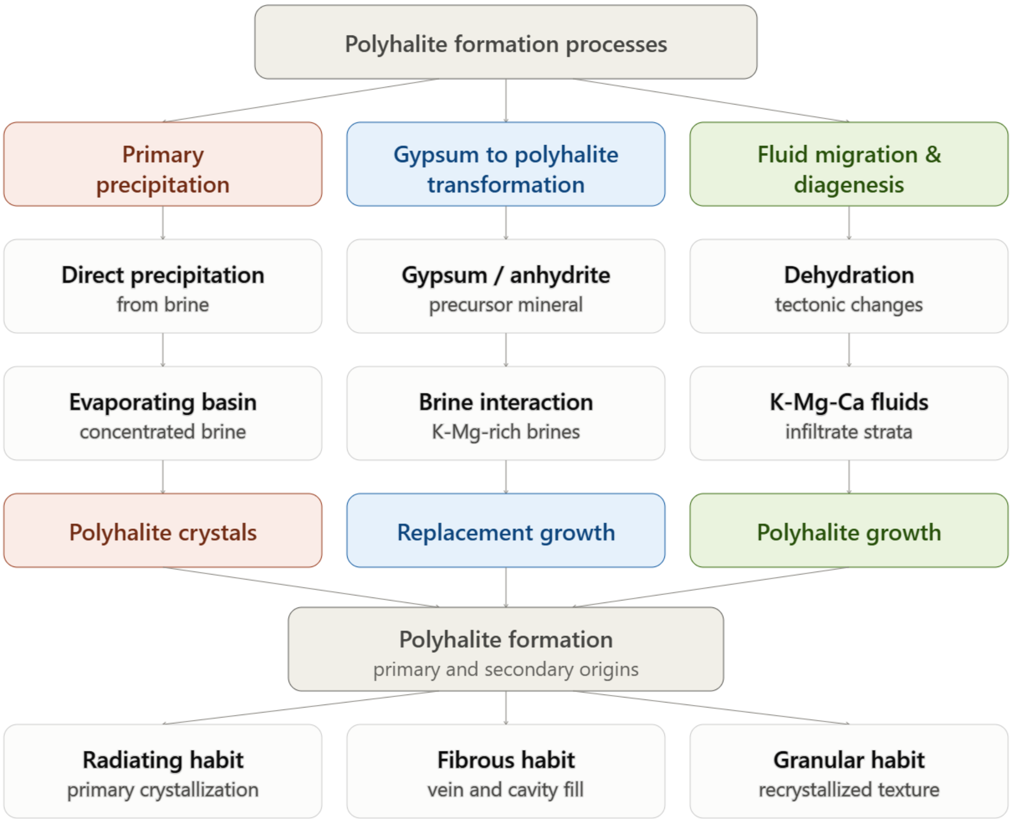

Fig 1: Overall process of polyhalite formation

Polyhalite is a naturally occurring mineral with low water solubility that gradually dissolves in soil moisture, providing a sustained supply of potassium, calcium, magnesium and sulfur throughout the crop growth period (Das et al., 2026). Relatively low solubility of polyhalite, when compared with highly soluble fertilizers such as MOP enables slow release of nutrients, resulting in a sustained supply of nutrients that better matches the crop's demand and improves nutrient use efficiency (Penkala et al., 2025). Dissolution kinetics are governed by soil moisture, temperature and environmental parameters leading to controlled ion mobility and sustained nutrient release during the cropping season (Arunachalam et al., 2025). Additionally, research suggests that nutrients are released in a steady pattern, sometimes controlled by mineral layers, further extending nutrient availability and improving efficiency (Hanafi et al., 2026). The slow, gradual release of nutrients from polyhalite reduces nutrient losses through leaching, particularly in sandy soils and high-rainfall areas, thereby reducing environmental risks and improving fertiliser use efficiency (Bhatt et al., 2024). In addition, polyhalite provides a steady and well-balanced supply of vital nutrients, enhances nutrient retention in the soil and facilitates continuous nutrient uptake by plants during the growing period. These properties guarantee that the nutrients are available at the critical stages of crop development, making polyhalite a promising slow-release multi-nutrient fertiliser for sustainable crop production (Qu et al., 2026).

