



Magnesium: Functions, Deficiency, Toxicity and Corrective Measures—A Review

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Abstract

Magnesium (Mg) is an essential secondary macronutrient that contributes to numerous structural, physiological, and biochemical processes in plants. This review examines the major functions of Mg in plant nutrition, the causes and consequences of Mg deficiency and excessive Mg supply, and the principal approaches used for corrective management. Magnesium is central to chlorophyll structure and is involved in photosynthesis, energy transfer, enzyme activation, protein and nucleic acid synthesis, carbohydrate metabolism, phloem loading, assimilate translocation, and ionic regulation. Deficiency commonly develops in acidic, coarse-textured, highly weathered, or intensively cultivated soils where Mg reserves are limited or losses through leaching and crop removal are substantial. Nutrient imbalance, particularly excessive potassium supply, may further restrict Mg uptake. Characteristic deficiency symptoms include interveinal chlorosis of older leaves, followed by progressive chlorosis, necrosis, premature senescence, impaired photosynthesis, disturbed carbohydrate partitioning, and reductions in crop growth and productivity. Excessive Mg is less frequent and primarily causes problems through antagonistic interactions with calcium and potassium and through unfavourable cation balance. Appropriate management therefore requires soil and plant diagnosis, balanced fertilisation, suitable Mg-containing amendments, correction of soil acidity, organic inputs, foliar supplementation where appropriate, and careful management of interacting nutrients. An integrated diagnostic approach can support adequate Mg nutrition while avoiding unnecessary nutrient application.

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1. Introduction

Plant nutrition is a fundamental component of agricultural productivity and sustainability. Among the essential nutrients required by plants, magnesium occupies a unique position as a secondary macronutrient. Although required in smaller quantities than nitrogen, phosphorus, and potassium, magnesium is indispensable for several physiological and biochemical processes. In Indian agriculture, magnesium deficiency has emerged as a significant constraint, particularly in acidic soils, sandy soils, and intensively cultivated areas.

Magnesium (Mg) is an essential plant nutrient that is frequently overlooked. Although weathering of primary and secondary minerals may provide sufficient magnesium in some soils, other soils benefit from magnesium additions. Different soluble and slowly dissolving magnesium sources are available to meet crop needs. The Earth's crust contains about 2.0% magnesium, largely in magnesium-containing minerals (Mikkelsen, 2010). The supply of available magnesium has been or is being depleted in certain soils through leaching, plant uptake, and removal processes. Among the secondary nutrients, Mg plays an indispensable role in crop development. The Mg requirement for optimal plant growth is 1.5–3.5 g per kg in vegetative parts, and Mg concentrations in soil solutions range between 125 $\mu\text{mol L}^{-1}$ and 8.5 mmol L^{-1} , values adequate to support plant development (Guo *et al.*, 2016).

Furthermore, magnesium is absorbed by plants in the divalent cationic form (Mg^{2+}) and is mobile within the plant system. Due to its mobility, deficiency symptoms generally appear first in older leaves. Understanding the role of magnesium and its management is essential for ensuring balanced plant nutrition and improving crop yield and quality. Crop-specific evidence also indicates that magnesium supplementation can improve productivity under responsive conditions; positive crop responses have been reported under the tested magnesium treatments in oil palm and coriander (Oliveira *et al.*, 2018; Ibrahim *et al.*, 2023). Recent research further shows that magnesium management can influence photosynthetic performance and yield formation, whereas magnesium deficiency may disrupt photosynthetic electron transport and energy balance (Gao *et al.*, 2024; Zhu *et al.*, 2025). Despite the established importance of magnesium, evidence concerning its physiological functions, deficiency and toxicity, and practical corrective measures remains dispersed across separate lines of research, creating a need for an integrated synthesis that links plant responses with nutrient-management approaches. This review article highlights the important functions and roles of magnesium in crop plants and provides an overview of the characteristic symptoms associated with magnesium deficiency.

1.1 Detailed Definitions of Key Concepts

1.1.1 Magnesium (Mg)

Magnesium (Mg) is an essential secondary macronutrient required by plants in relatively large amounts for normal growth, development, metabolism, and productivity. It is considered a key element in plant nutrition because it performs both structural and regulatory functions. Approximately 15–20% of total Mg in plant tissues may be associated with chlorophyll, where Mg occupies the central position in the chlorophyll molecule. The remaining Mg is distributed among the cytoplasm, chloroplasts, vacuoles, and other cellular compartments, where it participates in enzyme activation, energy metabolism, nucleic acid synthesis, protein synthesis, and carbohydrate metabolism (Cakmak and Kirkby, 2008; Gerendás and Führes, 2013). Magnesium is also involved in the stabilisation of ribosomes and nucleic acids and in the formation of Mg–ATP complexes, making it essential for numerous biochemical reactions (Shaul, 2002; Verbruggen and Hermans, 2013). Consequently, inadequate Mg nutrition can adversely affect photosynthesis, carbohydrate partitioning, plant growth, yield formation, and crop quality (Cakmak and Yazici, 2010; Hauer-Jákli and Tränkle, 2019).

1.1.2 Magnesium Ion (Mg^{2+})

The magnesium ion (Mg^{2+}) is the principal ionic form of Mg absorbed by plant roots from the soil solution. Following uptake, Mg^{2+} is transported through the xylem to shoots and can subsequently be redistributed through the phloem according to the metabolic demand of different plant organs (Shaul, 2002; Hermans *et al.*, 2013). Within plant cells, Mg^{2+} interacts with negatively charged molecules and forms complexes with ATP, phosphate-containing compounds, proteins, and nucleic acids. These interactions contribute to enzyme activation, membrane stability, energy transfer, and maintenance of cellular ionic balance (Shaul, 2002; Guo *et al.*, 2016). The uptake and intracellular homeostasis of Mg are regulated by specific transport proteins, including members of the MGT/MRS2 family, which are involved in Mg transport across cellular membranes (Gebert *et al.*, 2009; Hermans *et al.*, 2013).

