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Mitigating Nitrogen Pollution through Molybdenum Supplementation: A Review on Enhancing Nitrogen Use Efficiency in Crops

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ABSTRACT

With the global population projected to reach 11 billion by 2100, achieving sustainable agriculture is crucial to meet the increasing food demand. Nitrogen fertilizers, though essential for crop productivity, exhibit low use efficiency (30-40%), resulting in environmental pollution and soil nutrient imbalances. Molybdenum (Mo), a critical micronutrient, plays a vital role in enhancing nitrogen use efficiency (NUE) by acting as a cofactor for key enzymes like nitrate reductase and nitrogenase, which facilitate nitrogen assimilation and fixation. This review highlights the significance of Mo supplementation in agriculture, particularly in improving crop yields, nitrogen uptake, and nutritional quality. Research indicates that optimal Mo application boosts chlorophyll synthesis, stress tolerance, and phosphorus uptake while reducing nitrate leaching. Crops such as wheat, rice, and chickpeas show substantial benefits from Mo application under varying soil conditions. However, Mo availability remains limited in acidic and sandy soils, necessitating targeted approaches. The findings underscore Mo's potential to improve NUE, reduce dependency on chemical fertilizers, and promote environmental sustainability. Further exploration of Mo, including advancements in nanotechnology, offers promising prospects for developing efficient, eco-friendly agricultural practices to address global food security challenges.

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INTRODUCTION

Projections suggest that global food production must increase by approximately 60–70% to meet the dietary needs of an estimated 11 billion people by the end of the century (Babu *et al*., 2022; Dijk *et al*., 2021). This anticipated rise in demand underscores the urgency of adopting sustainable agricultural practices capable of maintaining productivity while minimizing environmental impacts. Food insecurity remains a major global challenge, particularly in developing regions where rapid population growth, resource limitations, and environmental pressures intensify the strain on agricultural systems. Meeting rising food demand in parallel with global population growth is essential for achieving the United Nations Sustainable Development Goals, especially those linked to food security and environmental sustainability (Ren et al., 2022). To achieve this goal, crop nutrition and soil fertility are the cornerstone of agricultural productivity. The belief that higher chemical fertilizer inputs lead to increased crop production has been a dominant approach for decades (Jayara *et al*., 2021). It was reported that Chemical fertilizers enhances the yield and productivity approximately 50-55% (Stewart

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et al., 2005). But the low nutrient use efficiency from conventional fertilizers, especially for nitrogen, phosphorus, and micronutrients, is a key challenge in modern agriculture. The nutrient use efficiency of conventional fertilizers typically varies 30–40% for nitrogen, 15–20% for phosphorus, 50–55% for potassium, and 2–5% for micronutrients—resulting in nutrient losses, reduced crop uptake, and significant environmental contamination (Adhikari & Ramana, 2019). These inefficiencies contribute to nitrate leaching, eutrophication, greenhouse gas emissions, and soil nutrient imbalances, highlighting the urgent need for sustainable nutrient management strategies; (Adhikari & Ramana, 2019, Babu et al., 2022).

Soil is the main primary source of nutrient for plants. There are 17 essential nutrients for plant which are differentiated as macronutrients and micronutrients, as macronutrients are required in large amount as compared to micronutrients. Among essential nutrients, nitrogen (N) is required in the greatest quantity due to its central role in amino acid and protein synthesis. It also contributes significantly to photosynthetic activity and overall plant metabolism (Omara, 2019). Since the 1960s, N fertilization has been recognized as an effective method for enhancing crop productivity. N plays a vital role in several plant growth processes since it is a component of chlorophyll and numerous enzymes (Fageria and Baligar, 2005; Baligar and Fageria, 2007). The two main types of N that plants can access in soil are ammonium (NH_4^+) and nitrate (NO_3^-). In subtropical climates with negatively charged soils, NH_4^+ has very low mobility due to its positive charge (Richter and Roelcke, 2000). However, as water flows through the soil profile, NO_3^- movement is six times greater than NH^{4+}, making it more vulnerable to leaching loss (Noor and Sadia, 2018). Inaccessible N may stay in the soil in various forms and/or be lost by multiple processes, including ammonia (NH_3) volatilization, denitrification to gaseous form, and nitrate leaching (Aulakh and Malhi, 2005). Apart from the low Nitrogen usage efficiency (NUE), the subsurface water stream becomes contaminated due to NO_3^- leaching below the soil profile. Since cereal grains, the most common food, contain very little nitrate, the primary ways nitrate enters the food chain are through drinking contaminated water or using it for crop irrigation. When NO_3^- is consumed, it is reduced down into nitrite (NO_2^-) by certain bacteria. This NO_2^- is absorbed by the blood where it helps in oxidation of ferrous iron of hemoglobin to ferric iron and results in conversion of hemoglobin to methemoglobin. Methemoglobin has less binding affinity for oxygen than hemoglobin, which creates a hypoxic condition known as methemoglobinemia or blue baby syndrome. Therefore, uptake of applied nitrate fertilizer is most important instead of fresh application of same. As a result, enhancing crop NUE, defined as total grain yield or biomass per unit of N applied (Liu *et al.*, 2017), is a viable approach to deal with this challenge. Crop NUE is determined by a variety of interrelated steps that include nitrogen intake, transport, assimilation, and remobilization (Liu *et al.*, 2022).