3. Polyhalite as a combined source of potassium, calcium, magnesium and sulphur

The simultaneous supply of K, Ca and Mg through a single fertilizer is agronomically desirable as these nutrients are taken up as cations, competing for common uptake sites in plant roots. Excess availability of one cation can depress uptake of the others, leading to nutrient imbalances and induced deficiencies. Therefore, a balanced and moderate supply of these nutrients through fertilizers helps in maintaining the nutrient balance and enhances the overall nutrient uptake efficiency in comparison to application of individual potassium or calcium based fertilizers (Mann et al., 2025). Polyhalite provides K, Ca, Mg and S, which all have different but complementary roles in plant growth. Calcium strengthens cell walls and contributes to membrane stability, while potassium regulates osmotic balance, activates many enzymes and helps to improve water use efficiency. Sulfur is needed to make proteins (as sulfate) and amino acids, and magnesium is needed for chlorophyll (which is needed for photosynthesis). It has been shown that the balanced supply of these nutrients from one fertilizer improves chlorophyll concentration, promotes root growth and increases biomass production in a variety of crops. These reactions are a consequence of the four nutrients' complementary physiological functions, not the action of a single nutrient (Mann 2025; Yermiyathu et al., 2017). Figure 2.

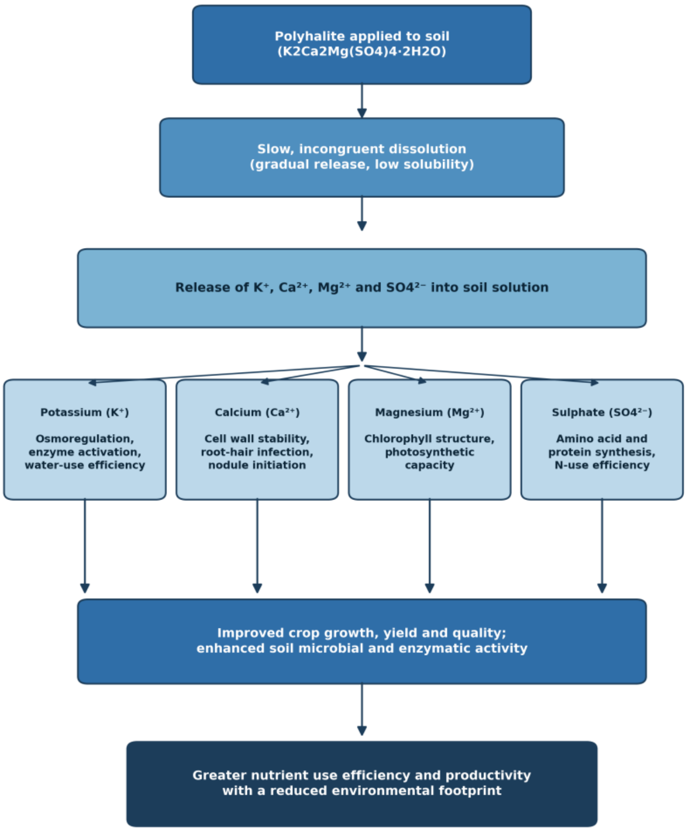

Fig 2: Nutrient release pathway and agronomic roles of polyhalite in soil–plant systems