1.1.3 Secondary Macronutrients

Secondary macronutrients comprise calcium (Ca), magnesium (Mg), and sulfur (S), which are required by plants in quantities greater than micronutrients but generally lower than the primary macronutrients nitrogen, phosphorus, and potassium. Magnesium has a particularly important role in photosynthesis, enzyme activation, ATP metabolism, and carbohydrate transport, whereas Ca is mainly associated with cell-wall structure and cellular signalling and S is essential for sulfur-containing amino acids and several coenzymes (Marschner, 2012). Despite being classified as a secondary macronutrient, Mg deficiency can considerably reduce crop productivity because of its involvement in several fundamental metabolic processes (Cakmak and Kirkby, 2008; Gerendás and Führes, 2013).

1.1.4 Chlorophyll Molecule

Chlorophyll is the principal photosynthetic pigment present in chloroplasts and is responsible for capturing solar radiation required for photosynthesis. Magnesium occupies the central position of the chlorophyll porphyrin ring and is therefore structurally essential for chlorophyll formation and photosynthetic activity (Marschner, 2012; Cakmak and Kirkby, 2008). Adequate Mg nutrition contributes to the maintenance of chlorophyll concentration, photosynthetic electron transport, and carbon assimilation. Under Mg deficiency, chlorophyll concentration and photosynthetic efficiency decline, resulting in characteristic chlorosis and reduced plant productivity (Cakmak and Yazici, 2010; Hauer-Jákli and Tränkner, 2019).

1.1.5 Photosynthesis

Photosynthesis is the fundamental biochemical process through which green plants convert light energy into chemical energy and synthesize carbohydrates from carbon dioxide and water. Magnesium contributes to photosynthesis through several mechanisms, including its structural role in chlorophyll, activation of enzymes involved in carbon fixation, and formation of Mg–ATP complexes required for energy-dependent reactions (Cakmak and Kirkby, 2008; Gerendás and Führes, 2013). Magnesium deficiency can therefore reduce chlorophyll concentration, stomatal function, carbon assimilation, and photosynthetic efficiency. A systematic review and meta-analysis demonstrated that Mg deficiency significantly decreases photosynthetic performance and biomass production across plant species (Hauer-Jákli and Tränkner, 2019).

1.1.6 Enzyme Cofactor

Magnesium acts as an essential cofactor or activator for numerous enzymes involved in plant metabolism. It is particularly important for enzymes associated with phosphorylation, carbohydrate metabolism, nucleic acid metabolism, protein synthesis, and energy transfer (Shaul, 2002; Cakmak and Kirkby, 2008). In many enzymatic reactions, Mg^{2+} either interacts directly with the enzyme or forms a complex with the substrate, thereby facilitating catalytic activity. Its association with ATP is particularly important because Mg stabilizes the negatively charged phosphate groups of ATP and enables efficient phosphorylation reactions (Guo *et al.*, 2016). Thus, Mg deficiency can affect multiple metabolic pathways simultaneously rather than being restricted to photosynthetic processes.

1.1.7 ATP–Magnesium Complex

A substantial proportion of cellular ATP exists physiologically as a Mg–ATP complex. Magnesium binds to the phosphate groups of ATP and reduces electrostatic repulsion, thereby facilitating the interaction of ATP with enzymes involved in phosphorylation and energy-transfer reactions (Shaul, 2002; Cakmak and Kirkby, 2008). Mg–ATP is consequently important for numerous cellular processes, including active transport, protein phosphorylation, carbohydrate metabolism, and biosynthetic reactions. A reduction in Mg availability may impair these ATP-dependent processes and contribute to the overall decline in plant growth and metabolic activity observed under Mg deficiency (Guo *et al.*, 2016).

1.1.8 Phloem Loading

Phloem loading is the physiological process through which photoassimilates, particularly sucrose, are transferred from source leaves into the phloem for transport to developing sink organs. Magnesium plays an important role in maintaining efficient carbohydrate production and translocation. Under Mg deficiency, sucrose export from source leaves can be impaired, resulting in the accumulation of sucrose and starch in mature leaves (Cakmak and Kirkby, 2008). This restriction in carbohydrate partitioning may occur even before severe visual deficiency symptoms become apparent, indicating that Mg deficiency can affect plant physiology at an early stage (Hermans *et al.*, 2005; Cakmak and Kirkby, 2008).

1.1.9 Source–Sink Relationship

The source–sink relationship represents the movement and partitioning of photosynthetically produced assimilates from source organs, particularly mature leaves, to sink organs such as roots, young leaves, flowers, fruits, seeds, and developing grains. Magnesium plays an important role in maintaining this relationship through its effects on photosynthesis, sucrose synthesis, phloem loading, and carbohydrate transport (Cakmak and Kirkby, 2008). Under Mg deficiency, impaired phloem export may cause sucrose and starch accumulation in source leaves while restricting carbohydrate supply to developing sink tissues. Consequently, Mg deficiency can alter dry matter partitioning, reproductive development, and ultimately crop yield (Hermans *et al.*, 2005; Cakmak and Yazici, 2010).

1.1.10 Magnesium Deficiency

Magnesium deficiency occurs when the supply of plant-available Mg is inadequate to meet crop requirements. It may result from naturally Mg-deficient soils, intensive cropping, high rainfall, excessive irrigation, soil acidification, sandy soil texture, low cation exchange capacity, and imbalanced fertiliser application (Gransee and Führes, 2013; Guo *et al.*, 2016). Since Mg is relatively mobile within plants, it can be retranslocated from older leaves to younger tissues and developing reproductive organs. Consequently, deficiency symptoms generally appear first in older leaves (Marschner, 2012). Initial symptoms commonly include pale green coloration and interveinal chlorosis, followed by severe chlorosis, necrosis, premature leaf senescence, reduced photosynthesis, impaired carbohydrate transport, and yield reduction (Cakmak and Kirkby, 2008; Hauer-Jákli and Tränkner, 2019).

1.1.11 Interveneal Chlorosis

Interveneal chlorosis is one of the most characteristic visual symptoms of Mg deficiency. It is expressed as yellowing of the leaf tissues between the veins while the veins remain relatively green. The symptom generally develops first on older leaves because Mg can be remobilized from older tissues toward actively growing tissues when external Mg supply becomes inadequate (Marschner, 2012; Guo *et al.*, 2016). As deficiency becomes more severe, chlorotic areas may develop necrotic lesions and premature leaf senescence. However, intervenal chlorosis should not be considered exclusively diagnostic of Mg deficiency because similar symptoms can occur under deficiencies of other nutrients and under certain environmental stresses. Therefore, visual diagnosis should ideally be complemented by plant tissue and soil analysis (Hauer-Jákli and Tränkner, 2019).