Micronutrients are vital for enhancing NUE by serving as cofactors for enzymes and regulating key metabolic pathways involved in nitrogen uptake, assimilation, and utilization. Proper levels of micronutrients help plants efficiently convert inorganic nitrogen into organic compounds like amino acids and proteins, minimizing losses to the environment. The essential micronutrients to improve NUE includes Molybdenum (Mo), Zinc (Zn), Iron (Fe), Copper (Cu), and Manganese (Mn). Zn showed the synergistic effect when applied with N under stress conditions with enhanced overall N uptake (Ji *et al*., 2021) also it acts as a cofactor in glutamine synthetase enzyme of N assimilation (Guan *et al*., 2025). Fe is critical for N assimilation as it helps in nitrite reduction, nitrogen fixation and in photosynthesis (Gao *et al*., 2025; Kong *et al*., 2023). Cu involves in the synthesis of molybdenum cofactor for Nitrate Reductase (NR), and is an important component for photosynthetic electron transport (Xin et al., 2024). Mo takes part in various enzymes of plants involving NR, nitrogenase, sulfite oxidase, and xanthine oxidase. It also affects the chlorophyll synthesis (Rana *et al.,* 2020a).

Mo as an essential plant element

Mo is a transition element found in trace amounts in soil. It is a crucial micronutrient for plants and animals. Mo takes part in various enzymes of plants involving NR, nitrogenase, sulfite oxidase, and xanthine oxidase. It also affects the chlorophyll synthesis(Rana *et al.,* 2020a). It is derived through the chemical and physical weathering of igneous and sedimentary rocks, forming parent material. Molybdenite, wulfenite, and ferrimolybdenite are the three natural raw materials containing Mo which is released for plant uptake after chemical weathering in the form of soluble molybdate (MoO_4) (Kaiser *et al.,* 2005; Rana *et al.*, 2020a). Plants require a minimal amount of Mo as compared to other micronutrients. The normal quantity sufficient for plant growth is 0.15-2ppm, deficiency is known when it is 0.03-0.15ppm and becomes toxic when found above 100 ppm (Jayara *et al.*, 2021). It forms the crucial component of NR enzyme and Nitrogenase enzyme thus essential for N metabolism. It enhances phosphorus uptake and promotes N fixation (Arabhanvi *et al.*,2015; Jayara *et al.*, 2021). Mo improves plant growth by increasing antioxidant enzyme activities or increasing oxidative tolerance (Moussa *et al.*, 2022). Mo is not biologically active, but it binds with the organic pterin and becomes a Mo cofactor, known as MoCo. This Moco takes part in one of the main steps of N metabolism (Shoaib *et al.*, 2020).

Recent studies of the Mo in plants, prokaryotes, and animals have revealed a wide range of research on the synthesis, regulation, and activity of Mo-dependent apoenzymes (Ahmed *et al.*, 2017). The molybdate transport system in lower-order eukaryotes and prokaryotes is well-defined and designed at the physiological, genetic, and biochemical levels. Aldehyde oxidase (AO), also known as plant molybdoenzyme, plays a crucial function in plant development in defense against environmental stresses (Folina *et al.*, 2021; Yoshida and Toyoda, 2000). The AO multigene family members, such as Abscisic acid (ABA) and Indole acetic acid (IAA), catalyze the biosynthesis of phytohormones in the previous stage by converting abscisic aldehyde and indole acetoaldehyde into the corresponding phytohormones. Plant hormones called auxins, of which IAA is an essential component, play a key role in several plant processes, including abscission, root initiation, phototropism, fruit development, gravitropism, and apical dominance (Taiz et al., 2015). It has also been proposed that IAA plays a role in stress including salt and plant water deficiencies. ABA is also very vital and significant in plants' responses to environmental stress (Kovács *et al.*, 2015).

Despite the extensive knowledge on nitrogen fertilization and its limitations, a clear synthesis linking molybdenum's multifaceted role in nitrogen metabolism with its potential to enhance NUE is still limited. Most existing studies focus either on general micronutrient management or on individual enzymatic functions of Mo, but they do not integrate these findings into a comprehensive framework for sustainable management.

This review addresses this gap by consolidating current evidence on Mo-dependent enzymes, Mo availability in soils, and the emerging role of nano-Mo formulations, thereby providing a novel, holistic perspective on how Mo supplementation can strategically enhance nutrition plant growth and development by improving NUE under diverse agro-ecosystems.

Availability of Mo in soil

Mo is a very rare element which is generally found between 0.6 and 3.5 ppm in most of the agricultural soil with an average of 2 ppm and also the available average Mo is only 0.2 ppm (Shoaib *et al.*, 2020). It is the least found micronutrient in the lithosphere (Behera *et al.*, 2015). According to Patel (2017), above 20.0 ppm of Mo value is toxic in soil (Patel *et al.*, 2017). It largely occurs in oxycomplex, due to which it resembles the phosphate and sulfate behavior in soil. It occurs in different oxidation states from zero to VI but most commonly in agricultural soil it is found in VI (Kaiser *et al.*, 2005). Under anoxic conditions, it occurs in IV oxidation state (Rana *et al.*, 2020a). There are various environmental factors deciding the availability of

