MOLYBDENUM IN CROP PRODUCTION AND SOIL TESTING FOR ITS PLANT AVAILABILITY

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Molybdenum (Mo) is an essential micronutrient for plant development due to its involvement in nitrogen (N) metabolism and N fixation, especially in leguminous crops. As a transition metal, Mo can exist in multiple oxidation states, from 0 to +6, with the +6 state being the most prevalent in agricultural soils. Its availability increases in alkaline conditions, where it is mainly taken up by plants as molybdate anion (MoO_4^{2-}). However, in acidic soils (pH below 5.5), its availability decreases due to greater adsorption of molybdate onto soil oxides. Molybdenum occurs in the Earth's crust at low concentrations, generally less than 3 mg kg^{-1} and its deficiency often observed in acidic soils and those subjected to intensive cultivation. In agricultural soils worldwide, its concentration typically ranges between 0.2 to 5 mg kg^{-1} (Kabata-Pendias and Szteke, 2015),

In the Indian context, Mo ranks as the third most common micronutrient deficiency after zinc and boron (Kumar et al., 2019), with around 11% of Indian soils reportedly lacking adequate Mo levels (Shukla et al., 2021). The concentration of Mo in soils is mainly influenced by their parent material and the conditions under which they formed. Soils that are coarse-textured, low in organic matter, or highly weathered and eroded are generally more prone to Mo deficiency.

When plants experience Mo deficiency, they develop various abnormal traits that negatively affect growth. It is a critical element in two key plant enzymes: nitrate reductase and nitrogenase. Nitrogenase, which facilitates biological nitrogen fixation, consists of two types of metalloproteins, an iron-sulfur (Fe-S) cluster protein and a molybdenum-iron-sulfur (Mo-Fe-S) protein. In addition to its role in nitrogen processes, molybdenum is also involved in sulfur metabolism, the synthesis of plant hormones, and the breakdown of purine compounds (Kaiser et al., 2005).

Among various plant species, legumes are particularly susceptible to Mo deficiency (Singh et al., 2017). Hence, ensuring sufficient Mo levels in soil is essential for sustaining crop yields and maintaining produce quality.

Mo DEFICIENCY SYMPTOMS IN PLANTS

Molybdenum is highly mobile within plants, and its deficiency symptoms typically manifest throughout the plant parts. Members of the Brassicaceae family exhibit especially distinct and consistent signs of Mo deficiency. In young plants, common visual symptoms include mottled leaves, cupping, a grayish hue, and limp foliage conditions often seen in stunted seedlings that may eventually die. In mature plants, particularly where deficiency is mild or has been partially corrected, symptoms are more noticeable in younger leaves. These may include malformed leaf blades (known as "whiptail"), tough, leathery leaves, and necrosis of the growing tips. Some Mo deficiency symptoms can be obscured due to its indirect role in nitrogen assimilation. Since Mo is essential for nitrogenase function, its deficiency impairs N fixation, leading to development of symptoms that closely resemble those of N deficiency. Mo concentrations in gramineous plants range from 0.2 to 1 mg kg^{-1}, whereas leguminous plants have much higher concentrations, ranging from 0.5 to 20 mg kg^{-1}. Tables 1 and 2 outline common deficiency symptoms in various crops and list crops particularly sensitive to molybdenum application, respectively.

Molybdenum deficiency in Cauliflower (Source: https://www.yara.co.uk/crop-nutrition/cauliflower/nutrient-deficiencies-cauliflower/molybdenum-deficiency-cauliflower/ https://agritech.tnau.ac.in/agriculture/English%20Version/Agriculture/plant_nutri/cauliflower_molybdenum.html)

Table 1. Molybdenum Deficiency Symptoms Reported in Different Crops

CROP	CROP RESPONSE TO MOLYBDENUM DEFICIENCY
Cauliflower	Whiptail symptoms, distorted young leaves
Cabbage	Poor head formation, leaf malformation
Broccoli	Similar to cauliflower, whiptail
Lettuce	Leaf necrosis, marginal chlorosis
Beans (French bean)	Poor pod formation, leaf curling
Pea	Yellowing, stunted growth
Soybean	Reduced nodulation, N deficiency symptoms
Wheat	Decreased grain protein, weak tillering
Maize (Corn)	Chlorosis, poor ear development
Rice	Reduced N-use efficiency, leaf tip burn
Barley	Mild symptoms under deficiency
Citrus	Yellow mottling, leaf curling
Lucerne (Alfalfa)	Poor nodulation, N deficiency
Clover	Poor N-fixation, stunted growth

(Sources: Compiled from various sources)

Table 2. Crop Sensitivity to Molybdenum Application

SENSITIVITY CATEGORY	CROPS	REMARKS / JUSTIFICATION
Highly Sensitive	Cauliflower, Groundnut, Lentil, Broccoli, Clover, Alfalfa, Rapeseed	Estimated ~$5 billion in wheat and $1.5 billion in rice losses using WRF-Chem model.
Moderately Sensitive	Chickpea, Soybean, Beet, Cotton, Spinach, Potato, Tomato	Annual wheat losses of 4.0–14.2 million tons (4.2–15.0%) and rice losses of 0.3–6.7 million tons (0.3–6.3%).
Less Sensitive	Wheat, Maize, Barley, Flax, Oat	Wheat losses: 20.8 ± 10.4 million tons; rice: 5.4 ± 1.2 million tons in Punjab & Haryana (2011–2013).