1.1.12 Hidden Hunger

Hidden hunger refers to a nutritional condition in which nutrient availability is inadequate for optimum physiological performance and yield despite the absence of obvious visible deficiency symptoms. In Mg-deficient plants, physiological disturbances such as reduced photosynthesis, impaired carbohydrate export, altered enzyme activity, and reduced biomass accumulation may occur before severe chlorosis becomes visible (Cakmak and Kirkby, 2008; Hauer-Jákli and Tränkner, 2019). Therefore, reliance solely on visual symptoms may underestimate the importance of Mg deficiency in crop production. Soil testing and plant tissue analysis can help identify marginal Mg nutrition before severe visual symptoms and yield losses develop.

1.1.13 Magnesium Toxicity

Magnesium toxicity is relatively uncommon under normal agricultural conditions compared with Mg deficiency. Excessive Mg availability is more commonly associated with nutritional imbalance and antagonistic interactions with other cations than with direct toxic effects. High Mg concentrations in the soil solution or exchange complex may influence the uptake and distribution of Ca and K, potentially disturbing the nutritional balance of plants (Marschner, 2012; Senbayram *et al.*, 2015). Therefore, Mg fertilisers should be applied according to soil-test results, crop requirement, and the existing balance of exchangeable cations.

1.1.14 Nutrient Antagonism

Nutrient antagonism occurs when an excess or high concentration of one nutrient suppresses the uptake, transport, or utilization of another nutrient. Magnesium exhibits important interactions with K and Ca. In particular, excessive K availability or heavy application of K fertilisers may suppress Mg uptake and induce Mg deficiency even when exchangeable Mg is present in the soil (Marschner, 2012; Xie *et al.*, 2021). Similarly, the balance between Mg and Ca can influence cation uptake and physiological functions. Therefore, Mg management should be considered within the broader framework of balanced cation nutrition rather than as an isolated nutrient-management practice (Senbayram *et al.*, 2015).

1.1.15 Soil Cation Exchange Capacity (CEC)

Cation exchange capacity (CEC) represents the total capacity of soil colloids to retain and exchange positively charged ions. Magnesium is present in soils in several forms, including soil-solution Mg, exchangeable Mg, and more strongly retained forms. Exchangeable Mg is an important source for plant uptake and is influenced by soil texture, clay mineralogy, organic matter, CEC, and the concentrations of competing cations (Gransee and Führs, 2013). Soils with low CEC, particularly sandy soils, have limited capacity to retain exchangeable Mg and are therefore more susceptible to Mg depletion through leaching. Consequently, CEC is an important soil property when assessing Mg availability and fertiliser requirements.

1.1.16 Magnesium Leaching

Magnesium leaching refers to the downward movement of soluble Mg beyond the plant root zone with percolating water. The risk of Mg loss is particularly high in coarse-textured soils with low CEC, especially under conditions of high rainfall or excessive irrigation (Gransee and Führs, 2013). Soil acidification can further increase Mg losses by increasing competition among cations and promoting displacement of Mg from exchange sites. Continuous cropping without adequate Mg replenishment may therefore gradually reduce soil Mg reserves and increase the likelihood of deficiency (Cakmak and Yazici, 2010; Senbayram *et al.*, 2015).

1.1.17 Dolomitic Limestone

Dolomitic limestone is a soil amendment containing calcium and magnesium carbonates and is commonly used for simultaneous correction of soil acidity and Mg deficiency. Application of dolomitic limestone increases soil pH while supplying Mg and Ca to the soil. It is particularly appropriate for acidic soils where both low pH and inadequate Mg availability occur. The selection of dolomitic limestone should, however, be based on soil pH, lime requirement, exchangeable Ca and Mg, soil texture, and crop requirements (Marschner, 2012; Gransee and Führs, 2013).

1.1.18 Magnesium Sulphate

Magnesium sulphate is a highly soluble fertilizer that supplies both Mg and sulfur and is commonly used for correcting Mg deficiency. Because of its high solubility, it can provide Mg relatively rapidly when compared with less soluble Mg-containing amendments. Magnesium sulphate may be applied to soil or used as a foliar nutrient source, depending on crop requirement and the

severity of deficiency. Foliar application can provide a rapid supplementary supply of Mg, although it should generally be considered complementary to adequate soil Mg management rather than a complete replacement for soil fertilisation (Senbayram *et al.*, 2015).

1.1.19 Foliar Nutrition

Foliar nutrition involves applying nutrient solutions directly to the foliage to facilitate nutrient absorption through the leaf surface. Foliar Mg application has been used as a supplementary strategy for rapidly alleviating Mg deficiency, particularly during periods of high crop demand or when soil conditions restrict nutrient availability. The effectiveness of foliar Mg depends on crop species, leaf characteristics, formulation, concentration, environmental conditions, and application timing. Therefore, foliar application should be integrated with soil-based nutrient management for sustainable correction of Mg deficiency (Cakmak and Kirkby, 2008; Senbayram *et al.*, 2015).

1.1.20 Integrated Nutrient Management (INM)

Integrated nutrient management involves the combined and balanced use of mineral fertilizers, organic amendments, crop residues, biological inputs, and appropriate soil-management practices to maintain soil fertility and crop productivity. In Mg management, INM may include the use of Mg-containing fertilizers, dolomitic materials, organic amendments, recycling of crop residues, and balanced application of K and other nutrients. Organic matter can contribute to nutrient retention and improve soil properties, while balanced mineral fertilisation can directly replenish plant-available Mg. An integrated approach is therefore important for maintaining long-term Mg fertility in intensively cultivated soils (Senbayram *et al.*, 2015; Gransee and Fühns, 2013).

1.1.21 Soil Acidity

Soil acidity is an important factor influencing Mg availability. Under acidic conditions, Mg may be displaced from soil exchange sites and subsequently lost through leaching, particularly in soils with low CEC (Gransee and Fühns, 2013). In addition, acidic soils may contain elevated concentrations of Al^{3+} and H^+ , which can adversely affect root development and nutrient uptake. Liming can improve the soil chemical environment, reduce acidity, and increase the efficiency of nutrient uptake. Where both soil acidity and Mg deficiency occur, dolomitic limestone provides an advantage because it supplies Mg while simultaneously neutralizing soil acidity (Marschner, 2012).