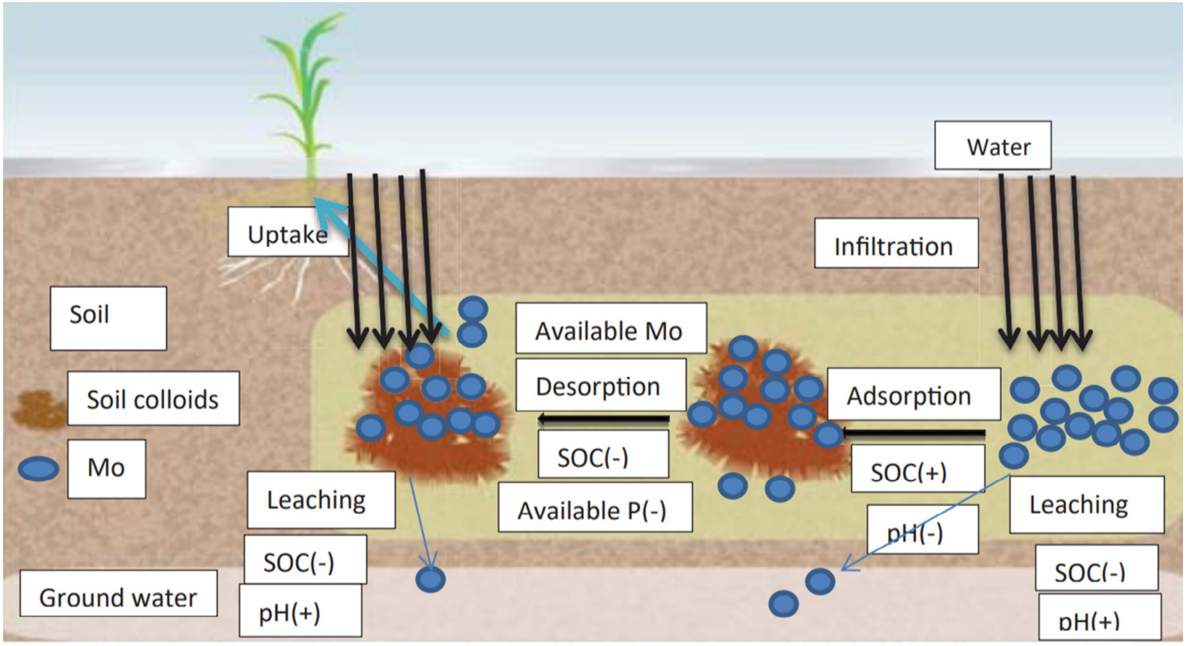

Fig. 1. Factors affecting the leaching and absorption of Mo (Shoaib *et al.*, 2020).

molybdenum which includes soil texture, soil pH, organic matter, water holding capacity, and other nutrients. Mo availability increases by one hundred-fold with every unit of increase in soil pH. Alkaline soil favours more availability of Mo to plants as it allows the adsorption of various cations such as magnesium, potassium, calcium, sodium; and which helps in increment of availability for plant uptake but this soluble form is then leached down. In acidic conditions, various oxides such as aluminium oxides, iron oxides, and manganese oxides are present which helps in adsorption of Mo to the soil particles forming complexes which make it unavailable for root uptake. Heavily textured soil drains out slowly. Mo binds with the clay and oxides present in the organic matter making it unavailable to plant then slowly Mo mineralize and become available to plants when this organic matter decomposes (Shoaib *et al.*, 2020; Rana *et al.*, 2020a; Syaifudin *et al.*, 2024) Figure. 1 shows details about factors affecting the leaching and absorption of Mo. Its deficiency is common in sandy, leached and acidic soil (Shukla *et al.*, 2014).

Various enzymes involving Mo

Nitrogenase

Fixed nitrogen is essential for synthesizing amino acids, nucleic acids, chlorophyll, and other vital biomolecules across living organisms (Fageria & Baligar, 2005). Although atmospheric nitrogen (N_2) constitutes approximately 78% of the atmosphere, it is unavailable for direct biological assimilation due to its strong triple bond and chemical inertness (Imran et al., 2019). The chemical stability of N_2 prevents its spontaneous conversion into bioavailable forms; however, specialized prokaryotes known as diazotrophs can convert N_2 into ammonium through the process of biological nitrogen fixation (BNF), which occurs under ambient environmental conditions (Mendoza-Suárez et al., 2021). Mo functions as a critical micronutrient in nitrogen metabolism and is indispensable for symbiotic nitrogen fixation, where it facilitates the development and functioning of root nodules formed by nitrogen-fixing bacteria (Kaiser et al., 2005).

Mo functions at the core of the nitrogenase enzyme via the iron–molybdenum cofactor (FeMoCo) complex (Shah et al., 1994). The FeMoCo within Mo-dependent nitrogenase serves

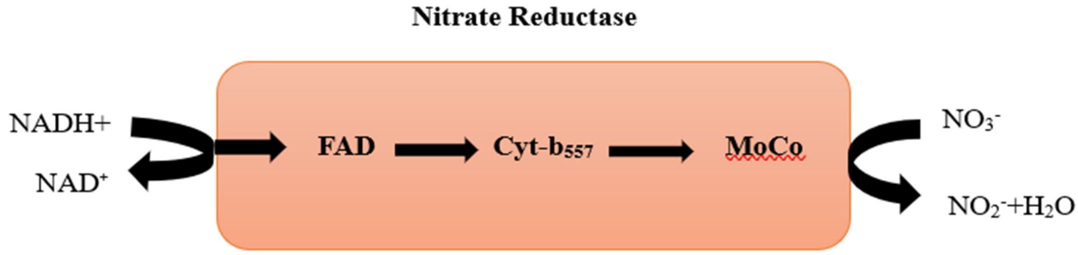

Fig. 2. Structure of Nitrate Reductase (Kovács *et al.*, 2015).