4. Comparison of polyhalite with conventional fertilizers

Potassium deficiency can reduce the yield by approximately 20% and diminish the capacity of plants to withstand abiotic stresses. MOP is a common potassium fertilizer, but its use is often associated with low nutrient recovery efficiency, poor nutrient balance and increased risk of environmental losses (Kumar et al., 2025). But polyhalite offers a balanced mix of multiple vital nutrients that can help to rectify nutrient imbalances, improve soil health and enhance crop productivity and farm profitability (Kumar et al., 2025). Although polyhalite is applied on a potassium equivalent basis like MOP, it supplies four essential plant nutrients at the same time: potassium (K), calcium (Ca), magnesium (Mg) and sulphur (S). The multi-nutrient composition reduces dependence on additional fertilizer inputs and enhances the economic efficiency of nutrient management. However, repeated application of MOP can result in the accumulation of chloride in the soil, which is detrimental to chloride-sensitive crops (Singh et al., 2023). Soils treated with polyhalite also contained higher amounts of exchangeable calcium and magnesium than soils fertilized with conventional potassium sources (Bhatt et al., 2024). Moreover, it has been reported that polyhalite enhances the activity of important soil enzymes such as β-glucosidase, phosphatase, urease and dehydrogenase, indicating improved biological activity in the soil. The dehydrogenase activity was significantly increased after complete substitution of potassium with polyhalite, indicating enhanced microbial oxidative metabolism and improved soil biochemical functioning (Kumar et al., 2023). Polyhalite has a lower salt index than traditional potassium fertilizers like MOP and SOP and therefore has a lower potential to induce salt stress in crops. In addition, it has a much lower carbon footprint, emitting approximately 0.034 kg CO_2e of greenhouse gases, compared to potassium chloride (KCL) at 0.23 kg CO_2e and potassium sulfate at 0.11 kg CO_2e. These characteristics highlight the environmental advantages of polyhalite as a more sustainable source of plant nutrients (Mann et al., 2025).

5. Effect of polyhalite on soil health and fertility improvement

The agronomic performance of polyhalite depends on soil type, since nutrient release and availability vary under different soil conditions. In sandy soils, the slow release of nutrients may help to reduce leaching losses, but split applications may be recommended where there is high rainfall. In loamy soils, polyhalite gives a regular flow of nutrients to sustain soil microbial activity and promote healthy crop growth (Amelie Van der Broeck et al., 2025). In clay soils, it reduces the fixation of nutrients, thus increasing crop productivity. Overall, polyhalite's balanced nutrient release contributes to long-term soil fertility and sustainable crop production (Lewis et al., 2020). Application of polyhalite significantly improved soil health and fertility by enhancing soil physicochemical and biological properties (Aziz et al., 2023). The balanced multi-nutrient composition of the product improves the bioavailability of nutrients and effectively addresses multiple nutrient deficiencies simultaneously (Das et al., 2026).

a. Soil pH and salinity

Polyhalite contains no chloride, unlike potassium chloride based fertilizers such as MOP, thereby decreasing the risk of soil salinity and helping to maintain a more balanced soil ionic environment (Bhatt et al., 2024). Polyhalite is regarded as a neutral to slightly acidifying fertilizer. A mild acidification during its dissolution, primarily in alkaline soils, may improve the availability of vital nutrients and micronutrients for plant uptake (Dal Molin et al., 2020). In addition, polyhalite supplies Ca and Mg, which enhance the buffering capacity of soil, thus helping to maintain a stable pH of soil and alleviate sudden changes in the soil environment. The slow dissolution of polyhalite provides a constant source of nutrients, which restricts leaching losses and prevents the accumulation of soluble salts in the soil (Yermiyahu et al., 2017; Hanafi et al., 2026).

b. Improves soil structure and CEC

Polyhalite provides Ca and Mg, which improve soil structure by flocculating clay particles, resulting in better soil aggregation, increased pore space and improved aeration (Arunachalam et al., 2025). Consequently, these structural improvements increase water infiltration, support deeper root growth and minimize the risk of soil erosion (Haung et al., 2020). This improved aggregation reduces soil compaction and enhances overall soil physical stability. The continuous and slow release of base cations from polyhalite contributes to an increase in soil CEC by enriching the soil exchange complex with essential nutrients, thereby improving the soil's ability to retain and supply nutrients to plants over time (Das et al., 2026). Furthermore, long-term application of polyhalite enhances cation exchange capacity and buffering capacity, ensuring stable nutrient availability under diverse conditions (Qu et al., 2026).

