

Managing Molybdenum for Unlocking Crop Yield Potential, Improving Crop Quality and Soil Fertility

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ABSTRACT

Molybdenum (Mo) is an essential micronutrient required in trace amounts (0.2–2 mg kg⁻¹) but plays a critical role in nitrogen metabolism through enzymes such as nitrate reductase and nitrogenase, thereby influencing crop productivity. Its deficiency, particularly in acidic soils, is an emerging concern in Indian agriculture, leading to poor plant growth and reduced yields, while excess Mo can cause toxicity. Molybdenum is also important for animal and human health, though imbalances may result in disorders such as molybdenosis. Its availability in soils is largely governed by pH, organic matter and nutrient interactions, with higher availability under alkaline conditions. Proper management of Mo is therefore essential for sustaining crop production and soil fertility.

INTRODUCTION

Soil contains a wide range of elements, of which seventeen are essential for plant nutrition. Among these, molybdenum (Mo) is an essential anionic micronutrient, the least abundant in plant

tissue and classified as an ‘ultra-micronutrient’, yet it plays a crucial role in metabolic functions. In soils, Mo exists in four major forms: dissolved in the soil solution, complexed with oxides (such as Al, Fe, Mn

oxides), in solid mineral phases (e.g., molybdenite (MoS₂), powellite (CaMoO₄), ferrimolybdate (Fe₂(MoO₄)₃), wulfenite (PbMoO₄) and bound to organic compounds. Plants primarily absorb Mo as molybdate ions (MoO₄²⁻), which are mobile within plants but immobile in soils (Reddy *et al.*, 1997). Molybdenum itself is not biologically active, but it functions as an integral part of an organic pterin complex called the molybdenum cofactor (Moco) (Kaiser *et al.*, 2005). Unlike cationic micronutrients, molybdate availability increases with an increase in soil pH, making soil reaction a key factor in Mo supply. Analysis of soil and plant samples has indicated that 11% of soils in India are potentially Mo-deficient (Singh, 2008). Globally, it is the third emerging micronutrient deficiency after Boron and Zinc (Graham, 2008). This often-overlooked deficiency can reduce nitrogen use efficiency, crop yield and quality. Therefore, this article summarises research on application methods, roles, deficiencies, toxicity and factors influencing Mo availability to better understand Mo.

Roles of molybdenum

Within plants, Mo's primary role is as a cofactor for 'molybdoenzymes' that perform critical functions (Table 1).

Table 1: Key molybdoenzymes, their substrates, Functions, and the effects of deficiency.

Enzyme	Substrate	Function	Effect of Mo Deficiency
Nitrate Reductase (NR)	NO ₃ ⁻	The rate-limiting step in nitrate assimilation, the reduction of NO ₃ ⁻ to NO ₂ ⁻	Nitrate accumulation, nitrogen starvation, reduced biomass and protein
Nitrogenase	N ₂	Catalyses biological nitrogen fixation in legume-rhizobia symbiosis	Nodule failure, dependence on external nitrogen inputs
Xanthine Dehydrogenase	Xanthine / Hypoxanthine	Purine degradation	Impaired N-cycling,

(XDH)		and ureide synthesis for nitrogen transport in legumes	poor nitrogen use efficiency
Aldehyde Oxidase (AO)	Aldehydes	Biosynthesis of ABA and auxins for stress response and growth	Wilting, impaired stress response and poor seed development
Sulphite Oxidase (SO)	SO ₃ ²⁻	Detoxification of sulphite, sulphur amino acid metabolism	Sulphur toxicity, impaired protein synthesis and sulphur cycling

In addition to these enzymes, Mo also improves chlorophyll biosynthesis, boosts Rubisco activity and increases the plant's ability to produce soluble proteins, directly contributing to better grain quality (Oliveira *et al.*, 2022).

Deficiency Symptoms

Mo has a major role in nitrogen assimilation, therefore, its deficiency symptoms often mimic nitrogen deficiency. Reduced NR activity leads to stunted growth, pale foliage and reduced protein content.

The most iconic symptom of Mo deficiency is 'whiptail', particularly seen in cauliflower. Other symptoms include: yellow spots on citrus leaves; mottling of leaves, i.e., irregular light and dark-green patterns develop on leaf surfaces, accompanied by marginal necrosis in tomato; chlorosis of leaves and premature grain formation in cereal crops such as maize. (Kaiser *et al.*, 2005; Rana *et al.*, 2025).