1.1.22 Magnesium in Sustainable Agriculture

Magnesium is an important component of sustainable crop nutrition because adequate Mg supply supports photosynthesis, carbohydrate production and transport, enzyme activity, biomass accumulation, yield formation, and crop quality (Cakmak and Kirkby, 2008; Gerendás and Fühns, 2013). Conversely, prolonged Mg depletion can reduce crop productivity even when N, P, and K are supplied adequately. Sustainable Mg management should therefore include regular soil and plant analysis, balanced fertilisation, appropriate selection of Mg sources, recycling of crop residues and organic resources, correction of soil acidity, and management of nutrient antagonism, particularly excessive K application (Cakmak and Yazici, 2010; Senbayram *et al.*, 2015). Maintaining adequate Mg availability may consequently improve nutrient-use efficiency, sustain crop productivity, and contribute to the nutritional quality of food crops.

2. Functions of Magnesium in Plants

Magnesium (Mg) performs a wide range of structural, biochemical, physiological, and regulatory functions in plants. Its importance extends beyond its well-known role as the central atom of the chlorophyll molecule. Magnesium participates in energy transfer, enzyme activation, photosynthesis, carbohydrate metabolism, protein synthesis, nucleic acid metabolism, ribosome stability, phloem loading, assimilate translocation, and regulation of ionic and cellular homeostasis (Shaul, 2002; Cakmak and Kirkby, 2008; Gerendás and Fühns, 2013). A large number of enzymes require Mg^{2+} either as an activator or through the formation of Mg-substrate complexes. In particular, Mg is essential for reactions involving ATP because the biologically functional form of ATP in many enzymatic reactions is Mg-ATP (Shaul, 2002; Guo *et al.*, 2016).

Magnesium also has an important role in photosynthetic carbon assimilation and carbohydrate partitioning. Adequate Mg nutrition promotes photosynthetic activity and facilitates the export of photoassimilates from source leaves to developing sink organs. Under Mg deficiency, carbohydrates may accumulate in mature leaves because of impaired phloem loading and transport, thereby disturbing the source-sink relationship and reducing biomass accumulation and yield (Cakmak and Kirkby, 2008; Hermans *et al.*, 2005). In addition, Mg contributes to the structural stability of ribosomes and nucleic acids, making it important for protein synthesis, cell division, and plant growth (Shaul, 2002; Verbruggen and Hermans, 2013).

2.1 Energy Transfer and ATP Formation

Magnesium is essential for cellular energy metabolism because of its close association with adenosine triphosphate (ATP). ATP contains three negatively charged phosphate groups that strongly interact with Mg^{2+} . The formation of a Mg-ATP complex stabilizes the phosphate groups and facilitates the interaction of ATP with enzymes involved in phosphorylation and energy-transfer reactions (Shaul, 2002; Cakmak and Kirkby, 2008).

The Mg–ATP complex serves as the functional substrate for numerous ATP-dependent reactions, including protein phosphorylation, carbohydrate metabolism, active transport, and several biosynthetic processes. Magnesium is therefore essential for the efficient utilisation of cellular energy rather than simply being involved in ATP formation itself (Guo *et al.*, 2016). A reduction in Mg availability can decrease the efficiency of ATP-dependent metabolic reactions and consequently restrict several physiological processes.

Magnesium is also closely associated with photosynthetic energy metabolism. Within chloroplasts, Mg^{2+} concentrations are dynamically regulated during light–dark transitions and influence the activity of several photosynthetic enzymes. The availability of Mg therefore contributes to the coordination between light energy capture, ATP production, and carbon fixation (Cakmak and Kirkby, 2008; Gerendás and Führs, 2013).

2.2 Protein and Nucleic Acid Synthesis

Magnesium plays an important role in protein synthesis through its effects on ribosome structure and function. Ribosomes contain negatively charged ribosomal RNA, and Mg^{2+} helps neutralize these charges and maintain the structural integrity of ribosomal subunits. Adequate Mg concentration is therefore necessary for proper ribosome assembly and stability and for efficient translation of messenger RNA into proteins (Shaul, 2002; Verbruggen and Hermans, 2013).

Magnesium is also associated with nucleic acid metabolism. Mg^{2+} interacts with the phosphate groups of DNA and RNA and contributes to the structural stabilisation of nucleic acids. It is also required for several enzymatic reactions associated with DNA and RNA synthesis because many nucleotide-utilizing enzymes require Mg^{2+} or Mg–nucleotide complexes for catalytic activity (Shaul, 2002).

Through these functions, Mg contributes indirectly to cell division, cell expansion, meristematic activity, protein accumulation, and overall plant growth. Consequently, Mg deficiency can affect not only chlorophyll formation and photosynthesis but also fundamental processes associated with cellular proliferation and development (Guo *et al.*, 2016).

2.3 Phloem Loading and Translocation

Magnesium plays an important role in the movement of photosynthetically produced carbohydrates from source leaves to sink tissues. Mature photosynthetic leaves function as major source organs, whereas roots, young leaves, fruits, seeds, grains, and tubers act as important sink organs. Efficient translocation of sucrose through the phloem is essential for the development and productivity of these sink organs (Cakmak and Kirkby, 2008).

Mg deficiency can interfere with carbohydrate partitioning and phloem transport. Under inadequate Mg supply, sucrose and starch may accumulate in source leaves because their export to sink tissues becomes restricted. This accumulation may occur even before severe chlorophyll loss becomes visible, making impaired carbohydrate partitioning an important early physiological response to Mg deficiency (Cakmak and Kirkby, 2008; Hermans *et al.*, 2005).

Efficient Mg nutrition consequently supports the movement of assimilates toward developing reproductive and storage organs. Adequate carbohydrate translocation is particularly important during grain filling in cereals and during fruit, seed, tuber, and pod development in horticultural and field crops. Therefore, Mg availability can influence not only vegetative growth but also yield formation and harvest index (Gerendás and Führs, 2013).

2.4 Nutrient Balance and Ionic Regulation

Magnesium contributes to the maintenance of cellular ionic balance and interacts extensively with other essential nutrients. As a divalent cation, Mg^{2+} participates in charge balancing and interacts with negatively charged cellular components, including phosphate-containing metabolites, proteins, nucleic acids, and membranes (Shaul, 2002).