as the catalytic site for N_2 reduction, enabling the conversion of atmospheric N into NH_3 (Brodrick & Giller, 1991). The MoFe protein of nitrogenase contains a single molybdenum atom per FeMoCo unit, along with iron–sulfur clusters that mediate electron transfer during nitrogen reduction (Shah et al., 1994). In N_2-fixing organisms, the FeMoCo of the nitrogenase protein serves as the active site of the Mo-containing nitrogenase protein (Shah *et al.*, 1994; Mendoza-Suárez *et al.*, 2021).

Nitrate Reductase

NR is a homodimer enzyme composed of two 100–120 kDa subunits, each containing three essential prosthetic groups- Flavin Adenine Dinucleotide (FAD), cytochrome b_{557}, and a Mo-containing molybdenum cofactor (MoCo) that mediate electron transfer in nitrate reduction (Campbell, 1999; Sanz-Luque et al., 2015). MoCo is comprised of pterin with a side chain to which molybdenum is attached by two sulfur bonds (Campbell, 1999; Sanz-Luque *et al.*, 2015; Kovács *et al.*, 2015) as shown in Figure. 2.

Most likely, the bonded Mo atom changes between oxidation states IV and VI. The nitrate reductase subunit is covalently attached to each of the three redox carriers. Using electrons from NAD(P)H, the enzyme Nitrate Reductase catalyses the conversion of nitrate to nitrite (Kovács *et al.*, 2015). Nitrate uptake in photosynthetic organisms involves two transport and reduction steps: Nitrate is first brought in the mesophyll cells, where it is converted to nitrite by cytosolic Nitrate Reductase (NR), which is then carried in the chloroplasts where Nitrite Reductase (NiR) catalyzes its conversion to ammonium. Finally, with the help of the glutamine synthetase/glutamine oxoglutarate aminotransferase or glutamate synthase (GS/GOGAT) cycle, ammonium is added to carbon skeletons. In a reaction combining glutamate (Glu), ATP, and GS, ammonium is first integrated as the amide group of glutamines (Gln). The amide group is then converted reductively to α-oxoglutarate to produce 2 molecules of glutamate (Imran *et al.*, 2019). This one molecule of glutamate is then further helps in the synthesis of amino acids which is shown in the Figure. 3 and another one molecule will again take part in nitrogen metabolism.

Xanthine oxidoreductase/ dehydrogenase (XDH)

It is a fundamental enzyme of purine degradation and oxidizes the purine nucleotides like adenine and guanine to xanthine and ultimately to uric acid. XDH is also involved in Reactive oxygen species regulation, developmental and hormonal regulation (Ma et al., 2016). It exists in 2 forms xanthine dehydrogenase and xanthine oxidase. It involves the oxidation of xanthine with the reduction of NAD^+ to NADH. This enzyme also has a specific property of hydrolyzing different aldehydes and aromatic heterocycles. It is a dimer of 150kDa subunits with three domains; nucleotide-binding domain, iron-sulfur cluster, and molybdenum cofactor (Ma *et al.* , 2016; Manuel *et al.*, 2018).

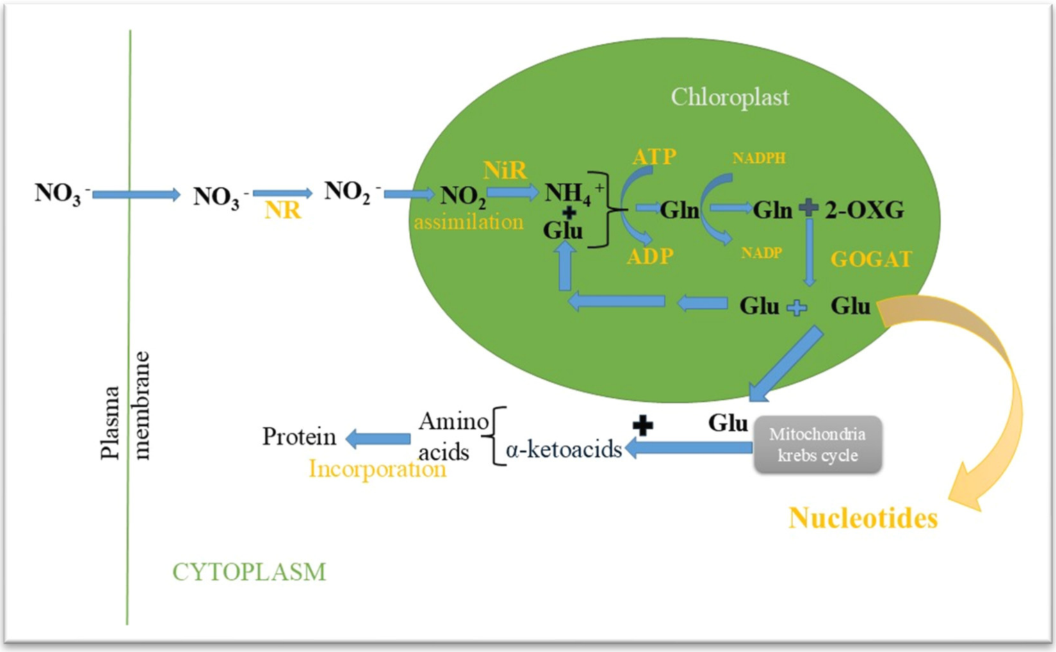

Fig. 3. The process of nitrogen metabolism in plants.

