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The role of molybdenum in crop production

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Abstract
Plants favour to micronutrients to maintain physiological balance in plants to maintain growth and development of the plants. Molybdenum (Mo) is essential micronutrients of the plants have a crucial role in growth and yield of the plants. Modern intensive agriculture gradually gains higher interest and importance of micronutrients to the researchers due to the diverse functional activities on plants. Documentation on the function of Molybdenum (Mo) on the growth and production of the crops were not accounted considerably. This mini-review point several improvements made in the communication of Mo in growth and development of crops.

Keywords: Role, molybdenum, crop production

Introduction
Molybdenum is an important plant micronutrient. Plants pick up molybdenum (as molybdate) from the soil and only small amounts (0.1 to 1.0 ppm) are necessary to meet their dietary requirements. It is essential for the production of two major enzymes in plants – nitrogenase and nitrate reductase – which enable nitrogen to be obtained, or 'fixed', from air or soil. Nitrogen is needed for compounds such as amino acids, proteins and chlorophyll. Plants suffer from poor growth without it, leaves may become pale and deformed, buds and flowers may not develop properly and fruit setting can be restricted. Acidic soils prevent the uptake of molybdate even if there are sufficient quantities in the soil. In these instances, lime can be added to the soil to reduce acidity, helping to increase the uptake of molybdate. Soils in some regions of the world are naturally low in molybdenum. This can also occur in peat soils and in highly weathered soils with low levels of nutrients. Since the importance of molybdenum in tomato crops was first recognized in 1939, deficiency symptoms have been identified in a number of crops. The element is critical for the nutrition of legumes, cereal, lettuce, tomatoes, cabbage, cauliflower and citrus fruit.
An international study involving field trials in 15 countries found that molybdenum deficiency was often only revealed by yield effects and without obvious symptoms of stress to the plant, yet was the most widespread deficiency after zinc and boron (Sillanpää 1990) [10].
Introduction of high-yielding varieties and higher use of nitrogen (N), phosphorus (P), and potassium (K), however, increased crop production several fold higher after the green revolution but this has led to micronutrient deficiency in most of the Indian soils (Singh 2001; Sahrawat *et al*. 2010) [11, 8]. Copper and Mo are likely to become critical in the future for sustaining high productivity in certain areas of India (Singh 2004) [12]. Indian soils are low in total Mo content, i.e., traces to 12 mgkg^{-1} (Sakal 2001), and about 11% of soils in India are deficient in available Mo (Singh 2001) [11].

Samples of wheat grown with and without molybdenum deficiency

Soybeans showing Mo deficiency in the foreground

Identification of Molybdenum as an Essential Plant Element

The requirement of molybdenum for plant growth was first demonstrated by Arnon and Stout (1939) [1] using hydroponically grown tomato. Plants grown in nutrient solution without molybdenum developed characteristic phenotypes including mottling lesions on the leaves, and altered leaf morphology where the lamellae became involuted, a phenotype commonly referred to as 'whiptail' (Arnon and Stout, 1939) [1]. The only trace element that could eliminate these phenotypes was found to be molybdenum.

Molybdenum Deficiency Symptoms

Molybdenum is mobile within plants and deficiency symptoms can appear on the entire plant.

Non-Legumes

Since adequate Mo is essential for proper N metabolism, deficiencies commonly appear as stunted plants and failure of leaves to develop a dark green color. In more severe deficiencies, the leaves may develop a pale green or yellow area around the edges and between the veins. Advanced symptoms of insufficient Mo may appear as burning (necrosis) around the leaf edges and between the veins, because the plant cannot assimilate the nitrate and convert it to protein. A well-known Mo deficiency symptom has been described for cauliflower, which develops a "whiptail" when the leaf tissue fails to develop surrounding the mid-leaf vein.

Legumes

These plants have an additional requirement for Mo, since it is required for N fixation by the root nodule bacteria, in addition to the internal utilization of nitrate. The symptoms of insufficient Mo include a general stunting and yellowing, typically seen as a result of insufficient N supply.