c. Role of polyhalite on soil microbes

Bacteria, fungi, and actinomycetes constitute the major soil microbial groups responsible for organic matter decomposition, nutrient mineralization, and the maintenance of soil productivity. Polyhalite improves soil physiological properties, enhances cation exchange capacity and creates favourable conditions for microbial activity. Its sustained nutrient availability also reduces nutrient losses through leaching, thereby supporting microbial diversity and long-term soil health (Adak and Sengupta, 2026). Studies have demonstrated that polyhalite stimulates the activity of important soil enzymes involved in nutrient transformation, such as β-glucosidase, phosphatase, urease and dehydrogenase more efficiently than traditional fertilizers. Replacing the entire potassium requirement with polyhalite markedly increased dehydrogenase activity, suggesting greater microbial respiration and biological activity in the soil (Kumar et al., 2023). Similarly, in the maize-wheat production system of the Indo-Gangetic Plains, polyhalite showed higher microbial biomass carbon and dehydrogenase activity than MOP, suggesting a balanced supply of calcium, magnesium and sulphur that helps create a more active rhizosphere and improves overall soil biological quality (Singh et al., 2023). In peanut cultivation under eastern China conditions, partial substitution of potassium chloride with polyhalite significantly increased rhizosphere microbial diversity and improved nutrient distribution in kernels. These beneficial responses were attributed to lower chloride accumulation in the soil under polyhalite fertilization, which created a more favourable environment for chloride sensitive soil microorganisms (Tan et al., 2022). Collectively, the balanced supply of potassium, calcium, magnesium and sulphur from polyhalite, its chloride-free nature and the gradual release of nutrients all support soil microbial populations, enhance the activity of soil biological fertility, thus contributing to sustainable crop productivity.

6. Suitable for chloride-sensitive crops

The chloride-free composition of polyhalite makes it an appropriate potassium source for chloride sensitive crops. Unlike MOP, which supplies potassium in the form of potassium chloride, polyhalite does not contribute to the buildup of chloride in the soil, decreasing the risk of salinity stress and chloride toxicity (Das et al., 2026). The absence of chloride in polyhalite makes it an ideal potassium source for chloride-sensitive crops, reducing the likelihood of salinity related stress and supporting healthy crop growth under a wide range of soil conditions (Barbier et al., 2024). This is particularly beneficial for chloride-sensitive crops such as fruits, vegetables and legumes (Singh et al., 2023; Tan et al., 2022). Polyhalite's chloride-free nature makes it suitable for chloride-sensitive crops by minimizing the risk of soil salinity. Unlike MOP, which supplies potassium as potassium chloride and may promote chloride accumulation in the soil with continuous use, polyhalite maintains a balanced soil chemical environment without causing significant changes in soil pH. These characteristics help minimize salinity-related problems and support long-term soil health (Adak and Sengupta, 2026). Owing to its low salt index, polyhalite imposes minimal osmotic stress on the soil, thereby creating favourable conditions for healthy plant growth and development (Mann et al., 2025). Polyhalite is a good supplement to traditional mineral fertilizers as it supplies nutrients slowly and reduces environmental impacts by having a low carbon footprint, minimal processing and a low salt index (Haung et al., 2020; Mann et al., 2025). Its gradual dissolution under soil moisture enables the progressive release of essential nutrients, providing crops with long-term nutrient availability. This results in more efficient use of fertiliser nutrients and less loss through leaching and runoff, limiting the need for repeated fertiliser applications (Penkala et al., 2025).

7. Effect of polyhalite on crops

7. 1. cereals

Polyhalite application in cereals includes rice, wheat and maize has been shown to increase grain yield, improve grain quality parameters and enhance resistance to abiotic stresses. The field studies on cereal crops have shown that the application of polyhalite as a source of potassium improves plant height, tiller production, leaf area and dry matter production and leads to an increase in grain yields than those obtained with conventional potassium fertilizers (Kumar et al., 2023). Through its gradual nutrient release, polyhalite maintains the availability of essential nutrients during key stages of crop development, supporting vigorous plant growth while minimizing nutrient losses (Das et al., 2026). Repeated application of polyhalite also improves soil fertility and creates positive residual nutrient effects that help to maintain the productivity of cereal-based cropping systems over subsequent seasons (Mann et al., 2025). Research evidence shows that polyhalite is a sustainable alternative to conventional fertilizers such as MOP, particularly in improving yield stability, quality and nutrient use efficiency as shown in Table 1.