Aldehyde oxidase (AO)

It is a versatile enzyme involved in a variety of biochemical pathways such as stress response, lipid metabolism, nitrogen metabolism, secondary metabolism (flavonoid and terpenoid synthesis), synthesis of plant hormones, and various developmental processes. It plays a crucial role in metabolic detoxification, as the metabolism of drugs and xenobiotics also the conversion of endogenous aldehydes. This enzyme catalyzes the oxidation of aldehydes to carboxylic acids. Its structure is similar as the Xanthine dehydrogenase; it contains molybdenum cofactor, iron-sulfur cluster and flavoprotein domain. This molybdenum cofactor and iron-sulfur cluster are essential for its oxidation function (Mendel, 2009; Hille, 2013; Manuel *et al.*, 2018).

Sulfite oxidase (SO)

SO catalyzes the oxidation of toxic sulfite (SO_3^{2-}) to sulfate (SO_4^{2-}), a crucial step in sulfur metabolism and cellular detoxification (Brychkova et al., 2015). SO is a single dimer of 45kDa subunits which has two prosthetic groups, the heme group in the N terminal region and the other one is Mo cofactor at its C terminal sequence. Sulfite is a highly reactive nucleophile that can damage cellular components; therefore, SO acts as a protective enzyme by preventing sulfite accumulation and maintaining sulfur homeostasis (Xia et al., 2012). It is necessary for maintaining homeostasis in the cell. Along with the prevention of sulfite toxicity, it also maintains optimal metabolism of carbon, sulfur and nitrogen by balancing key metabolites in stressed and unstressed plants (Brychkova *et al.*, 2015; Xia *et al.*, 2012).

Impact of Mo's insufficiency on growth

Sulfate competes with molybdate ions in soil, reducing Mo uptake by plants, whereas phosphorus enhances Mo availability by reducing molybdate adsorption to soil particles (Kaiser et al., 2005). Excessive sulfate fertilization can therefore predispose plants to Mo deficiency. Mo deficiency is commonly characterized by yellowing of the leaves, slowed development, curling, rolling, and burning of the leaf margins (Aulakh and Malhi, 2005; Kaiser *et al.*, 2005). Because Mo influences iron mobilization and nitrate reduction, plants deficient in Mo often

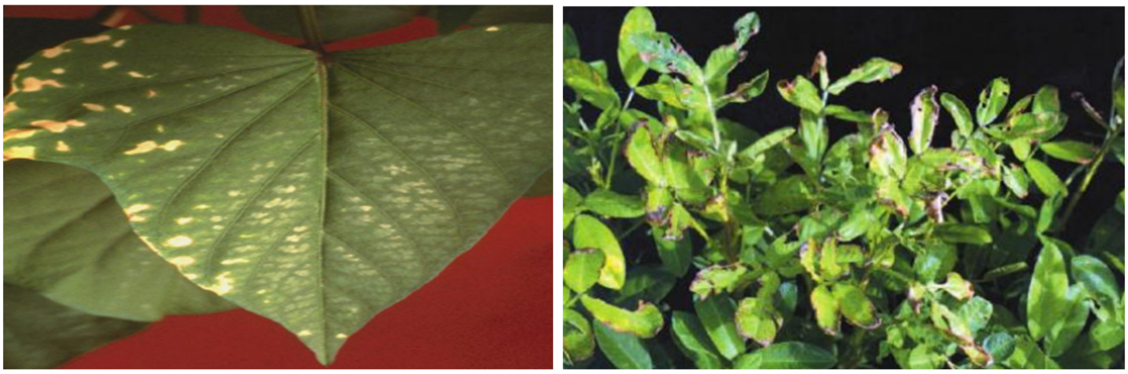

Fig.4. Molybdenum deficiency shows nitrogen toxicity from nitrate accumulation (Kaiser et al., 2005).

exhibit symptoms similar to iron deficiency, such as interveinal chlorosis (Olsen & Watanabe, 1979; Mitra, 2015).

Since Mo's most important function in plant metabolism is the assimilation of NO_3^-, Mo deficit is similar to N deficiency. According to Shoaib (2020), plants that lack Mo show signs of leaf pallor, stunted growth, and flower development as shown in Fig.4 (Shoaib *et al.*, 2020). Such symptoms are frequently misinterpreted as nitrogen deficiency, often prompting unnecessary nitrogen fertilization, which further increases environmental nitrogen losses (Aulakh & Malhi, 2005). The significant abnormality in size is the most common visible effect in dicotyledons. These are brought on by necrosis in the tissue and inadequate disparity of the vascular bundles at the beginning phases of leaf development (Shoaib *et al.*, 2020). Several studies demonstrate that Mo deficiency disrupts other nutrient pathways particularly phosphorus, iron, and sulfur, leading to impaired chlorophyll biosynthesis, reduced enzyme activity, and compromised antioxidant defense (Imran et al., 2019; Rana et al., 2020b; Moussa et al., 2022).

