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Molybdenum as a context-dependent lever for crop nitrogen use efficiency: a review

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KEYWORDS

Molybdenum, nitrogen use efficiency, nitrate reductase, micronutrient management, crop nutrition

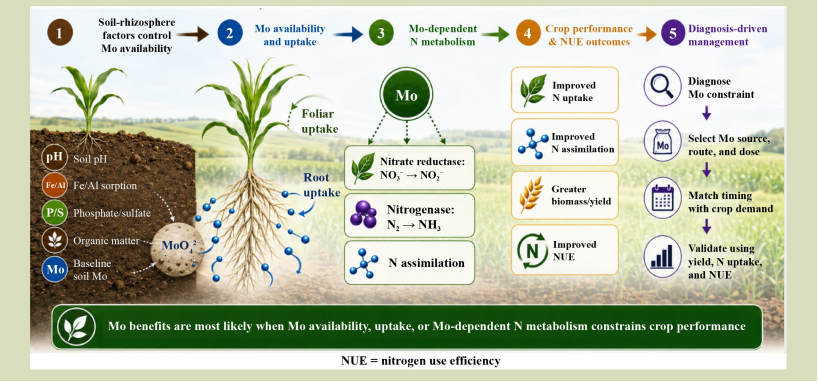
HIGHLIGHTS

- A Scopus-based synthesis coded 249 Mo observations from 141 reports.
- Mo effects on crop NUE were strongly context- and constraint-dependent.
- Mixed responses dominated, rejecting universal Mo benefits for NUE.
- No conventional Mo application route showed consistent superiority.
- Diagnosis-based Mo management can improve route and dose calibration.

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GRAPHICAL ABSTRACT



ABSTRACT

Molybdenum (Mo), an essential cofactor for nitrate reductase and nitrogenase, has demonstrated variable crop responses across soil conditions, crop species, application methods, and environmental stress factors. We conducted a Scopus-based scoping review and evidence mapping of studies published from 2015 to 2025 that evaluated Mo effects on NUE-related agronomic, physiological, biochemical, and symbiotic outcomes. Rather than pooling effect sizes, we applied context-stratified direction-of-effect coding and quality-sensitivity analyses. Of the 495 records identified, 141 reports were retained, and the cleaned dataset comprised 249 coded observations, including 233 route-assigned observations. Mixed responses represented the predominant pattern across all coded observations (114/249; 45.8%), whereas clearly positive responses accounted for 86/249 (34.5%). This imbalance indicates that Mo responses are strongly conditional rather than reliably positive. Mixed responses also persisted after lower-support evidence was

excluded (97/215; 45.1%), and no conventional application route showed consistent superiority. More importantly, nano-Mo did not demonstrate a favorable route-level pattern: none of the 13 route-assigned observations was clearly positive, whereas 11 (84.6%) were categorized as mixed. The evidence is therefore insufficient to support field-scale recommendation of nano-Mo. Mo management should be guided by constraint-based diagnosis, route- and dose-specific calibration, and field validation using yield, N uptake, and standardized NUE-related endpoints.

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1 Introduction

Nitrogen (N) is the most intensively managed nutrient in crop production; however, the conversion of applied N into harvested yield remains inefficient. Global crop N recovery is frequently estimated at only 40%–50%, leaving a substantial proportion of fertilizer N susceptible to leaching, runoff, ammonia volatilization, denitrification, and nitrous oxide emissions[1,2]. These losses diminish profitability and exacerbate eutrophication and climate forcing. Consequently, improving nitrogen use efficiency (NUE) has become central to sustainable intensification, particularly amid fertilizer market volatility and increasing pressure to reduce reactive N losses while sustaining crop yield[3,4]. Most NUE strategies focus on N rate, timing, placement, and inhibitors. However, NUE also depends on the capacity of crops to acquire, reduce, assimilate, and remobilize N, processes partly constrained by micronutrient-dependent enzymes.

Molybdenum (Mo) plays a direct role in plant N metabolism. In higher plants, Mo is incorporated into the mo cofactor (Moco), which activates molybdoenzymes such as nitrate reductase, a key enzyme involved in nitrate assimilation[5,6]. In legumes and other symbiotic N-fixing systems, Mo is also required for nitrogenase, the enzyme complex responsible for biological N fixation. Through these functions, Mo can influence mineral N assimilation, symbiotic N_2 fixation, plant N status, protein accumulation, chlorophyll synthesis, nodulation, biomass production, yield, and NUE-related indices. Nevertheless, the biochemical necessity of Mo does not imply that Mo fertilization will consistently enhance crop performance. Mo is expected to improve NUE only when Mo availability, uptake, or Mo-dependent enzymatic activity constrains N conversion relative to crop demand and prevailing environmental conditions.

This conditionality originates in the soil. In well-aerated soils, plant-available Mo occurs primarily as molybdate, an oxyanion whose availability is governed by soil pH, sorption surfaces, and competing anions. Under acidic conditions, molybdate can be strongly sorbed by Fe and Al oxides, reducing root-accessible Mo. This mechanism remains agronomically relevant because low soil pH is associated with aluminum toxicity, Mo deficiency, and other plant-growth constraints. Rather than relying on older fixed global-area estimates, recent global digital soil information systems provide spatially explicit predictions of soil properties, including soil pH. For example, SoilGrids 2.0 generates global soil-property maps at 250 m resolution with quantified spatial uncertainty by integrating soil profile observations with environmental covariates[7]. Liming and increases in soil pH often enhance Mo availability; however, responses also depend on calcium chemistry, phosphate and sulfate competition, organic matter content, oxide abundance, and baseline soil Mo levels. Consequently, the same Mo dose may correct deficiency in one soil, remain ineffective in another, or even induce imbalance or toxicity.