Magnesium also exhibits important interactions with potassium (K^+) and calcium (Ca^{2+}). Potassium and Mg are particularly important in crop nutrition because excessive K availability or high rates of K fertilisation can suppress Mg uptake and may induce Mg deficiency. Conversely, adequate Mg nutrition can improve several physiological processes associated with K utilization (Marschner, 2012; Senbayram *et al.*, 2015; Xie *et al.*, 2021).

The Mg–Ca relationship is also important because both nutrients contribute to cellular stability, although their physiological functions differ. Maintaining an appropriate balance among Mg, Ca, and K is therefore important for normal plant nutrition. Nutrient antagonism becomes particularly significant under intensive fertilisation, where excessive application of one nutrient can disturb the uptake and utilization of another (Marschner, 2012).

2.5 Role of Magnesium in Photosynthesis

Magnesium is fundamental to photosynthesis because it is the central atom of the chlorophyll molecule and contributes to the structural and functional organization of the photosynthetic apparatus. Adequate Mg supply supports chlorophyll synthesis, light absorption, electron transport, and carbon fixation (Cakmak and Kirkby, 2008).

In addition to its structural role in chlorophyll, Mg activates several enzymes involved in photosynthetic carbon metabolism. Magnesium deficiency can therefore reduce chlorophyll concentration, net photosynthetic rate, stomatal function, and carbon assimilation. A systematic review and meta-analysis demonstrated that Mg deficiency can substantially decrease photosynthetic performance and biomass production across a range of plant species (Hauer-Jákli and Tränkner, 2019).

2.6 Role of Magnesium in Carbohydrate Metabolism

Magnesium is closely involved in carbohydrate metabolism through its effects on photosynthesis, enzyme activity, ATP utilisation, and assimilate transport. Several enzymes involved in carbohydrate metabolism require Mg^{2+} for their activity or depend on Mg–ATP complexes for phosphorylation reactions (Shaul, 2002; Cakmak and Kirkby, 2008).

When Mg is deficient, photosynthetic carbon fixation may decline while sucrose and starch accumulate in source leaves. This apparent accumulation does not necessarily indicate increased carbohydrate production; rather, it can result from reduced export of carbohydrates from source leaves to sink tissues. Thus, Mg deficiency can disrupt both carbohydrate synthesis and carbohydrate partitioning (Cakmak and Kirkby, 2008).

2.7 Role of Magnesium in Enzyme Activation

Magnesium activates a large number of enzymes involved in fundamental plant metabolic pathways. Its functions include stabilisation of enzyme–substrate complexes, interaction with phosphate groups, maintenance of appropriate enzyme conformation, and participation in catalytic reactions (Shaul, 2002; Guo *et al.*, 2016).

Enzymes involved in phosphorylation, glycolysis, carbohydrate metabolism, nucleic acid synthesis, and protein metabolism are particularly dependent on Mg. Therefore, Mg deficiency can cause widespread metabolic disturbances rather than affecting a single biochemical pathway.

2.8 Magnesium and Ribosome Stability

Ribosomes are essential cellular structures responsible for protein synthesis. Magnesium stabilizes ribosomal particles by interacting with the negatively charged phosphate groups of ribosomal RNA. Adequate Mg concentration is therefore necessary for maintaining ribosomal structure and efficient translation (Shaul, 2002).

Under Mg deficiency, ribosomal stability and protein synthesis may be affected, contributing to reduced growth and impaired development. This function demonstrates that Mg is essential not only for photosynthetic tissues but also for fundamental cellular processes occurring throughout the plant.

2.9 Magnesium and Root Growth

Magnesium nutrition also influences root development and nutrient acquisition. Adequate Mg supports energy metabolism, enzyme activity, and carbohydrate supply to roots. Since roots depend partly on photoassimilates transported from shoots, impaired phloem transport under Mg deficiency can restrict root growth and development (Cakmak and Kirkby, 2008).

A healthy root system is essential for water and nutrient acquisition. Consequently, Mg deficiency may create a feedback effect in which reduced photosynthesis and carbohydrate transport restrict root growth, which in turn may further reduce nutrient acquisition and plant growth (Guo *et al.*, 2016).

2.10 Magnesium and Nitrogen Metabolism

Magnesium interacts with nitrogen metabolism because several processes involved in N assimilation and protein formation depend on Mg-mediated enzyme activity and energy transfer. Adequate Mg supports photosynthetic carbon fixation, ATP production, and protein synthesis, thereby providing an appropriate metabolic environment for efficient nitrogen utilisation (Cakmak and Kirkby, 2008; Gerendás and Führs, 2013).

An adequate balance between N and Mg is particularly important in high-input cropping systems. Excessive N fertilisation without sufficient Mg supply may increase crop demand for Mg and aggravate Mg deficiency. Therefore, Mg should be considered as part of balanced N management rather than as an independent nutrient.

2.11 Magnesium and Phosphorus Metabolism

Magnesium has a close biochemical relationship with phosphorus because Mg^{2+} forms complexes with phosphate-containing compounds, including ATP. Many phosphorylation reactions depend on Mg–ATP rather than free ATP (Shaul, 2002).

Magnesium therefore contributes to the efficient utilisation of phosphorus in energy metabolism and phosphorylation reactions. However, the relationship between Mg and P in plants is complex and depends on plant species, nutrient concentrations, and soil conditions. Maintaining balanced Mg and P nutrition is consequently more important than maximizing either nutrient independently.

2.12 Magnesium and Oxidative Stress

Magnesium deficiency can disturb photosynthetic electron transport and increase the risk of oxidative stress. Under Mg-deficient conditions, impaired photosynthetic activity can increase the formation of reactive oxygen species (ROS), which may damage proteins, lipids, pigments, and cellular membranes (Cakmak and Kirkby, 2008; Hauer-Jákli and Tränkner, 2019).

Plants possess antioxidant systems to control ROS, but prolonged Mg deficiency may overwhelm these protective mechanisms. Consequently, Mg deficiency can result in oxidative damage, premature leaf senescence, and reduced photosynthetic capacity. This provides another mechanism through which Mg deficiency contributes to yield reduction.

2.13 Magnesium and Plant Growth and Yield

The combined effects of Mg on photosynthesis, ATP metabolism, enzyme activity, protein synthesis, carbohydrate translocation, and nutrient interactions ultimately influence plant growth and yield. Adequate Mg supply promotes leaf development, photosynthetic productivity, biomass accumulation, root growth, and reproductive development (Gerendás and Fühns, 2013).