Molybdenum Toxicity

Visual symptoms of toxicity include abnormal anthocyanin accumulation (purpling) and generalised leaf yellowing, reflecting disrupted chlorophyll metabolism. In animals, particularly ruminants, excess dietary Mo (>10 mg kg⁻¹ dry matter) causes molybdenosis, characterised by disrupted copper absorption,

leading to diarrhoea, weight loss and reproductive failure. In humans, Mo toxicity causes hypertension, anaemia, gout and reproductive disorders (Coughlan, 1983).

Factors Affecting Molybdenum Availability in Soils

1. Soil pH

Soil pH is the most important factor controlling Mo availability. Unlike most micronutrients, Mo availability increases with soil pH. At low pH, iron and aluminium oxides strongly adsorb molybdate ions, thereby making them unavailable. This means that liming acidic soils is a cost-effective strategy for correcting Mo deficiency.

2. Soil Texture and Organic Matter

Well-drained sandy soils with low organic matter are most susceptible to Mo deficiency because Mo is leached and weakly binds to coarse mineral particles. Heavy clay soils with high iron/aluminium oxides can immobilise Mo, especially at low pH. Organic matter enhances Mo availability through chelation and helps maintain soil pH, but its direct effect on available Mo is secondary to pH. (Kaiser *et al.*, 2005).

3. Nutrient interaction

Antagonism with sulphur: sulphate and molybdate ions compete for the same carrier proteins on root cell membranes, blocking molybdate entry and causing molybdenum deficiency despite adequate soil levels.

Synergism with phosphorus: high phosphorus application displaces molybdate from soil colloids, increasing its availability for plant absorption. Therefore, Mo salts are often applied along with superphosphate to Mo-deficient soils (Li *et al.*, 2023).

Strategies for Managing Molybdenum

1. Molybdenum Fertiliser Sources

Several inorganic Mo compounds are commercially available for agricultural use. Their Mo content varies significantly (Table 2):

Table 2: Common molybdenum fertiliser sources and their Mo content

Sources	Chemical Formula	Mo Content (%)
Sodium molybdate	$\text{Na}_2\text{MoO}_4 \cdot 2\text{H}_2\text{O}$	39
Ammonium molybdate	$(\text{NH}_4)_2\text{MoO}_4$	52
Molybdenum trioxide	MoO_3	66
Molybdic acid	$\text{H}_2\text{MoO}_4 \cdot \text{H}_2\text{O}$	53
Molybdenum frits	Fritted glass	0.1–0.4

2. Application Methods

Soil application: Direct incorporation of Mo fertiliser into soil at sowing or as a basal dressing. Most appropriate for severely deficient soils and for crops where repeated foliar sprays are impractical.

Foliar spray: Aqueous solutions of sodium or ammonium molybdate are sprayed on the vegetative canopy. This method is highly efficient for correcting mid-season deficiency.

Seed treatment (priming): Soaking seeds or coating them with a Mo solution before sowing is considered economical and effective for legumes, thereby ensuring nodulation in Mo-limited soils.

Integrated management, combining soil application with foliar spray, has consistently produced the highest yields in research trials, particularly for nutrient-demanding crops such as cauliflower and legumes. (Table 3)

(Chakkal *et al.*, 2023; Oliveira *et al.*, 2022; Rana *et al.*, 2025)

Table 3: Comparison of Molybdenum Application Methods

Method	Dose	Efficiency	Key Notes
Seed Treatment	2-4 g Mo per kg seed	>80%	Most cost-effective, ideal for legumes and nodulation
Foliar Spray	0.05-0.15% solution on leaves	50-80%	Bypasses soil fixation, quick mid-season fix
Soil Application	0.5-2 kg Mo per hectare	<5%	Easy to broadcast, highly prone to fixation in acidic soils

3. Liming as an Indirect Strategy

Application of agricultural lime (calcium carbonate) to raise soil pH from acidic levels to near-neutral is a highly effective indirect approach to improving Mo availability.

CONCLUSION

A significant yield gap caused by undiagnosed Mo deficiency is often overlooked, which reduces enzymatic activity without visible symptoms and requires targeted soil testing. Mo is crucial for key enzymes that regulate nitrogen assimilation, biological nitrogen fixation and plant stress responses, thereby ensuring the efficiency of vital nutrient cycles. Mo fertilisation enhances not only yield but also crop quality by increasing protein content and micronutrient uptake. Integrated practice, such as combining soil application with foliar sprays and pH adjustment via liming, delivers the best agronomic results and ensures adequate Mo supply throughout all growth stages.

Future Prospects

- Development of rapid soil and plant testing methods for Mo that are accessible to regional soil testing laboratories across India.
- Evaluation of nano-molybdenum formulations for more efficient foliar delivery with reduced input quantities.
- Investigation of gene expression changes in molybdoenzyme to identify molecular markers for early detection of Mo deficiency.

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