Plant functional type and management practices determine whether Mo availability translates into NUE improvements. In non-leguminous crops, the most direct Mo–NUE pathway involves nitrate reduction and subsequent N assimilation. In legumes, Mo may additionally regulate nodulation and nitrogenase-mediated N fixation. Genotypic variation in Mo uptake, transport, tissue allocation, and enzyme activity may explain contrasting cultivar responses. Application route is also important because soil application, foliar spraying, seed priming or coating, nutrient-solution delivery, and nano-Mo formulations differ in soil exposure, uptake pathways, application timing, dose sensitivity, and the risk of overapplication. Stress conditions such as salinity, drought,

acidity, heavy metal contamination, or redox imbalance may further influence crop responses

Despite strong mechanistic plausibility, the available evidence remains difficult to translate into practical recommendations. Studies vary considerably in crop species, cultivar, experimental conditions, Mo source, dose units, application timing, co-applied nutrients, soil or growth-medium pH, N form, stress conditions, and the definition of NUE. Outcomes are also heterogeneous: some studies emphasize yield or biomass, whereas others focus on nitrate reductase activity, N concentration, nodulation, nitrogenase indicators, chlorophyll, protein, or stress markers. These endpoints are related but not interchangeable. Enhanced nitrate reductase activity does not necessarily translate into higher yield or improved fertilizer recovery, and yield increases do not reveal the underlying mechanism. Therefore, direction-of-effect evidence should be interpreted within a mechanistic and context-stratified framework rather than through simple response counts.

Previous reviews leave a critical gap at this interface. While NUE syntheses have advanced N management and loss-mitigation strategies, micronutrient constraints affecting soil–plant N processes have rarely been evaluated. Although previous Mo-focused reviews have addressed soil chemistry, molybdoenzymes, deficiency correction, and multiple delivery routes—particularly in legume systems—they have not provided a cross-crop synthesis that simultaneously stratifies evidence by application route, environmental moderators, crop functional type, and NUE-related outcomes. Unlike reviews that examine Mo chemistry, plant molybdoenzymes, or N management separately, this review integrates Mo availability, Mo-dependent enzymatic constraints, crop functional type, application route, and NUE-related outcomes into a diagnosis-based framework for predicting when Mo interventions are agronomically effective.

To address this gap, we conducted a structured evidence synthesis of published crop studies assessing the effects of Mo on NUE-related physiological, agronomic, and biochemical outcomes. Rather than assuming a universally positive response to Mo supplementation, we hypothesized that agronomic benefits would arise primarily when three conditions coincide: low plant-available Mo, active demand for nitrate assimilation or symbiotic N fixation, and a context in which Mo-dependent enzyme activity limits N conversion efficiency. Accordingly, response inconsistency was treated as biologically informative evidence of context dependence rather than as analytical noise. The objectives were to: (1) develop a mechanistic soil–plant framework linking Mo availability to N assimilation, symbiotic N fixation, and NUE-related outcomes; (2) synthesize crop responses using context-stratified evidence rather than simple route-based rankings; (3) identify environmental, crop-specific, and management-related moderators of response direction; and (4) define reporting gaps and decision criteria for diagnosis-driven Mo recommendations.

2 Materials and methods

2.1 Review design and reporting standard

This study was designed as a Scopus-based scoping review combined with bibliometric synthesis and structured evidence mapping of empirical crop and plant studies assessing the effects of Mo on NUE-related physiological, biochemical, symbiotic, and agronomic outcomes. Because the primary search was restricted to Scopus, this review is not presented as an exhaustive multi-database systematic review. PRISMA 2020 elements were applied solely to enhance transparency in reporting record identification, screening, eligibility assessment, and study inclusion[8]. Search reporting was aligned with PRISMA-S, and the full Scopus search strategy and auxiliary search procedures are described in Section 2.2.

No separate review protocol was prepared or registered. The review process was conducted using predefined eligibility criteria, extraction variables, observation-unit definitions, context stratification, direction-of-effect coding, methodological appraisal, and sensitivity analyses, as described in the Methods. Reporting completeness was documented using the PRISMA 2020 checklist provided in Supplementary S1.

Because the evidence base was heterogeneous with respect to crop species, experimental settings, Mo formulations, dose units, application routes, N regimes, stress contexts, outcome definitions, and statistical reporting, a conventional effect-size meta-analysis was not performed. Instead, a mechanistic and context-stratified evidence synthesis was applied. Interpretation was conducted at two levels: the study level for characterizing the evidence base and the observation level for studies reporting multiple routes, doses, genotypes, stress conditions, or outcome domains.

2.2 Information sources, search strategy, eligibility criteria, and study selection

The primary search was conducted in Scopus on 12 November 2025 because Scopus provides standardized metadata suitable for reproducible screening, PRISMA reporting, and bibliometric mapping. Accordingly, the formal evidence denominator used in this review comprises Scopus-indexed records only. The 141 retained reports should therefore not be interpreted as the complete global literature on Mo-mediated crop NUE. Records identified through these supplementary procedures were not used to redefine the Scopus-derived denominator unless they satisfied the predefined inclusion and documentation criteria described above. Database coverage may influence both the contextual composition and direction-of-effect distribution of the evidence map. For example, if non-Scopus literature is disproportionately enriched with field trials conducted in tropical acidic or Mo-deficient soils, the inclusion of such studies could increase the proportion of clearly positive responses. Conversely, additional literature could also contribute neutral, negative, or mixed outcomes. The direction and magnitude of this potential coverage bias cannot be determined without a reproducible multi-database search. This review is therefore presented as a Scopus-indexed structured evidence synthesis rather than an exhaustive global systematic review. Google Scholar and backward and forward citation tracking were used only as auxiliary procedures to assess topic coverage and facilitate full-text retrieval; they were not used to redefine the Scopus-derived evidence denominator. The Scopus search was: TITLE-ABS-KEY (molybdenum OR molybdate OR "ammonium molybdate" OR "sodium molybdate" OR "nano-molybdenum" OR nanomolybdenum OR "molybdenum disulfide" OR MoS2) AND TITLE-ABS-KEY (nitrogen OR nitrate OR "nitrate reductase" OR "nitrogen fixation" OR nitrogenase OR "nitrogen assimilation" OR NUE OR "nitrogen use efficiency") AND TITLE-ABS-KEY (plant* OR crop* OR cereal* OR legume* OR soybean OR wheat OR rice OR maize OR horticultur*) AND PUBYEAR > 2014 AND PUBYEAR < 2026.

Studies were eligible when they: (1) were published during 2015–2025; (2) investigated higher plants; (3) evaluated Mo sufficiency, deficiency, supplementation, formulation, or application in a way that allowed Mo effects to be attributed; (4) included a usable comparator; and (5) reported at least one NUE-related agronomic, physiological, biochemical, or symbiotic outcome. Eligible outcomes encompassed yield, biomass, NUE indices, N uptake, tissue N status, nitrate reductase, nitrite reductase, glutamine synthetase, glutamate synthase, nodulation, nitrogenase activity, biological N fixation indicators, chlorophyll or protein serving as proxies of N status, as well as stress and redox responses that were explicitly associated with N metabolism or crop performance. Reviews, editorials, commentaries, non-plant studies, inaccessible full-text articles, studies lacking comparators or extractable outcomes, and co-treatment studies in which the effects of Mo could not be independently distinguished were excluded.