Table 1: Effect of polyhalite on cereal crops

Crop / system	Location	Key findings	References
Wheat	ICAR-IARI, New Delhi, India.	Replacing MOP entirely with polyhalite at 100% K dose boosted wheat grain yield by nearly 30%. The multi-nutrient package-K, Ca, Mg and S delivered together- activated key soil enzymes, including dehydrogenase and improved microbial biomass carbon, meaning the soil itself became more biologically active	Kumar et al., 2023
Maize	Trans Indo-Gangetic Plains, India (2 yrs)	Polyhalite increased grain yield by over 20% at 100% potassium application and exceeded 26% at 150% potassium levels compared to potassium deficient plots. It also enhances photosynthetic efficiency and carbohydrate translocation, while calcium contributed to maintaining cell structure during cob formation.	Singh et al., 2023
Rice	Annamalai University, Tamil Nadu, kharif 2023	Comparing the Pot application of polyhalite with MOP at different potassium levels, the highest plant height, tiller density, panicle length and grain filling percentage were observed at 200% potassium supplied through polyhalite. This is due to the presence of Ca and Mg in polyhalite, which enhance chlorophyll synthesis, cell division and early tillering.	Karthikeyan et al., 2025
Rice-wheat sequence	ICAR-IARI, New Delhi-rabi 2021-22	Supplying 100% K through polyhalite shows better results in nutrient uptake, root growth and nutrient balance. It also improves soil fertility by increasing available potassium (about 5 Kg/ha) and sulphur (about 2 Kg) compared to MOP. Overall, its balanced nutrients and slow release help crops grow better and support long term soil health.	Kumar et al., 2025
Sugarcane	Arachalur, Erode, Tamil Nadu	Application of 150% K through polyhalite along with recommended nitrogen and P significantly improved growth, cane yield (481 t ha^{-1}) and sugar yield (30.5 t ha^{-1}) in sugarcane. This was mainly due to the balanced and steady nutrient supply from polyhalite. It also improves juice and sugar quality.	Gokul et al., 2023
Sugarcane	Kapurthala, PAU- Panjab, India.	The experiment was conducted during the summer season in semi-arid tropical locations of Ca-deficient soil. The results indicated that application of 80 kg of K2O ha^{-1} as MOP + polyhalite 50% ratio of MOP obtained superior quality, growth, yield and reduced pest incidence compared to the other convention fertilizer treatments.	Bhatt et al., 2024

7. 2. Legumes

Sulfur from polyhalite plays a crucial role in amino acid and protein biosynthesis, and its deficiency limits the efficient utilization of macronutrients such as N, P and K. That emphasizing the importance of adequate sulfur supply for improving crop yield and quality (Arunachalam et al., 2025). In legumes, sulfur from polyhalite facilitates the biosynthesis of iron-sulfur proteins such as ferredoxin and nitrogenase, which are integral to biological nitrogen fixation in root nodules. Polyhalite not only provides nutrients directly but also improves nitrogen fixation in plants.