Availability of Molybdenum in Agricultural Soils

Mineral forms of molybdenum found in rocks include molybdenite (MoS_2), wulfenite ($PbMoO_4$) and ferrimolybdenite [Fe_2 (MoO_4)] (Reddy *et al*., 1997) [7]. Release of molybdenum from solid mineral forms is through weathering, a process involving continual solution and oxidation reactions (Lindsay, 1979; Gupta, 1997) [4, 2]. Dissolved molybdenum available to plants is commonly found in the soluble MoO^-_4 anion form (Lindsay, 1979) [4]. Once in solution, the MoO^-_4 anion is subject to normal anion adsorption/desorption reactions, which are dependent on the specific chemistry of the soil solution. MoO^-_4 can adsorb onto positively charged metal oxides (Fe, Al, Mn), clay minerals, dissolved organic compounds and carbonates. The adsorption of molybdenum onto positively charged metal oxides is strongly pH dependent with maximum adsorption occurring between pH 4 and 5 (K. S. Smith *et al*., 1997) [13]. As the soil solution becomes more alkaline MoO^-_4 availability increases. Every unit increase above pH 3, MoO^-_4 solubility increases approx. 100-fold primarily through decreased adsorption of metal oxides (Lindsay, 1979) [4]. Consequently, the application of lime to agricultural soils has been an important tool to adjust soil pH and increase soluble molybdate.

Fertilizing with Molybdenum

In many soils, application of a liming material to increase pH will release Mo from insoluble forms. For example, a study showed that addition of lime alone resulted in the same soybean yield as when Mo fertilizer was added to unlimed soil2. However, the chemical release of soluble Mo following lime application may take weeks or months to occur. If lime is not required for crop growth or when the Mo concentration of the soil is low, it may be useful to fertilize with additional Mo in the following ways:

Soil

Molybdenum fertilizers can be banded or broadcast on the soil. It is commonly added in small amounts, ranging from 0.5 to 2 lb/A. It is often mixed with other fertilizer materials to help with uniform application or it may be dissolved in water and sprayed on the soil before planting. Molybdenum trioxide (MoO_3) is only suitable for soil application due to its low solubility.

Foliar

Soluble Mo sources, such as sodium or ammonium molybdate, are used for foliar application to plants. Foliar application of dilute solutions of Mo is generally most effective when applied at earlier stages of plant development.
Foliar applications are beneficial for immediate correction of Mo deficiency symptoms, compared with soil applications, which have a longer residual benefit.

Seed

Treatment of seed with small amounts of Mo fertilizer is common in regions where deficiency occurs. This technique ensures that each seed is uniformly provided a small, but adequate amount of Mo for healthy growth. Rhizobia inoculants for legume crops are sometimes amended with small amounts of Mo to promote vigorous N fixation. Excessively high application rates can lower seed germination or cause Mo accumulation to concentrations that may be harmful for grazing animals.
The selection of a specific Mo fertilizer depends largely on how the material will be applied. Some common fertilizer products containing Mo are given in Table 1.

Table 1: Some common fertilizer products containing Molybdenum (Mo).

Name	Chemical formula	Mo content	solubility
Sodium Molybdate	Na_2MoO_4•2H2O	39%	653 g/L
Ammonium Molybdate	$(NH_4)_6$Mo7O_{24}•$4H_2O$	54%	400 g/L
Molybdenum Trioxide	MoO_3	66%	3 g/L

Crop Response to Molybdenum

The benefit of supplying adequate Mo most commonly relates to boosting the ability of plants to utilize N. Plant Mo deficiencies may not always require supplemental fertilization, especially in acid soils where application of lime will increase Mo availability to plants. Similarly, addition of P fertilizer releases Mo into solution after it exchanges with MoO^{2-}_4 on soil adsorption sites. Where adequate Mo is lacking, supplemental fertilization has resulted in large increases in plant growth and yield.