All records were deduplicated and screened through a two-stage process, consisting of title and abstract screening followed by full-text assessment. Screening and eligibility evaluations were performed independently by two reviewers after completing a calibration exercise using a pilot subset. Ambiguous criteria were discussed and harmonized before full screening. Disagreements arising during screening, data extraction, or coding were resolved through consensus, while unresolved cases were adjudicated by a third reviewer. Formal kappa statistics were not calculated; however, all disagreements and final decisions were systematically documented during the review process. Full-text exclusion reasons were recorded using predefined categories and reflected in the PRISMA flow diagram.

2.3 Evidence extraction, observation-unit definition, and context stratification

A structured data-extraction form was used to capture bibliographic information, crop species, cultivar or genotype, crop functional group, legume status, experimental setting, location, soil or growth-medium type, pH, baseline Mo status, Mo form, application route, dose, unit, timing, frequency, co-applied inputs, N source and rate, inoculation status, stress condition, comparator, replication, statistical measures, and study limitations.

Outcomes were extracted across five domains: agronomic outcomes; NUE-related outcomes; plant N-status outcomes; mechanistic N-assimilation outcomes; and symbiotic N-fixation outcomes. The primary unit of observation was the study × Mo application route. A single study could contribute multiple observations if it evaluated more than one application route. When multiple doses were assessed within the same route, the route was treated as a single observation and coded according to the overall dose–response pattern. Non-monotonic responses or toxicity observed at higher doses were

classified as mixed, while beneficial, neutral, and inhibitory dose ranges were retained within the extracted study-level evidence matrix provided in Supplementary S2. Missing information was coded as "not reported" and was not inferred from the available data.

Observations were stratified according to predefined moderators, including pH class, experimental setting, stress context, baseline Mo status, crop species, crop functional group, legume versus non-legume status, genotype, Mo route, form, dose, and timing, as well as N source and rate, inoculation, and co-application. Exact pH values were classified as acidic when pH < 6.5 and as neutral–alkaline when pH ⩾ 6.5. This operational agronomic threshold distinguishes acidic from neutral-to-alkaline growth conditions while preserving subgroup size and reflecting the stronger sorption of molybdate by Fe and Al oxides under acidic environments. Qualitative pH classifications reported in the original studies were retained and appropriately flagged.

2.4 Direction-of-effect coding, methodological appraisal, heterogeneity, and sensitivity analysis

Direction-of-effect coding was used to summarize Mo responses without performing unsupported quantitative pooling. Primary coding prioritized outcomes related to yield, biomass, and/or NUE. When these were absent, N status, N-assimilation enzymes, or N-fixation indicators were coded as mechanistic evidence but not interpreted as direct agronomic improvement unless linked to yield, biomass, or NUE. Observations were categorized as clearly positive, neutral/no evident effect, clearly negative, or mixed. Clearly positive or negative classifications required statistical evidence, variance data, or an interpretable treatment comparison. Numerical differences lacking sufficient support were classified conservatively.

Methodological appraisal evaluated reporting quality and selected internal validity indicators rather than applying a formal clinical-style risk-of-bias assessment. Each study was scored using an eight-item checklist, with one point awarded for each adequately reported item and zero points assigned when the item was absent, unclear, or insufficiently reported. The checklist included: (1) clear description of experimental design and setting, to distinguish field, pot, greenhouse, hydroponic, and diagnostic evidence; (2) presence of a usable comparator or control, to support attribution of Mo effects; (3) adequate reporting of replication and experimental units, to evaluate reliability; (4) reporting of randomization, blocking, or other design controls, to assess internal validity; (5) clear specification of Mo source, form, route, dose, timing, and unit, to enable route- and dose-specific interpretation; (6) reporting of key contextual moderators, including soil or growth-medium pH, N regime, baseline Mo status where available, stress condition, inoculation, or co-applied inputs; (7) interpretable NUE-related, agronomic, physiological, biochemical, or symbiotic outcomes; and (8) sufficient statistical information to support direction-of-effect coding. Scores ranged from 0 to 8 and were categorized as higher support (7–8), moderate support (5–6), or lower support (⩽4). Appraisal was performed independently by two reviewers following calibration on a pilot subset. Disagreements were resolved through discussion and, when necessary, through consultation with a third reviewer. Quality scores were not used to automatically exclude studies; rather, they were applied to contextualize confidence in the evidence and to perform sensitivity analyses by comparing all observations with higher- and moderate-support subsets.

Meta-analysis was not undertaken because Mo formulations, application routes, dose units, crops, genotypes, settings, stress conditions, N regimes, outcome definitions, and statistical approaches were excessively heterogeneous. Directional summaries were interpreted within route, crop group, pH class, setting, stress context, and outcome domain. Route-level percentages were treated as descriptive evidence-mapping indicators rather than pooled effects. Non-independence was addressed by distinguishing study-level and observation-level evidence and by documenting multi-route contributions within the evidence matrix.

Sensitivity analyses evaluated robustness by: excluding lower-support studies; restricting analyses to statistically supported observations; excluding mechanistic-only observations without yield, biomass, or NUE; restricting pH analyses to exact pH values; comparing study-level and observation-level patterns; and treating mixed responses as non-positive responses.

2.5 Bibliometric analysis and supplementary transparency materials

Bibliometric analysis was used only as supporting evidence to characterize research concentration, thematic evolution, and evidence gaps. Scopus metadata were imported into

VOSviewer for co-authorship, author-keyword, and title/abstract term analyses. Network, overlay, and density maps were interpreted only when they assisted in diagnosing evidence structure, such as concentration around crops, nano-Mo, stress studies, or limited integration of NUE terminology with Mo physiology. Scientific conclusions were derived from structured extraction, appraisal, stratification, direction coding, and sensitivity analysis rather than from bibliometric patterns alone.

Supplementary materials include: Supplementary S1, providing the completed PRISMA 2020 reporting checklist. Supplementary S2, containing the included studies and extracted study-level variables used in the evidence synthesis; Supplementary S3, containing the database of included studies together with the extracted bibliographic and study-level variables.