Among grain legumes, the response of blackgram (Vigna mungo) to polyhalite was evaluated under field conditions in Cuddalore, Tamil Nadu. comparative studies with MOP applied at varying potassium levels, the highest grain (1,439 kg ha^{-1}) and haulm (1,876 kg ha^{-1}) yields were obtained with polyhalite, showing its superior performance as a source of potassium (Karthikeyan et al., 2023). Similarly, in groundnut, the combined application of polyhalite with NP fertilizers significantly improved pod yield, haulm yield, kernel yield, and harvest index over two cropping seasons. Pod yield increased by 7.5-29.0% compared with gypsum-treated and untreated control plots, which was attributed to the balanced and gradual release of essential nutrients from polyhalite (Gopinath et al., 2024). In alfalfa, polyhalite application produced significantly greater biomass yields and improved the uptake of potassium, sulphur, calcium and magnesium than potassium chloride (KCl), irrespective of gypsum application. In contrast, the highest KCl dose reduced calcium uptake because of ionic antagonism, whereas polyhalite sustained greater calcium absorption across most treatment combinations owing to its balanced nutrient composition (Bernardi et al., 2018). A corn-bean rotation system demonstrated that the polyhalite applied to the preceding corn crop exerted favourable residual effects on the following bean crop. The prolonged availability of nutrients released through its gradual dissolution contributed to improved crop performance, emphasizing the long-term benefits of polyhalite in rotational cropping systems (Baez-Perez et al., 2021).

7. 3. Horticultural crops

Polyhalite has proven highly effective in horticultural crops such as onion, garlic, cabbage and tomato by improving yield, nutrient use efficiency and crop quality. Its slow release behaviour ensures a sustained supply of potassium, calcium, magnesium, and sulphur throughout the growing season, making it particularly suitable for high-value horticultural crops (Yermiyahu et al., 2017). Research indicates that applying 100% POLY4 alone significantly enhanced bulb yield and nutrient uptake in onion and garlic due to its balanced and slow release nutrient supply compared to MOP-based treatments (Arunachalam et al., 2025; Singh et al., 2026). In tomato, polyhalite resulted in significantly increased marketable fruit yield and enhanced foliar potassium and sulfur concentrations in both leaves and fruits under soil with low potassium content. It also improved postharvest soil fertility by increasing residual Ca, Mg and S compared to other K sources. Fruits from polyhalite treated plants resulted in higher S concentration, whereas MOP exhibited reduced S levels, likely due to competitive inhibition between chloride and sulfate ions during uptake (De Costa Mello et al., 2018). Because of its progressive and prolonged nutrient availability, studies have shown that polyhalite promotes vigorous vegetative growth and greater nutrient uptake in leafy plants like lettuce, leading to higher productivity and decreased nutrient losses (Wu et al., 2025). A balanced supply of potassium, calcium, magnesium and sulfur has been shown to enhance crop yield, nutrient use efficiency and marketable quality in cabbage and other horticultural crops (Yermiyahu et al., 2017).

7 .4. Oilseed crops

Polyhalite plays a significant role in oilseed crops by enhancing both yield and quality due to its ability to supply multiple essential nutrients, particularly sulfur, potassium, calcium and magnesium in a balanced form (Das et al., 2026). Oilseed crops such as mustard, soybean and groundnut have a high requirement for sulphur because it plays a vital role in oil synthesis and protein formation (Manoj et al., 2023). Consequently, the application of polyhalite has been reported to improve seed quality and increase oil content by supplying sulphur along with potassium, calcium and magnesium in a balanced form (Pramanick et al., 2023). It also supports better seed development by facilitating efficient nutrient acquisition and supporting essential physiological processes required for normal plant growth and seed formation (Singh et al., 2023).

Studies on peanut cultivation have shown that polyhalite improves pod yield, nutrient uptake and soil properties, which enhance overall crop performance under field conditions (Gopinath et al., 2024). In mustard and sesame, the application of polyhalite has been reported to increase seed yield and improve quality attributes by providing a balanced supply of potassium, calcium, magnesium, and sulphur, thereby enhancing sulphur availability to the crop (Tiwari et al., 2015). The additional supply of calcium and magnesium supports root development, photosynthetic activity and nutrient translocation, resulting in improved crop growth and productivity (Dal et al., 2020). Likewise, in soybean-based production systems, polyhalite improves the movement and availability of calcium and magnesium throughout the soil profile, thereby enhancing nutrient acquisition and supporting vigorous plant growth (Vale, 2016).