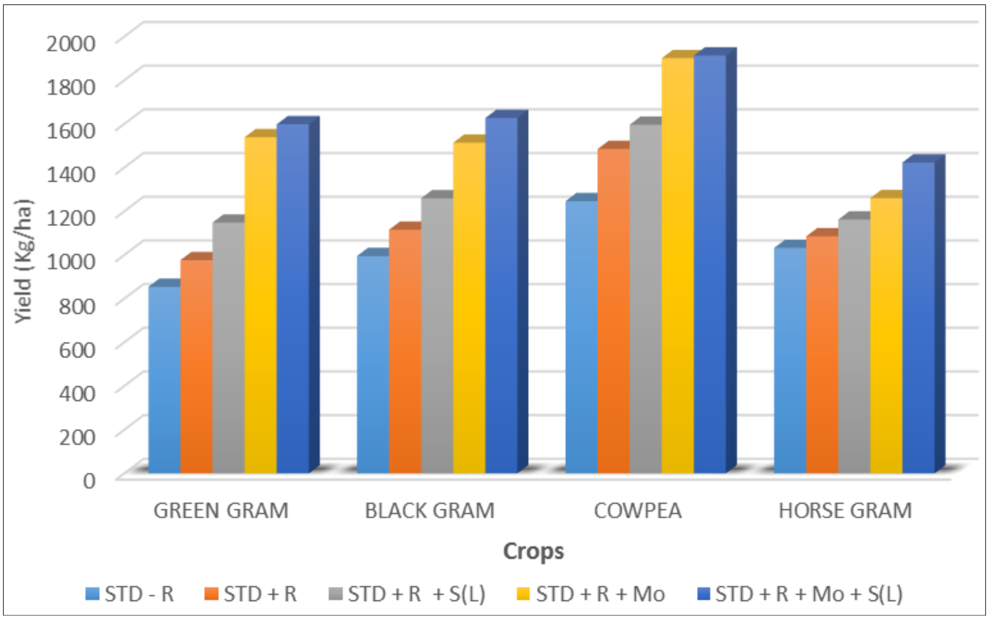

Fig 1: Effect of lime and fertilizer Molybdenum (Mo) application on yields of three crops (Padhi *et al*., 2018)

Table 2: Treatments and their details

S. No	Abbreviated Package of Practices (treatments)	Treatment details
T_1	STD - R	Seed without *Rhizobium*, FYM application @ 3 t ha^{-1} and with soil test based fertilizers.
T_2	STD + R	Seed inoculated with *Rhizobium*, FYM @ 1 t ha^{-1}, and applied with soil test based fertilizers.
T_3	STD + R+SEED$_{(LIME)}$	Seed inoculated with *Rhizobium* coated with lime using sago (tapioca root extract) as sticker, applied with soil test based fertilizers and FYM @ 1 t ha^{-1}
T_4	STD + R+ Mo	Seed treated with sodium molybdate @ 10g 25kg^{-1} seed in combinations with *Rhizobium* culture FYM @ 1 t ha^{-1}, and applied with soil test based fertilizers.
T_5	STD + R+ S_L+Mo	Seed treated with sodium molybdate @ 10g 25kg^{-1} seed in combinations with *Rhizobium* and coated with lime, FYM @ 1 t ha^{-1}, and applied with soil test based fertilizers.

The results of the experiment conducted "Effect of Lime Coating and Molybdenum Seed Treatment on Nodulation, Growth and Yield of Different Pulses Grown in *Alfisols*" in Odisha during summer 2017 in the farmers field demonstrated that lowest productivity was recorded with STD alone and highest with STD integrated with all the packages. Adoption of POPs with *Rhizobium* seed inoculation, seed coating with lime, seed treatment with Mo or combination of all, influenced the crop productivity.

Conclusion

Molybdenum is essential to plant growth. Deficiencies are often caused by acidic soils which prevent uptake and can be corrected by liming. However, where there is not enough in the soil, applying fertilizer, seed or foliar treatments containing molybdenum can increase productivity significantly. Correcting molybdenum deficiency also ensures that the use of nitrogen fertilizer is more efficient, cost effective and less harmful to the environment. Optimizing output from existing production minimizes the amount of additional land turned over to food production as demand increases, thereby helping to preserve biodiversity.

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