3 Results

3.1 Study selection and extraction audit

The corrected PRISMA workflow is presented in Fig. 1. The Scopus search identified 495 records. Five duplicate records were removed before screening, leaving 490 records for title and abstract screening. Of these, 343 records were excluded because they fell outside the review scope, were non-English, represented non-article publications, or were not relevant to Mo-mediated crop N metabolism and NUE. A total of 147 reports were sought for retrieval, and six reports could not be obtained. The remaining 141 reports were assessed for eligibility and retained in the final synthesis. No retrieved full-text report was excluded at this stage because full-text assessment served as an eligibility-confirmation step after

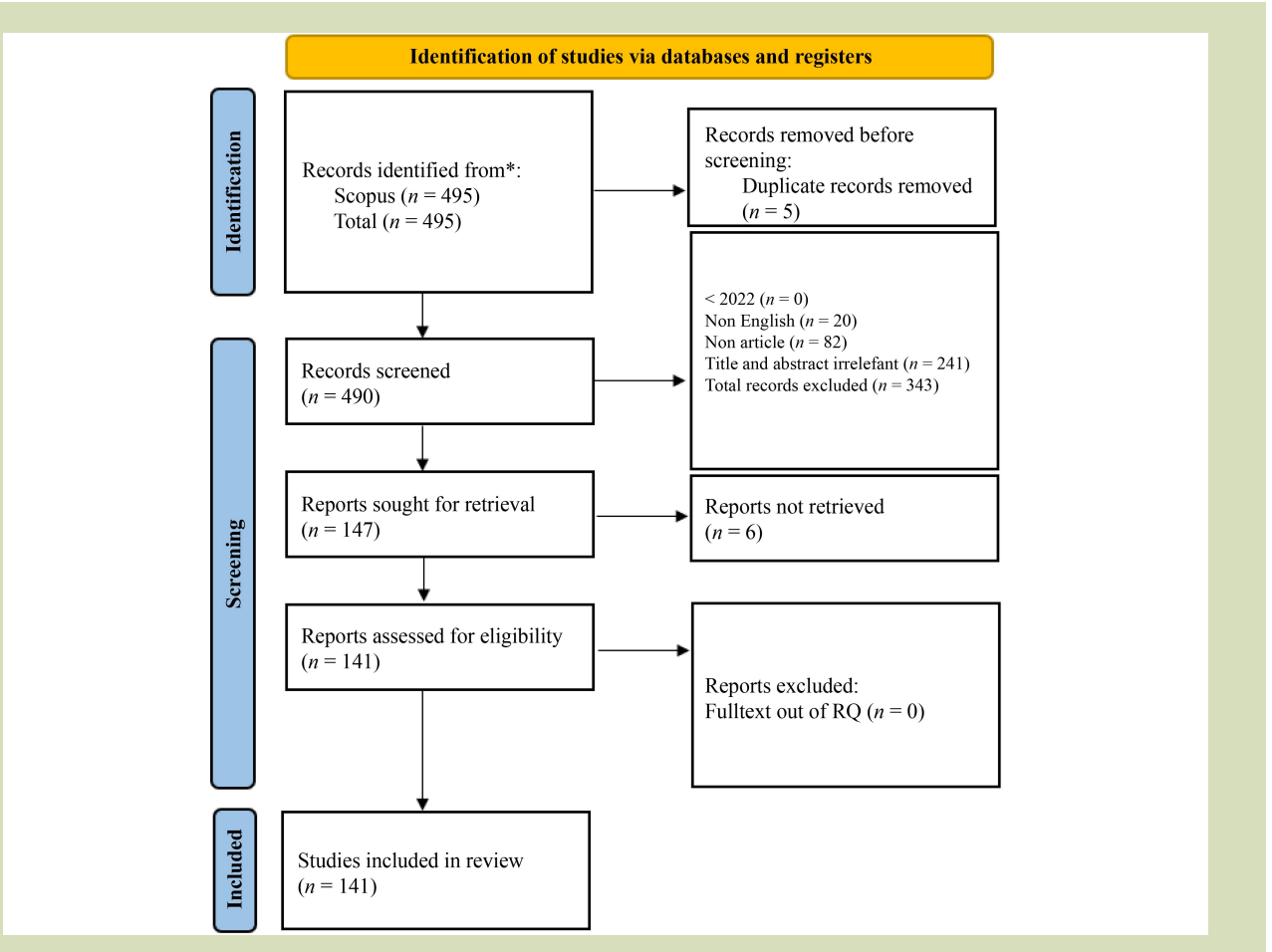


Fig. 1 PRISMA 2020 flow diagram for study selection.

rigorous title/abstract screening and retrieval filtering had already removed clearly ineligible or unavailable records. All retained full texts were nevertheless evaluated against the predefined eligibility criteria before inclusion.

The extraction files provided an auditable study- and observation-level evidence base. Four denominator levels were consistently distinguished throughout the Results. "Reports" referred to the 141 retained full texts included in the PRISMA flow. "Study identifiers" referred to unique study labels in the cleaned extraction and quality-score matrices. "Coded observations" referred to direction-of-effect entries extracted from the studies. "Route-assigned observations" referred only to coded observations with an identifiable Mo application route. After cleaning repeated header entries in the extraction workbook, the direction-of-effect matrix contained 249 coded observations linked to 129 unique study identifiers with quality scores. The difference between 141 retained reports and 129 quality-scored study identifiers reflected the structure of the supplied extraction matrix: some retained reports did not contribute a complete quality-scored study identifier to the direction-of-effect matrix and therefore were not included in quantitative observation-level summaries. Consequently, the PRISMA flow describes the broader retained report set, whereas the numerical evidence maps presented below are based on the cleaned and quality-scored coding matrix. Of the 249 coded observations, 233 were assigned an Mo application route, whereas 16 had no assignable route because Mo was measured diagnostically, incorporated within a co-treatment, or could not be separated as a route-specific intervention. Because several studies contributed multiple observations, observation-level counts were interpreted as study × application-route evidence rather than as independent study counts.

3.2 Study characteristics, Mo routes, and reporting quality

The extracted evidence encompassed a broad range of crop systems, including cereals, legumes, horticultural crops, and model or specialty plant systems. Crops included soybean, maize, wheat, rice, *Brassica* spp., common bean, French bean, chickpea, lentil, clover, coconut, and apple rootstock systems. Experimental contexts included field trials, greenhouse or pot studies, hydroponic and nutrient-solution experiments, as well as diagnostic soil or plant surveys. Several studies directly evaluated agronomic Mo application, whereas others investigated Mo availability, Mo transport, Mo-containing amendments, or Mo behavior under stress or toxicity conditions.