Nanotechnology in Agriculture

Nanofertilizers represent a novel class of nutrient delivery systems engineered at the nanoscale (1–100 nm) to improve nutrient solubility, reactivity, and uptake efficiency by plants (Mejias et al., 2021). Depending on their formulation, nanofertilizers may consist of: (i) nutrients in nanoscale form, (ii) bulk nutrients encapsulated in nanoscale carriers, or (iii) surface-modified nanoparticles that enhance nutrient transport—an important distinction in understanding their mechanisms (Mikkelsen, 2018).Nanostructured carriers allow controlled nutrient release through mechanisms such as diffusion, dissolution, ion exchange, or gradual degradation of nanomaterials, thereby improving nutrient retention and reducing leaching losses (Babu et al., 2022). Nanofertilizers may be applied to soil or as foliar sprays, allowing flexible nutrient management. Soil applications ensure sustained nutrient availability at the root zone, while foliar sprays enable direct uptake through stomata (Mikkelsen, 2018). The different Mechanism action including ways of application, plant uptake, movement through plant, and Penetration into the cell of nanoparticles are shown in figure 5. Nanofertilizers represent a significant advancement in agriculture by providing precise nutrient delivery, improved nutrient use efficiency, and lower environmental impact. They help balance productivity with sustainability, supporting food security and reducing ecological harm. Compared with conventional fertilizers, nanoparticles enhance nutrient use efficiency by increasing surface reactivity, improving adhesion to leaf surfaces, and enabling targeted delivery to specific cellular compartments—mechanisms illustrated in Figure 6 (Hussain & Sharma, 2025).

Review Methodology

This review was conducted by systematically collecting, screening, and analyzing published

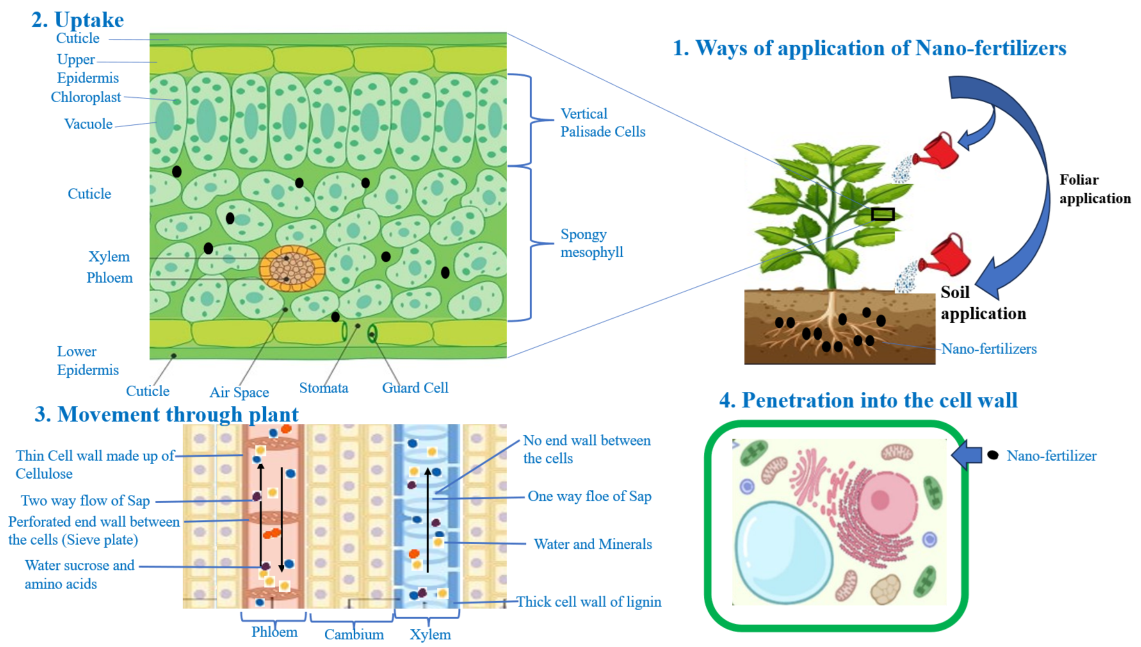

Fig. 5. Mechanism of action of Nano-fertilizers; 1) Ways of application. 2) Plant Uptake. 3) Movement through plant. 4) Penetration into the cell