Under Mg deficiency, reductions in photosynthesis and carbohydrate export can restrict the development of reproductive and storage organs. Consequently, deficiencies may result in lower grain, fruit, seed, pod, tuber, or root yield depending on the crop. A systematic analysis of Mg nutrition has demonstrated that Mg deficiency is associated with reductions in plant growth and photosynthetic performance across diverse plant species (Hauer-Jákli and Tränkner, 2019).

3. Magnesium Deficiency

Magnesium (Mg) deficiency is an increasingly important nutritional constraint in intensive agricultural systems, particularly where soils are acidic, coarse-textured, highly weathered or subjected to continuous cropping without adequate replacement of Mg removed through harvested biomass. Although Mg is required in smaller quantities than nitrogen, phosphorus and potassium, inadequate Mg supply can substantially impair photosynthesis, carbohydrate partitioning, enzyme activity, plant growth and ultimately crop productivity. The occurrence and severity of Mg deficiency are determined by the interaction between soil Mg reserves, soil pH, texture, cation exchange characteristics, rainfall, fertiliser management and competition with other cations, particularly potassium (K) and ammonium (NH_4^+) (Verbruggen and Hermans, 2013; Chen *et al.*, 2018; Wang *et al.*, 2020). Recent meta-analytical evidence indicates that Mg fertilisation increases crop yield across a wide range of production systems, with larger responses generally occurring in soils with low exchangeable Mg (Wang *et al.*, 2020).

3.1 Causes of Magnesium Deficiency

Magnesium deficiency may develop through several interacting soil and crop-management processes. Acidic soils are particularly vulnerable because increased proton activity promotes the displacement and leaching of Mg^{2+} from exchange sites, while low cation exchange capacity in sandy soils further reduces the capacity of the soil to retain Mg. Highly weathered tropical soils may therefore experience substantial Mg losses under high rainfall or excessive irrigation. The problem is particularly pronounced in coarse-textured soils because Mg^{2+} is relatively mobile in the soil profile and can be transported below the active rooting zone (Gransee and Fühns, 2013; Senbayram *et al.*, 2015; Wang *et al.*, 2020).

Continuous cultivation without Mg replenishment is another important cause. Modern fertiliser programmes have traditionally emphasized N, P and K, while Mg removal through harvested crops has frequently received less attention. Repeated removal of Mg-containing crop residues, high-yielding cultivars and intensive cropping can progressively reduce exchangeable Mg reserves. This depletion becomes particularly important when the native soil Mg pool is small or when the soil parent material contains limited Mg-bearing minerals (Cakmak *et al.*, 1994; Grzebisz, 2011).

Nutrient imbalance can further aggravate Mg deficiency. High rates of K fertilisation may suppress Mg uptake because K^+ and Mg^{2+} interact during root uptake and transport. The antagonistic effect can become particularly important in high-K soils or under intensive potash fertilisation. High NH_4^+ concentrations can also interfere with Mg acquisition because competing cations alter the ionic environment around roots and influence Mg transport. Experimental work in rice demonstrated that high K supply can intensify the physiological consequences of Mg deficiency, including reductions in chlorophyll and photosynthesis and increases in oxidative stress (Ding *et al.*, 2008; Rietra *et al.*, 2015).

Low soil organic matter may indirectly increase the risk of Mg deficiency by reducing cation retention, aggregate stability and the capacity of the soil to buffer nutrient losses. Organic amendments can contribute Mg directly while also improving soil physical and chemical properties. Thus, Mg deficiency should not be considered solely a fertiliser problem; it is often the outcome of long-term imbalance among soil mineralogy, nutrient removal, leaching and fertiliser management (Gransee and Fühns, 2013; Dechen *et al.*, 2015).

3.2 Visual Deficiency Symptoms

Because Mg is relatively mobile within the phloem, plants can redistribute Mg from older tissues towards actively growing tissues when external Mg supply becomes inadequate. Consequently, the earliest visible symptoms commonly develop on fully expanded older leaves. The characteristic symptom is interveinal chlorosis, in which the tissue between the veins becomes yellow while the

vascular tissues initially remain green. With increasing severity, chlorosis may progress to yellow-orange, bronze, reddish or purplish coloration, followed by necrotic patches and premature leaf senescence (Bang *et al.*, 2021; Guo *et al.*, 2016).

The visual pattern is influenced by plant species, genotype, leaf age and severity of Mg deprivation. In cereals such as maize and wheat, Mg deficiency commonly produces longitudinal or striped interveinal chlorosis, sometimes accompanied by reddish-purple pigmentation and marginal necrosis. In rice, orange-yellow interveinal chlorosis, drooping leaves and subsequent necrosis may occur. In dicotyledonous crops such as beans, spinach and tomato, the interveinal pattern may be more conspicuous, with progressive chlorosis of older foliage (Fischer, 1993; Fischer *et al.*, 1998; Kobayashi *et al.*, 2013).

At the physiological level, visible chlorosis is preceded by biochemical disturbances. Mg deficiency decreases photosynthetic carbon assimilation and promotes accumulation of sucrose and starch in source leaves. This can disturb source-sink relationships and stimulate oxidative stress, thereby accelerating leaf senescence. Consequently, visual diagnosis alone may underestimate the onset of Mg deficiency because physiological impairment can occur before pronounced chlorosis becomes visible (Hermans *et al.*, 2010; Farhat *et al.*, 2015).

3.3 Effects on Crop Yield and Quality

The effects of Mg deficiency extend beyond leaf chlorosis and can result in significant reductions in biomass, harvestable yield and product quality. Magnesium deficiency reduces chlorophyll formation and photosynthetic CO₂ assimilation, restricts carbohydrate production and alters assimilate distribution between source and sink organs. The resulting limitation in carbon supply and utilisation can reduce root growth, reproductive development, grain filling and biomass accumulation (Fischer, 1993; Fischer *et al.*, 1998; Hermans *et al.*, 2010).

A systematic review and meta-analysis demonstrated that adequate Mg nutrition substantially improves photosynthetic CO₂ assimilation and biomass production compared with Mg-deficient conditions, while also reducing oxidative stress. Critical leaf Mg concentrations vary among crops, but values in the range of approximately 0.1–0.2% dry weight have been identified for several major cereals and crops (Hauer-Jákli and Tränkner, 2019).