Among the 233 observations with an assigned application route, soil application was the most frequent route, followed by foliar application, nutrient-solution delivery, seed priming/coating, and nano-Mo formulations (Table 1). These route counts describe the structure of the extracted observation-level evidence and should not be interpreted as independent study totals.

The quality-score matrix contained 129 unique study identifiers. Using the 8-item quality-appraisal scale available in the extraction file, 37 studies (28.7%) were categorized as higher support (score = 7–8), 72 (55.8%) as moderate support (score = 5–6), and 20 (15.5%) as lower support (score ⩽ 4) (Table 2). Most studies therefore provided at least moderate reporting support, although fewer than one-third satisfied the higher-support category. Lower scores generally reflected incomplete reporting of Mo dose or formulation, experimental

Table 1 Mo application routes in the cleaned observation-level extraction matrix

Application route	Observation (*n*)	Share of route-assigned observations (%)	Main interpretation
Soil application	70	30.0	Most frequent route; strongly mediated by pH, soil sorption, liming history, baseline Mo status, and co-applied amendments
Foliar application	63	27.0	May bypass soil sorption but remains dependent on crop stage, leaf uptake, dose, and stress context
Nutrient solution/hydroponic delivery	49	21.0	Mechanistically informative; field extrapolation is limited
Seed priming/coating	38	16.3	Relevant for early establishment and legume systems but dose-sensitive
Nano-Mo formulation	13	5.6	Small evidence base; mainly useful for identifying research gaps
Total assigned routes	233	100.0	Study × application-route observations

design, soil or pH context, statistical support, or interpretable NUE/yield endpoints.

3.3 Mechanistic pathways linking Mo to crop NUE

The extracted evidence supports a soil–plant mechanism through which Mo influences NUE when Mo availability, Mo uptake, or Mo-dependent enzyme function limits N conversion. In the soil layer, Mo availability is governed by molybdate chemistry, pH, Fe/Al oxide sorption, competing anions, organic matter, calcium chemistry, liming history, and baseline soil Mo. Diagnostic and soil-based studies emphasized this soil-chemical control[9] identified marginal available Mo in several acidic coconut-growing soils of Kerala and associated low pH, high Al^{3+}, and multiple nutrient deficiencies with low soil fertility[10] reported positive biomass and grain-yield responses to soil-applied ammonium molybdate in acidic maize systems, whereas[11,12] showed that Mo addition improved legume performance in strongly acidic, Mo-limited soils[13] further indicated that dairy-manure biochar increased soil pH and available Mo, thereby enhancing biomass production and N uptake in white clover.

In the plant layer, Mo functioned through Mo-dependent enzymes and N-related physiological processes. In non-legumes, the most direct pathway involved nitrate assimilation via nitrate reductase and associated N-assimilation processes[14] reported that nano-Mo under arsenic stress increased NR, NiR, GS, and GOGAT activities and partially restored maize growth, although NUE was not directly calculated[15] similarly showed Mo-mediated mitigation of nickel stress in wheat seedlings through changes in NR and oxidative-stress indicators. In field crops[16],reported that foliar Mo increased leaf N, active nitrate reductase, photosynthetic metabolism, shoot dry matter, and yield components in soybean and maize.

In legumes, Mo responses were additionally linked to symbiotic N fixation[17] showed that foliar Mo fertilization combined with Bradyrhizobium inoculation increased soybean yield relative to the control and enhanced nodulation-related crop performance. Linked genetic variation in soybean Mo transporters to Mo accumulation, nitrate reductase activity, nitrogenase-related traits, and differences in seed weight. These studies support the interpretation that crop functional type modifies Mo response: non-legumes respond primarily through nitrate reduction and N assimilation, whereas legumes may respond through both nitrate assimilation and biological N fixation.

Cross-nutrient and amendment-mediated mechanisms were also important but more difficult to attribute[18] showed that powellite solubility and pH/Ca chemistry regulate slow-release Mo behavior, while[10,13,19] emphasized rhizosphere- or amendment-mediated controls on Mo availability and plant response. Because several studies included co-applied nutrients, biochar, inoculants, or nanomaterials, these mechanisms were interpreted as context-dependent pathways rather than universal Mo effects.

3.4 Conceptual synthesis of the soil-plant Mo-NUE pathway

Figure 2 integrates the mechanistic evidence into a diagnosis-driven soil–plant framework. The framework connects soil pH, Fe/Al oxide sorption, phosphate/sulfate competition, organic matter, liming history, and baseline Mo status to molybdate availability and plant Mo uptake. Once absorbed, Mo supports Mo-dependent enzymes, including nitrate reductase and nitrogenase, and interacts with downstream N-assimilation processes involving GS/GOGAT-linked pathways. These mechanisms influence N uptake, biomass production, yield, protein accumulation, stress recovery, and NUE indices. The response is further moderated by crop functional type,

Table 2 Reporting-quality appraisal based on the extraction file

Quality category	Score range	Study (*n*)	Share of scored study (%)	Interpretation
Higher support	7–8	37	28.7	Stronger reporting of design, treatment, context, statistics, and interpretable outcomes
Moderate support	5–6	72	55.8	Usable evidence but with some reporting gaps
Lower support	⩽4	20	15.5	Limited confidence; interpreted cautiously
Total	0–8	129	100.0	Unique study identifiers in the quality-score sheet