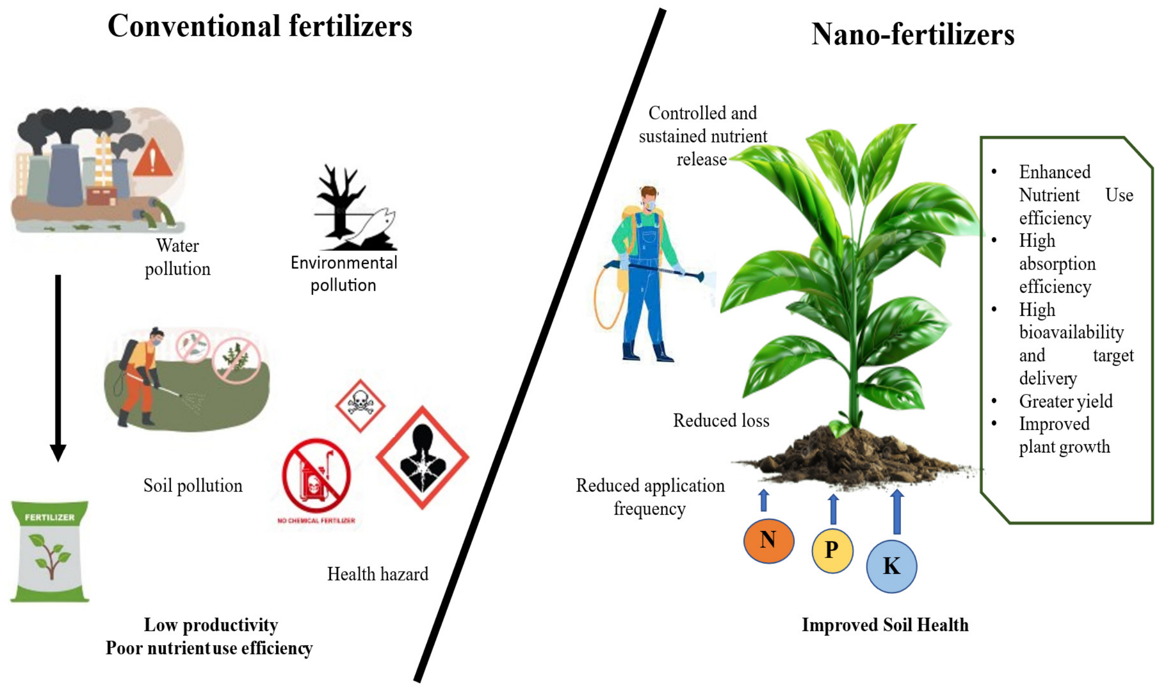

Fig. 6. Potential of nanofertilizers over conventional fertilizers (Hussain and sharma, 2025)

research articles, reports, and review papers related to the role of molybdenum (Mo) in improving NUE and crop productivity. Publications were retrieved from multiple scientific databases, including Scopus, Web of Science, PubMed, Google Scholar, and OpenAlex. The search strategy involved combinations of keywords such as "molybdenum fertilizer," "nitrogen use efficiency," "nitrate reductase," "nitrogen fixation," "Mo application in crops," and "sustainable

Table 1. Various studies of Mo application on different plants.

Sr. No.	Conc.	Plant name	Results	References
1.	Different levels of molybdenum and iron were applied at the rate of 0, 0.25 and 0.50 and 0, 2 and 5.0 kg ha^{-1}, respectively.	Chickpea (*Cicer Arietinum L.*)	From the study it was concluded that 0.5 Mo and 2.0 kg/ha Fe resulted in maximum growth, nitrogen content and yield	(Khan *et al.*, 2014)
2.	Four rates of Mo (0, 0.01, 0.1 ,1 mg/l)	Rice (*Oryza sativa*)	Mo application significantly increased the shoot phosphorus uptake and maximum uptake was at 1mg/l also it enhanced the manganese uptake by shoot.	(Zakikhani *et al.*, 2014)
3.	Mo treatment(0, 0.13, 0.25, 0.5, 1.0 mg/kg)	hairy vetch (*Vicia villosa Roth*)	0.5mg/kg of Mo dose was found optimum for maximum No. and size of nodules and biomass production along with increased enzymatic activity of NR.	(Alam *et al.*, 2015)
4.	Molybdenum with boron was applied with recommended dose and borax	Broccoli (*Brassica oleracea L.*)	Application of 2.5% Mo was found optimum for better growth, and yield production.	(Patel *et al.*, 2017)
5.	0.15 mg Mo/kg soil, (Mo) 1 mg Zn/kg soil (Zn), and 0.15 mg Mo/kg + 1 mg Zn/kg soil (Mo + Zn)	winter wheat (*Triticum aestivum L.*)	Mo and Mo+Zn application increases the grain yield , thousand kernal weight, chlorophyll a and a+b contents along with the photosynthetic rate and nitrate reductase activity.	(Liu *et al.*, 2019)
6.	Mo: 0.0, 0.5, 2.0, and 4.0 $\mu mol\ L^{-1}$	Tomato (*Solanum lycopersicum*)	2.0 µmol L−1 of Mo effectively enhance crop performance and overall fruit quality of tomato	(Sabatino *et al.*, 2019)
7.	Different concentrations of Mo (0, 50, 100, and 200 mg/kg)	Rape plant (*Brassica napus L.*)	Application of 100 mg/kg Mo enhanced the physiological activities and biomass along with the mitigation of Cadmium stress.	(Ravutla *et al.*, 2020)
8.	Four concentrations of Mo (0, 15, 30, and 45 $mg{\cdot}L^{-1}$)	Mung Bean (*Vigna radiata L.*)	15 and 30mg/l dose of Mo significantly increases the yield parameters with an enhanced defense system by up regulating antioxidant expressions (proline, catalase, and peroxidase), and also showed a positive impact on drought tolerance	(Hayyawi *et al.*,2020)
9.	9 concentrations of molybdenum was given with borax	Blackgram (*Vigna mungo L.*)	Optimum concentration was 105kg/ha which showed the maximum growth and grain yield	(Singh *et al.*,2021)
10.	Mo: 0 ,1 kg, 1.5 kg ha^{-1} .	Soybean (*Glycine max L.*)	1.5kg/ha dose of molybdenum significantly increased the growth and yield production.	(Khatun, 2021)
11.	Various conc. of Mo was given as foliar and basal	cauliflower (*Brassica oleracea var. botrytis L.*)	Conjoint application of Mo (soil plus foliar)0.15% as foliar and 1.0% as basal was recorded as the optimum for highest production.	(Chakkal *et al.*, 2023)
12.	Sodium molybdate was given in various conc. (0, 50, 100, 150, and 200 g ha^{-1})	*Brassica parachinensis L.* and *Brassica integrifolia L.*	. The application of 150g/ha is found to be optimum for increment in nitrogen assimilation, starch synthesis, chlorophyll synthesis, protein production, growth and physiology of brassica under drought stress	(Tran *et al.*, 2024)

agriculture.” The inclusion criteria focused on studies published between 2000 and 2024, which reported experimental evidence on Mo supplementation in different crops (cereals, pulses, vegetables, and oilseeds) under varied soil and climatic conditions. Both field-based and pot-based experiments were considered, along with recent studies on nanomolybdenum fertilizers.