7. 5. Tuber crops

Potassium application in potato and sweet potato improves tuber productivity and quality by supplying a balanced amount of potassium, calcium, magnesium and sulphur over a long period. Sufficient potassium helps in the production of carbohydrates and the movement of assimilates to the developing tubers, while the long-term availability of nutrients enhances the development of tubers, leading to higher yields, larger tubers and better size uniformity (De Costa Mello et al., 2018). In addition, the calcium in polyhalite contributes to the formation of stronger cell walls, improving skin integrity and reducing physiological defects such as tuber cracking (Keren Keiserman et al., 2019).

Polyhalite increases the availability of nutrients in soil and improves long-term fertility of soil, both of which are important for sustaining tubber-based production systems. Studies in temperate regions have shown that polyhalite increases total and marketable potato yield and improves quality characters like tuber dry matter content, an important feature for the processing industry (Garnett, 2021). Recent studies have also shown its efficiency in sweet potato production, where the gradual supply of vital nutrients enhances yield and nutrient use efficiency while reducing nutrient leaching losses (Kile et al., 2025). Overall, the use of polyhalite in nutrient management programs provides an effective approach to increasing tuber yields, improving the quality of produce and maintaining soil fertility and thus promoting sustainable crop production.

8. Effect of polyhalite on environmental sustainability and carbon footprint

Polyhalite is a naturally occurring mineral fertilizer that needs little processing before use. The only processes involved in its production are mining, crushing, screening and bagging without any chemical treatment. This results in negligible processing waste and a relatively low environmental footprint (ICL India, 2024). Life cycle assessments show that polyhalite has a carbon footprint of 0.034 kg CO2e per kg fertilizer, which is much lower than potassium chloride (0.23 kg CO_2e per kg) and potassium sulphate (0.11 kg CO_2e per kg). Polyhalite is one of the most environmentally sustainable potassium fertilizers, as it has low greenhouse gas emissions and a simple production process (Vale and Girotto, 2022). As a naturally occurring mineral fertilizer, it is widely recognised and approved for use in organic agriculture across the globe and possesses organic certification across multiple countries according to the USDA National Organic Program regulations. (ICL Growing Solutions, 2026). These characteristics make polyhalite more appropriate to farming systems that are concerned about carbon emissions, and it also has a lower carbon footprint than conventional fertilizers, which helps to reduce greenhouse gas emissions and promote sustainable farming practices. Therefore, polyhalite has a very low impact on the environment (ICL India, 2024). This makes polyhalite one of the most sustainable potassium fertilisers available on the market today, allowing reductions in greenhouse gas emissions without compromising agronomic performance (Vale and Girotto, 2022).

CONCLUSION:

Polyhalite has established itself as an agronomically superior and environmentally responsible multi-nutrient fertilizer for sustainable crop production. Its unique ability to supply potassium, calcium, magnesium and sulfur simultaneously through a single chloride-free, slow-release mineral source addresses the critical secondary and tertiary nutrient deficiencies that conventional NPK programs routinely fail to correct. Across cereals, legumes, oilseeds, horticultural and tuber crops, polyhalite consistently improved grain yield, crop quality, oil content and nutrient use efficiency, while its sustained nutrient release supported vigorous root growth, enhanced photosynthesis and strengthened biological nitrogen fixation in legumes. Beyond its direct nutritional benefits, polyhalite improved soil cation exchange capacity, microbial biomass carbon, enzyme activity and rhizosphere biodiversity, functioning simultaneously as a soil biological amendment. Its chloride-free composition prevented the salinity stress and Rhizobium inhibition associated with long-term MOP use. With the lowest carbon footprint among commercially available potassium fertilizers and approval for certified organic farming systems worldwide, polyhalite aligns uniquely with the dual imperatives of agricultural productivity and environmental sustainability. Future research should focus on crop and soil specific calibration of application rates, long-term residual effects in diverse rotational systems, and integration with biofertilizers and precision nutrient management technologies to maximize the potential of polyhalite across varied agroecological settings.

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