(Sources: Compiled from Havlin et al. (2016) and other sources)

FACTORS AFFECTING THE AVAILABILITY OF MOLYBDENUM IN SOIL

Multiple factors influence the availability of Mo in soil, which in turn affects its uptake by plants. The most critical influences include soil pH, organic matter levels, interactions with other nutrients, notably sulfur (S) and phosphorus (P), and the specific soil type (Figure 1).

Mo availability typically rises as soil pH increases. In acidic soils, Mo is less available due to its strong adsorption to clay minerals and the formation of poorly soluble compounds. At low pH, molybdate ions are strongly retained by iron and aluminum oxides, which are more prevalent under acidic conditions. Thus, Mo deficiency is more common in acidic soils. For every unit increase in pH, the concentration of molybdate ions (MoO_4^{2-}) increase by a factor of 100, making alkaline soils more favorable for Mo solubility and plant uptake.

High levels of organic matter can also enhance Mo availability, particularly in acidic soils. Organic compounds may function as chelators, improving Mo solubility in soils and plant accessibility. As organic matter decomposes, it releases bound Mo through mineralization, making it available to plants. Phosphorus (P) tends to promote Mo uptake, while S can inhibit it. Phosphates (PO_4^{3-}) may enhance Mo absorption by facilitating the formation of more readily absorbed phosphomolybdate complexes. In contrast, S has been observed to reduce Mo concentration in plant tissues, likely due to antagonistic interactions during uptake and possibly during Mo transport from roots to shoots.

Soils originating from granite or other Mo-rich parent materials typically contain more molybdenum. In comparison, sandy soils generally have lower Mo levels than clay or loamy soils. Well-drained soils also support better Mo availability than poorly drained, waterlogged ones. Lastly, plant species differ in their Mo requirements. Leguminous plants, which rely on Mo for nitrogen fixation, usually have higher Mo demands than non-legumes.

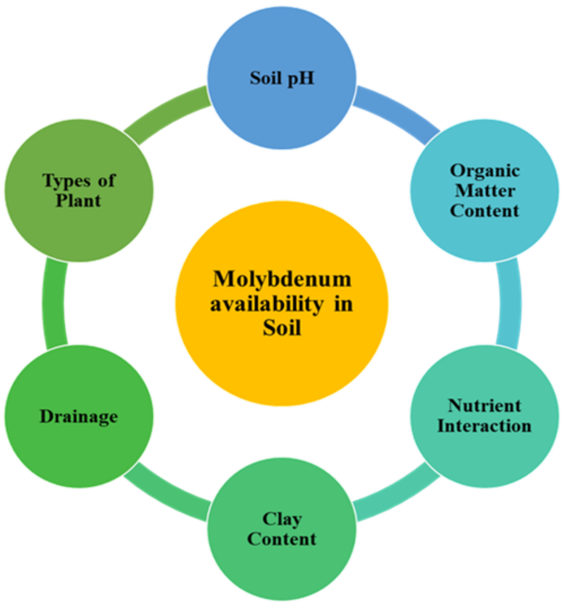

Figure 1. Some of the key factors affect Mo availability to plants in soil

SOIL TESTING FOR MOLYBDENUM

To assess the amount of molybdenum (Mo) available to plants, researchers have employed various extracting agents, including acids, alkalis, and salt solutions such as ammonium oxalate, hot water, anion exchange resins, ammonium bicarbonate DTPA, ammonium acetate, and EDTA. Of these, acid ammonium oxalate is the most widely used worldwide. This is because it effectively releases Mo from soil colloids into the soil solution. Unlike many other micronutrients, Mo is not heavily retained in the residual fraction but is mainly associated with amorphous iron oxides. Since ammonium oxalate was originally developed to extract amorphous Fe oxides, it has become a standard method for estimating plant-available Mo and remains the most commonly used extractant for this purpose.

MANAGEMENT OF MOLYBDENUM

There is limited information on the effectiveness of different application methods to address Mo deficiency in soils and crops. However, soil application of Mo at a rate of 0.1 to 0.5 kg ha^{-1} has generally effective to correct deficiencies. Most commonly used Mo fertilizers include sodium molybdate ($Na_2MoO_4{\cdot}2H_2O$) and ammonium molybdate [$(NH_4)_6Mo_7O_{24}{\cdot}4H_2O$], which typically contain 52–54% Mo (Table 3). Foliar application using a sodium molybdate solution at concentrations of 0.07–0.1% is also effective in alleviating Mo deficiency.

Table 3. Sources of Molybdenum for plant

FERTILIZER SOURCE	Mo CONTENT (%)	METHOD OF APPLICATION	USAGE NOTES / REMARKS
Sodium molybdate (Na2MoO4.2H2O)	39–41%	**Seed treatment:** 0.5–1.0 g/kg seed **Foliar spray:** 0.01–0.05% Soil application: 50–100 g/ha	Most commonly used source; effective in pulses, oilseeds, vegetables
Ammonium molybdate ($(NH_4)_6Mo_7O_{24}{\cdot}4H_2O$)	52–54%	Foliar spray or soil application	Higher Mo content than sodium molybdate; used in blends
Molybdenum trioxide (MoO_3)	66%	Soil application only	Slow-release source; used in acidic soils
Molybdenum-enriched SSP/DAP	~0.05–0.1%	Applied with P fertilizers in soil	Used in fortified phosphate fertilizers

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Article Received on: 29 September 2025