Crop quality may also be affected. In oilseed crops, Mg deficiency can alter carbon allocation and lipid metabolism, potentially reducing oil accumulation. In sugar crops, inadequate Mg can restrict photosynthetic carbon supply and sugar accumulation, while in cereals it may interfere with grain filling and final grain quality. Field experiments with sugar beet have demonstrated that Mg fertilisation can increase sugar yield and reduce the occurrence of visible Mg deficiency (Draycott and Durrant, 1972).

Overall, the consequences of Mg deficiency should be evaluated in terms of both yield quantity and quality. Even moderate deficiency may reduce physiological efficiency before severe visual symptoms appear, making soil testing and plant tissue analysis important components of diagnostic Mg management.

4. Magnesium Toxicity

Magnesium toxicity is considerably less frequently reported than Mg deficiency in agricultural systems. Nevertheless, excessive Mg accumulation can occur in soils developed from Mg-rich parent materials, in soils receiving repeated applications of Mg-containing amendments, or where irrigation water contains high concentrations of Mg. The principal concern is generally not a direct toxic effect of Mg²⁺ on plant metabolism, but rather an imbalance among exchangeable cations, particularly Mg, Ca and K. Thus, Mg toxicity should be evaluated in relation to the overall ionic composition of the soil solution and exchange complex rather than by considering total Mg concentration alone (Dixon and Todd, 2001; Rengasamy, 2010).

4.1 Causes of Magnesium Toxicity

High Mg status can develop naturally in soils derived from dolomitic, ultramafic or other Mg-rich parent materials. Magnesium can also accumulate when Mg-rich irrigation water is used over prolonged periods or when large quantities of Mg fertilisers or amendments are repeatedly applied without considering soil-test values. Such conditions are particularly important where drainage is restricted and the downward movement of soluble Mg is limited.

An important cause of Mg-related nutritional stress is an excessively low Ca/Mg ratio. High concentrations of exchangeable Mg can compete with Ca for root uptake and transport. Consequently, a plant may develop symptoms associated with Ca deficiency even when the absolute amount of Ca in the soil is not extremely low. FAO guidance indicates that high Mg in soil or irrigation water can induce Ca deficiency when the Ca/Mg relationship becomes sufficiently unfavourable, with effects reported in crops such as barley, wheat, maize and sugar beet (Ayers and Westcot, 1985).

The risk of Mg-induced imbalance is also influenced by K. High exchangeable Mg may interfere with K nutrition under some soil and plant conditions, whereas high K can produce Mg deficiency. Therefore, Mg toxicity and deficiency cannot be interpreted independently from the broader balance of exchangeable Ca, Mg and K.

4.2 Toxicity Symptoms

Direct foliar toxicity caused solely by Mg is relatively uncommon. Instead, excessive Mg availability generally produces symptoms indirectly through nutrient antagonism. High Mg concentrations can suppress Ca uptake or translocation, resulting in physiological

symptoms characteristic of Ca deficiency, including reduced meristem activity, weak tissue development and, in susceptible fruit crops, disorders associated with inadequate Ca delivery to developing fruits (Ayers and Westcot, 1985).

Root growth may also decline when the ionic balance of the rhizosphere becomes severely disturbed. The magnitude of the response depends on plant species, genotype, Ca/Mg ratio, soil pH, competing cations and the concentration of Mg in the soil solution. Experiments on different plant populations have demonstrated considerable genotypic variation in plant response to Ca relationships, emphasizing that a single universal critical Ca/Mg ratio cannot be applied to all crops (Dixon and Todd, 2001).

Therefore, diagnosis of Mg toxicity should involve soil and plant analysis rather than visual symptoms alone. If excessive Mg is suspected, exchangeable Ca, Mg and K, cation saturation percentages, soil electrical conductivity and, where relevant, the composition of irrigation water should be evaluated.

4.3 Impact on Soil Properties

The influence of high Mg on soil structure is more complex than is sometimes suggested. Magnesium does not universally cause soil dispersion. However, under particular combinations of high exchangeable Mg, low Ca ratio, elevated exchangeable Na and susceptible clay mineralogy, Mg can contribute to aggregate disaggregation, clay dispersion and reduction in hydraulic conductivity.

Experimental studies have shown that exchangeable Mg can exert a specific effect on soil structural stability and may increase clay dispersion under sodic conditions. In one study, Mg was estimated to be substantially less dispersive than Na but still capable of contributing to structural degradation under appropriate chemical conditions (Emerson and Bakker, 1973; McNeal *et al.*, 1968).

More recent work has shown that Mg-induced structural changes may involve disaggregation rather than simple clay dispersion, with effects on saturated hydraulic conductivity and the release of dissolved organic carbon from clay surfaces (Zhang and Norton, 2002; Zhu *et al.*, 2019).

Consequently, high Mg should be considered a potential soil-structural risk particularly in soils already affected by sodicity or unfavourable Ca/Mg relationships. Management should focus on restoring a favorable balance of exchangeable cations rather than attempting to reduce Mg concentration in isolation.

5. Corrective Measures for Magnesium Deficiency and Toxicity

Effective Mg management requires diagnosis of the underlying cause before selecting a corrective practice. Soil-test information, plant tissue analysis, crop requirement, soil pH, texture, exchangeable Mg and the relative abundance of Ca and K should be considered together. The objective should not simply be to increase Mg concentration but to maintain an adequate and balanced Mg supply throughout the crop-growing period. Meta-analysis of field studies has demonstrated that Mg fertilisation can increase crop yield across diverse production systems, with larger responses generally occurring where exchangeable Mg is low (Wang *et al.*, 2020).

5.1 Soil Application

Soil application is the principal long-term approach for correcting Mg deficiency. The selection of fertiliser should be based on soil pH, required rate of Mg, solubility and the need for accompanying nutrients.

Magnesium sulphate ($\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$; Epsom salt) is highly soluble and supplies readily available Mg along with sulphur. Because of its rapid dissolution, it is particularly useful when relatively rapid correction is required. However, its high solubility also means that repeated applications on highly leachable soils should be carefully managed to minimise nutrient losses (Loganathan *et al.*, 2005; Senbayram *et al.*, 2015).