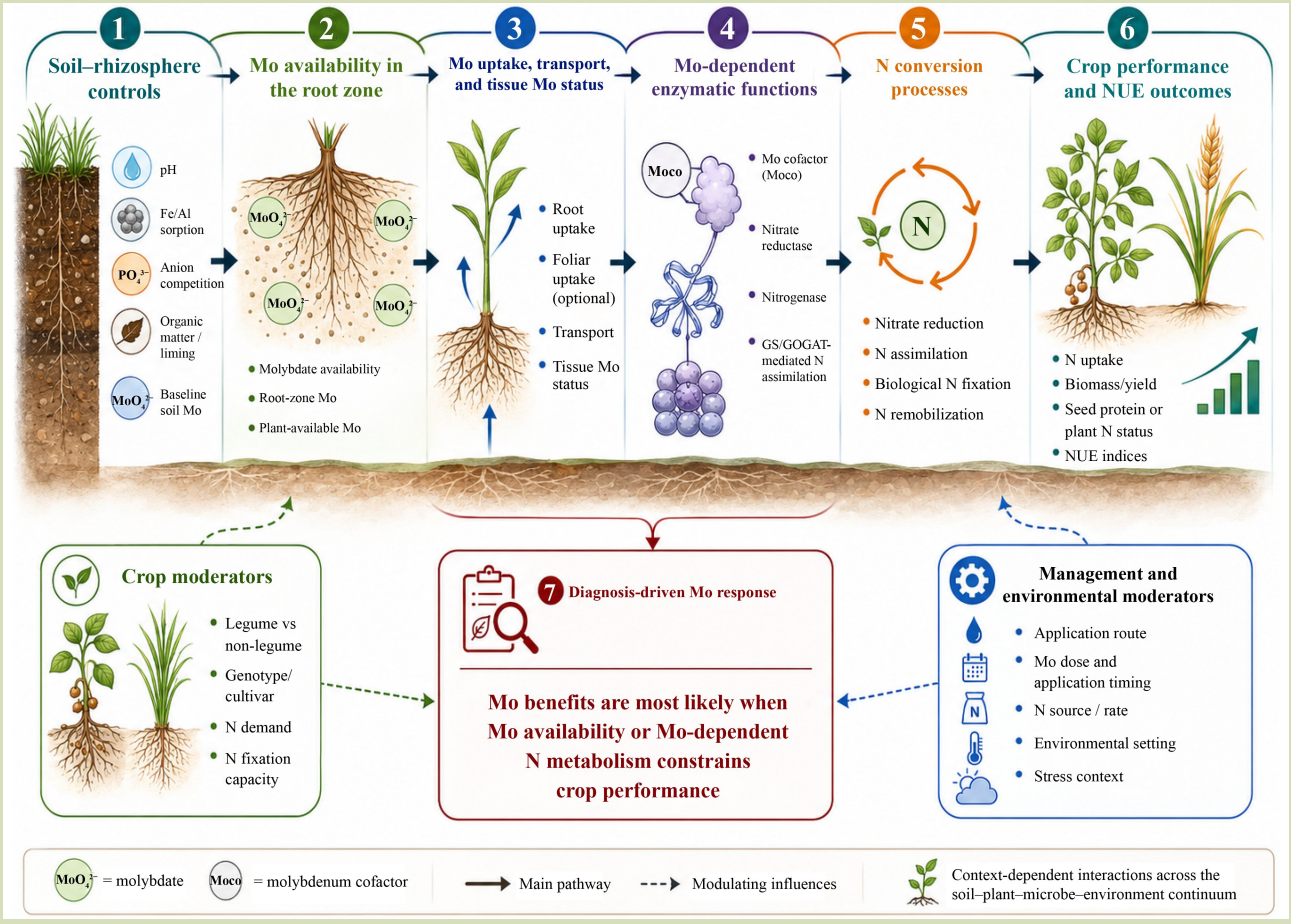


Fig. 2 Conceptual framework linking Mo availability with crop NUE.

genotype, Mo dose, application route, experimental setting, and stress context.

Soil chemical conditions regulate molybdate availability and Mo uptake. Once absorbed, Mo contributes to Mo-dependent enzymes involved in nitrate reduction, N assimilation, and symbiotic N fixation. Agronomic outcomes depend on whether Mo availability or Mo-dependent enzyme activity is limiting under a given crop, soil, route, dose, and stress context. This framework explains why Mo responses are diagnosis-dependent rather than being universally positive.

3.5 Outcome hierarchy and overall direction-of-effect distribution

Direction-of-effect coding was interpreted using an outcome hierarchy (Table 3). Agronomic outcomes were prioritized over mechanistic outcomes because increases in nitrate reductase, nitrogenase, chlorophyll, antioxidant activity, or stress tolerance do not necessarily translate into improved yield, biomass, N uptake, or NUE. Mechanistic outcomes were used to support causal interpretation, but they were not treated as direct agronomic improvement unless linked to agronomic endpoints.

Across all 249 coded observations, mixed responses predominated (114 observations; 45.8%), followed by clearly positive responses (86; 34.5%), clearly negative responses (33; 13.3%), and neutral/no clear responses (16; 6.4%) (Table 4). The high proportion of mixed responses indicates that Mo effects were frequently dose-, crop-, setting-, stress-, route-, or outcome-dependent. Treating Mo as a universally beneficial input is therefore not supported by the extracted evidence.

Table 3 Operational hierarchy for interpreting Mo response direction

Evidence level	Outcome domain	Example	Interpretation rule
Primary agronomic evidence	Yield, biomass, NUE, N uptake	Grain/seed yield, biomass, agronomic efficiency, recovery efficiency, partial factor productivity, N accumulation	Main basis for agronomic positive, neutral, negative, or mixed response
Secondary physiological evidence	Plant N status and N assimilation	Tissue N, protein, chlorophyll/SPAD, NR, NiR, GS, GOGAT	Supports mechanism but is not sufficient alone for agronomic benefit
Symbiotic evidence	Biological N fixation	Nodulation, nodule biomass, nitrogenase activity, ureide-related indicators	Functional evidence, especially for legumes
Stress/redox evidence	Stress physiology	Antioxidant enzymes, ROS markers, osmotic or ion-balance indicators	Included only when linked to N metabolism or crop performance

Table 4 Overall direction-of-effect distribution in the cleaned coding matrix

Direction category	Observation (*n*)	Share (%)	Interpretation
Clearly positive	86	34.5	Mo improved the prioritized outcome with sufficient support
Neutral/no clear effect	16	6.4	No supported response or insufficient evidence for direction
Clearly negative	33	13.3	Mo reduced performance or produced inhibitory/toxicity-related effects
Mixed	114	45.8	Response varied across dose, route, cultivar, stress condition, or outcome domain
Total	249	100.0	All coded observations, including observations without assignable route

3.6 Application-route response patterns

Route-level patterns confirmed that no Mo application route was consistently superior (Table 5). Among route-assigned observations, mixed responses remained the largest category overall (109/233; 46.8%). Positive responses represented 81/233 observations (34.8%), whereas negative and neutral responses accounted for 29/233 (12.4%) and 14/233 (6.0%), respectively.