Studies reporting the enzymatic roles of Mo (e.g., nitrate reductase, nitrogenase, sulfite oxidase, aldehyde oxidase, and xanthine oxidase) and their direct impacts on NUE were prioritized. Relevant data were extracted regarding experimental design, Mo application rates, crop type, soil properties, and observed agronomic and physiological responses. Particular attention was given to research that evaluated Mo's effects on: Crop yield and grain nutritional quality, Nitrogen uptake, assimilation, and fixation, Enzymatic activity related to nitrogen metabolism, Stress tolerance and antioxidant defense, Uptake of other macro- and micronutrients.

Comparative synthesis was then performed to examine how Mo application contributes to NUE improvement and reduction of environmental nitrogen losses. Studies were cross-verified to highlight common trends, contrasting results, and knowledge gaps. The methodological approach ensured that the review draws upon a wide base of scientific evidence, thereby strengthening the reliability of conclusions.

Impact of Nano Mo supplementation on crops

Various studies were extensively reviewed with respect to research conducted to enhance nitrogen use efficiency with the application of molybdenum. A brief description is given below in the table 1. It was found that the application of molybdenum mitigates the risk of N accumulation in vegetables and environmental N Emissions with increasing cumulative crop yield and N uptake (Wen *et al.*, 2018). Many studies reported that a positive correlation is there between photosynthesis, chlorophyll content with N availability(Liu *et al.*, 2017). Wheat, the cereal crop, staple food worldwide was studied and it was estimated that Mo results in a significant positive increment in the nutritional value of grain, crop yield, and production (Imran *et al.*, 2019; Moussa *et al.*, 2021). Many studies had concluded from different researches that Mo deficiency affects various other macronutrients and micronutrient uptake (Imran *et al.*, 2019; Rana *et al.*, 2020b; Moussa *et al.*, 2021). Mo is the key component and limiting factor as by the application of Mo, the translocation from upper grains to grains increased resulting in high nutritional quality of wheat grains. The content of other macro-micronutrients was also found higher than Mo deficient plants (Moussa *et al.*, 2022). In grapevine seedlings, reduced nitrate content, and increased amino acid and chlorophyll content were reported. Also the synergistic effect of Mo and N was seen as enhanced NUE and N absorption was found by the addition of Mo under different N sources (Liu *et al.*, 2022).

Mo toxicity

Although molybdenum supplementation is essential for optimizing nitrogen metabolism, its excessive application may pose toxicity risks for both plants and the environment. Elevated Mo concentrations can lead to leaf chlorosis, reduced biomass, and metabolic imbalance in sensitive plant species (Gupta & Lipsett, 2020). Moreover, excessive Mo in soil may alter microbial community structure and enzyme activity, potentially disrupting nitrogen cycling processes (Sun et al., 2019). Therefore, balanced Mo application and soil-specific management are crucial to prevent unintended ecological and animal-health impacts."

CONCLUSION

Global food demand is increasing rapidly due to population growth, underscoring the need for efficient and sustainable nutrient management in agriculture. Although N fertilizers are fundamental to achieving high crop yields, their low NUE results in considerable nutrient losses and environmental pollution. Enhancing NUE is therefore essential for improving crop productivity while minimizing ecological impacts. This review highlights the pivotal role of Mo in improving NUE through its involvement in key enzymatic pathways such as nitrate reductase, nitrogenase, sulfite oxidase, aldehyde oxidase, and xanthine dehydrogenase. Adequate Mo availability facilitates nitrogen uptake, assimilation, and redistribution, contributing to enhanced plant growth, grain quality, and resilience to abiotic stresses. Research across cereals, legumes, and horticultural crops consistently demonstrates that Mo supplementation reduces nitrate accumulation, increases enzymatic activity, and improves macro and micronutrient uptake. Mo deficiency is widespread, particularly in acidic and sandy soils where its bioavailability is limited due to soil chemistry constraints. Addressing Mo deficiency through soil or foliar application, as well as emerging nanomolybdenum formulations, offers a cost-effective strategy to improve plant performance while reducing reliance on excessive nitrogen fertilization. Overall, optimizing Mo management in agriculture can significantly enhance nitrogen efficiency, reduce nitrogen losses, and support more sustainable crop production. Future work should refine Mo application practices across diverse environments and advance nano-enabled Mo technologies can significantly enhance the sustainability and productivity of agricultural systems.

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CONFLICT OF INTEREST

The author declares that there is not any conflict of interests regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/ or falsification, double publication and/or submission and redundancy have been completely observed by the authors.

LIFE SCIENCE REPORTING

No life science threat was practised in this research.

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