Dolomitic limestone [$\text{CaMg}(\text{CO}_3)_2$] is particularly appropriate for acidic soils because it supplies Mg while simultaneously neutralizing soil acidity. Its relatively slow dissolution makes it more suitable for building long-term Mg fertility than for immediately correcting a severe deficiency during an advanced crop-growth stage. Historical field experiments have demonstrated that dolomitic limestone can increase crop yield and reduce Mg deficiency under responsive conditions (Draycott and Durrant, 1972).

Magnesite (MgCO_3) and calcined magnesite (MgO) are relatively concentrated Mg sources. Calcined magnesite is generally less soluble than kieserite and therefore has potential for longer-term Mg supply. Field studies in forest soils have shown that calcined magnesite can increase exchangeable and soil-solution Mg and increase plant Mg status, although dissolution rate depends strongly on soil properties and fertiliser characteristics (Mitchell *et al.*, 1999; Mitchell *et al.*, 2000).

Kieserite ($\text{MgSO}_4 \cdot \text{H}_2\text{O}$) is another important soil-applied Mg fertiliser containing both Mg and sulphur. Comparative field experiments in potato and sugar beet have shown that kieserite can increase leaf Mg concentration and yield, with greater responses than calcined magnesite under some conditions because of its greater solubility (Orlovius and McHoul, 2015).

5.2 Foliar Application

Foliar Mg application provides a rapid corrective approach when soil Mg availability is inadequate or when symptoms develop during a critical crop-growth stage. Magnesium sulphate is commonly used because of its high water solubility and relatively low

cost. Foliar feeding can bypass limitations associated with root uptake, soil fixation and temporary nutrient antagonism and can rapidly increase Mg availability to photosynthetically active tissues (Adnan *et al.*, 2021).

Foliar Mg concentration should not be treated as a universal fixed value for every crop. The appropriate concentration depends on crop species, cultivar, leaf age, environmental conditions, formulation and frequency of application. Concentrations around 0.5–2% MgSO₄ are commonly reported in crop-specific recommendations, but crop safety should always be established before large-scale application. For example, Tamil Nadu agricultural recommendations include 0.5% MgSO₄ foliar sprays for maize and rice under deficiency conditions (TNAU, 2023).

Foliar fertilisation should therefore be considered a rapid corrective or supplementary measure, rather than a complete substitute for maintaining adequate soil Mg reserves.

5.3 Balanced Fertilization

Balanced fertilisation is essential because Mg nutrition is strongly influenced by interactions with K, Ca and ammonium. Excessive K fertilisation can suppress Mg uptake, whereas inadequate Mg can reduce the efficiency with which crops utilize other nutrients. Fertilizer programmes should therefore be based on soil-test results rather than routine application of high rates of individual nutrients.

The K relationship deserves particular attention in high-input systems. High K availability can induce Mg deficiency in sensitive crops, particularly when Mg reserves are already low. Therefore, correction of Mg deficiency should be integrated with appropriate K management rather than simply increasing the Mg dose without modifying the underlying imbalance (Rietra *et al.*, 2015).

5.4 Organic Amendments

Farmyard manure, compost, crop residues and green manures can contribute Mg while simultaneously improving soil organic matter, aggregation, water retention and cation exchange capacity. Organic amendments can therefore reduce the susceptibility of Mg to leaching and improve the overall nutrient-buffering capacity of soil.

The effect of organic amendments should nevertheless be interpreted according to their actual Mg content and mineralization behavior. Organic materials should complement, rather than automatically replace, mineral Mg fertilisers where soil-test results indicate a substantial Mg deficit.

5.5 Management of Magnesium Toxicity

Management of excessive Mg requires identification and correction of the source of Mg accumulation. Indiscriminate application of Mg fertilisers should be avoided when exchangeable Mg is already high. Where high Mg is associated with an unfavorable Ca relationship, calcium-containing amendments may help restore cation balance.

Gypsum (CaSO₄·2H₂O) can be useful where additional Ca is required without substantially increasing soil pH. Calcium supplied through gypsum can compete with Mg on exchange sites and may improve the Ca/Mg balance under appropriate conditions. However, gypsum should not be recommended solely on the basis of high Mg without soil testing; its effectiveness depends on soil mineralogy, exchangeable cation composition, drainage and the severity of the imbalance.

Improved drainage is particularly important where Mg accumulation is associated with restricted water movement or Mg-rich irrigation water. The objective is to facilitate the movement of soluble Mg beyond the effective root zone while avoiding secondary salinity problems. Where irrigation water itself contains excessive Mg, water-quality assessment and alternative water sources or blending strategies should be considered (Ayers and Westcot, 1985).

Overall, Mg management should be based on the principle of **“right source, right rate, right time and right placement”**, supported by soil and plant diagnostics. Such an approach improves fertiliser-use efficiency while minimizing unnecessary nutrient inputs and potential environmental losses.

6. Conclusion

Magnesium is essential for plant growth because of its roles in chlorophyll formation, photosynthesis, energy metabolism, enzyme activation, protein synthesis, carbohydrate transport, and nutrient balance. Deficiency may arise from low soil Mg reserves, leaching, soil acidity, intensive cropping, and antagonistic interactions with other cations, and can impair plant growth, yield, and quality. Excessive Mg is less common and is mainly important where it disrupts the balance of calcium, potassium, and other exchangeable cations. Effective Mg management should therefore be based on soil and plant diagnosis rather than routine fertilizer application. Appropriate Mg sources, balanced fertilisation, correction of soil acidity, organic amendments, foliar supplementation where justified, and management of cation interactions can collectively maintain adequate Mg nutrition. A balanced diagnostic approach is necessary to support sustainable crop production while avoiding both deficiency and unnecessary nutrient application.

7. Limitation

This review is based on previously published information concerning magnesium functions, deficiency, toxicity, and corrective management in plants. The responses described may vary with crop species, genotype, soil properties, environmental conditions,

nutrient interactions, and fertiliser source or application method. Consequently, general Mg thresholds, fertiliser rates, and cation ratios should not be applied uniformly across crops or soils. Site-specific soil and plant analyses remain necessary when translating the reviewed information into practical nutrient-management recommendations.

Declaration of AI Use

This manuscript was prepared through the intellectual contributions of the author(s) to the study design, data analysis, interpretation of results, and scholarly content. Grammarly and ChatGPT were used solely to assist with grammatical refinement and reference formatting during manuscript revision. The author(s) accept full responsibility for the accuracy, integrity, and final content of the manuscript.

Competing Interests

Authors have declared that no competing interests exist.

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