Among conventional routes, nutrient-solution delivery exhibited the highest positive share (20/49; 40.8%), followed by foliar application (24/63; 38.1%), soil application (25/70; 35.7%), and seed priming/coating (12/38; 31.6%). These proportions should not be interpreted as route rankings because each route was confounded by crop type, setting, dose, stress condition, and outcome domain. Nutrient-solution studies were largely mechanistic and frequently conducted under controlled conditions; foliar responses depended on timing, dose, and crop stage; soil responses depended on pH and sorption chemistry; and seed-based responses were especially dose-sensitive.

Table 5 Direction-of-effect by Mo application route in the cleaned extraction matrix

Route	N entry	Positive *n* (%)	Neutral *n* (%)	Negative *n* (%)	Mixed *n* (%)	Main interpretation
Soil	70	25 (35.7)	4 (5.7)	9 (12.9)	32 (45.7)	Context-dependent; strongest rationale in acidic or Mo-limited soils
Foliar	63	24 (38.1)	4 (6.3)	8 (12.7)	27 (42.9)	May bypass soil sorption but remains timing- and dose-dependent
Nutrient solution	49	20 (40.8)	3 (6.1)	5 (10.2)	21 (42.9)	Mechanistically useful; field translation limited
Seed priming/coating	38	12 (31.6)	2 (5.3)	6 (15.8)	18 (47.4)	Useful for early establishment but dose-sensitive
Nano-Mo	13	0 (0.0)	1 (7.7)	1 (7.7)	11 (84.6)	Evidence gap; not yet agronomically established
Total assigned routes	233	81 (34.8)	14 (6.0)	29 (12.4)	109 (46.8)	Route-assigned observations only

Nano-Mo was treated primarily as an evidence gap. In the cleaned extraction file, none of the 13 nano-Mo route observations was coded as clearly positive, whereas 11/13 (84.6%) were mixed. Although studies such as Riaz et al.[14], Li et al.[20], and Shaghaleh et al.[21] indicate that although nano-Mo or MoS_2 materials can influence N-related physiology, stress tolerance, or biomass under specific conditions, the current evidence remains too limited and inconsistent to support an agronomic recommendation. Particle characterization, release kinetics, transformation, dose-response behavior, plant-available Mo fractions, and toxicity thresholds remain critical evidence gaps.

3.7 Reporting-quality sensitivity and robustness

Quality-based sensitivity analysis showed that mixed responses remained dominant after excluding lower-support studies. Among higher- and moderate-support observations combined (quality score ⩾ 5), 97/215 observations (45.1%) were mixed, 76/215 (35.3%) were positive, 30/215 (14.0%) were negative, and 12/215 (5.6%) were neutral (Table 6). Therefore, the main conclusion that Mo responses are highly context-dependent was not driven solely by lower-support studies.

When the analysis was restricted to higher-support studies only (score = 7–8), the response pattern shifted: positive responses became the largest category (36/73; 49.3%), followed by mixed responses (26/73; 35.6%). This suggests that better-reported studies may more clearly identify contexts in which Mo is beneficial, although mixed and negative outcomes were still observed. Therefore, higher reporting quality strengthens but does not eliminate the need for diagnosis-driven interpretation.

Route-specific sensitivity analysis showed similar patterns. After excluding lower-support studies, mixed responses remained common for soil application (28/58; 48.3%), foliar application (24/54; 44.4%), seed priming/coating (15/34; 44.1%), and nano-Mo (9/11; 81.8%). Nutrient-solution observations showed a slightly higher positive share (19/45; 42.2%) than mixed share (18/45; 40.0%), but this route remained dominated by controlled-system evidence. These results support the conclusion that Mo responses are conditional rather than universally beneficial.

3.8 Environmental, stress, and genotype moderators

Environmental moderation was most evident in studies that explicitly reported pH, soil acidity, salinity, heavy metal stress, or amendment effects. The extraction matrix captured pH and environmental context primarily within narrative fields rather than as a fully coded pH variable; therefore, pH and soil acidity were interpreted as recurring mechanistic moderators rather than pooled quantitative moderators.

pH reporting was also selective across the evidence base. Studies specifically focused on acid-soil fertility, Mo deficiency, liming, or molybdate sorption were more likely to measure and report pH than studies centered on foliar delivery, controlled nutrient solutions, nanomaterials, or non-soil stress responses. Consequently, the apparent concentration of favorable responses in acidic or Mo-limited systems may partly reflect differential reporting and greater contextual characterization in acid-soil studies. The available evidence therefore does not support a quantitative comparison of response probability across acidic, neutral–alkaline, and unreported-pH conditions.

Several studies nevertheless provided mechanistic evidence supporting Mo responsiveness in acidic or Mo-limited systems[9] identified marginal Mo availability in acidic coconut soils[11], reported improved French bean performance after Mo

Table 6 Sensitivity of direction-of-effect patterns to reporting quality

Analysis subset	N observation	Positive *n* (%)	Neutral *n* (%)	Negative *n* (%)	Mixed *n* (%)	Interpretation
All coded observations	249	86 (34.5)	16 (6.4)	33 (13.3)	114 (45.8)	Mixed responses dominate overall
Route-assigned observations	233	81 (34.8)	14 (6.0)	29 (12.4)	109 (46.8)	Same pattern after excluding observations without assigned route
Higher + moderate support	215	76 (35.3)	12 (5.6)	30 (14.0)	97 (45.1)	Mixed responses remain dominant after excluding lower-support studies
Higher support only	73	36 (49.3)	3 (4.1)	8 (11.0)	26 (35.6)	Positive responses become more frequent, but mixed outcomes remain substantial

application in strongly acidic Alfisol[12], observed a Mo-related yield response in acidic Oxisol, and reported higher maize biomass and grain yield under soil-applied Mo in acidic field conditions[10]. Conversely, showed that Mo could improve soybean performance under saline-alkaline field conditions, indicating that Mo responsiveness is not limited to acidic soils but depends on the dominant physiological constraint[22].

Stress context also modified Mo responses. Mo or Mo-containing treatments were associated with partial recovery of growth and N-related physiology under arsenic stress in maize[14], nickel stress in wheat seedlings[15], and salinity or saline–alkaline stress in soybean[22]. However, several stress-related studies primarily emphasized biochemical or vegetative responses rather than final yield or NUE; therefore, their agronomic relevance should be interpreted with caution.

Genotype-specific evidence remained limited but nonetheless important. Comparative studies of salt-sensitive and salt-tolerant soybean varieties demonstrated differences in the magnitude of response. In addition, soybean Mo-transporter haplotypes were linked to Mo accumulation and N-related functional traits. These studies support the hypothesis that genotype × environment × management interactions condition Mo responsiveness, but the evidence base remains too sparse for general crop-specific recommendations.

3.9 Expanded citation base supporting the extracted evidence domains

To better reflect the breadth of the extraction matrix, Table 7 summarizes representative studies that support the main evidence domains included in the synthesis. These citations are not intended to provide a ranking of application routes; rather, they demonstrate that the coded observations were distributed across soil-based studies, foliar interventions, seed treatments, nutrient-solution systems, nanomaterial studies, stress-related contexts, and diagnostic or mechanistic investigations.

3.10 Bibliometric patterns as evidence-gap diagnosis

Bibliometric outputs were used solely to characterize the research structure and identify evidence gaps. Keyword and term maps indicated that Mo-related research spans soil chemistry, plant nutrition, crop performance, legume symbiosis, stress physiology, and nanomaterial-related themes. These patterns support the premise that evidence linking Mo and NUE remains fragmented across both mechanistic and agronomic domains. The maps also indicate growing attention to soybean and other legume systems, stress-related studies, and nano-Mo formulations (Fig. 3).

Author collaboration patterns did not directly contribute to the mechanistic understanding of Mo-mediated NUE and were therefore not used to derive the main scientific conclusions of this review. Within the main text, the most relevant bibliometric contribution is the demonstration that Mo physiology, soil Mo chemistry, and crop-level NUE outcomes remain insufficiently integrated. This fragmentation supports the need for the mechanistic and context-stratified framework developed in this review.

4 Discussion

4.1 Reframing Mo management: from application route to constraint diagnosis

This structured evidence synthesis indicates that Mo can

Table 7 Representative studies supporting the main evidence domains in the extraction matrix

Evidence domain	Representative studies from the extraction matrix
Soil application, soil chemistry, amendments, and field response	[9,10,18,23–28,29–38,13,39–42]
Foliar Mo, crop performance, and in-season correction	[16,17,22,43–49,50–59,60–63]
Seed priming/coating and early establishment	[6,21,64–71,72–81]
Nutrient-solution, hydroponic, and controlled-system mechanisms	[15,82,83, 84–90,91–100,101–106]
Nano-Mo, MoS_2, and emerging material formulations	[14,21,41,43,44,54,64,86,107,108,109]
Diagnostic, contextual, and non-route-coded mechanistic evidence	[110,111,112–119,120–122]

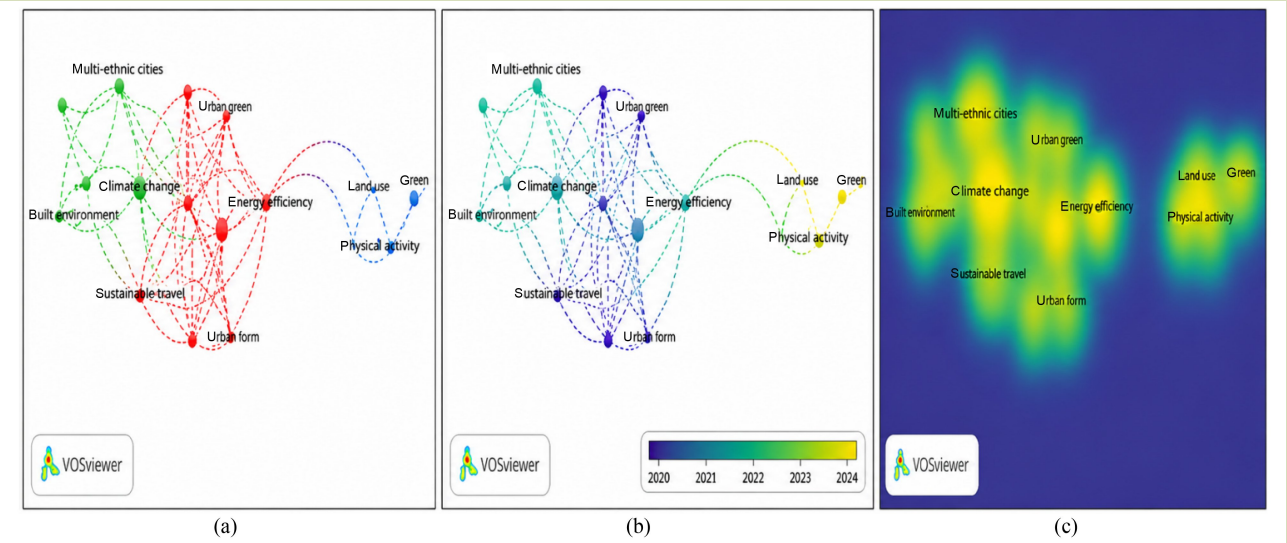


Fig. 3 Bibliometric keyword co-occurrence analysis of research themes related to Mo-mediated crop NUE. (a) Network visualization illustrating keyword clusters and co-occurrence linkages among the major research themes. Node size reflects keyword occurrence frequency, whereas connecting lines represent the strength of keyword co-occurrence. (b) Overlay visualization illustrating the temporal evolution of keyword occurrence from 2020 to 2024, with colors representing the average publication year associated with each keyword. (c) Density visualization illustrating areas of high thematic concentration, where yellow regions denote greater keyword density and more intensive research activity. Collectively, the three panels depict the thematic structure, temporal evolution, and research concentration within the keyword network.

enhance crop NUE-related outcomes through its roles in nitrate assimilation, symbiotic N fixation, and soil–plant nutrient interactions. However, the evidence does not support a uniformly positive or route-independent effect of Mo application. Across the cleaned coding matrix, mixed responses represented the dominant category among all coded observations (114/249; 45.8%) and among route-assigned observations (109/233; 46.8%). Clearly positive responses accounted for 86/249 coded observations (34.5%) and 81/233 route-assigned observations (34.8%). These patterns show that the central question is not which Mo route is "best", but whether Mo application resolves the limiting constraint in a given soil–plant system.

The principal conceptual contribution of this review is the reframing of Mo management from an application-route paradigm to a constraint-diagnosis paradigm. The Mo-related literature encompasses both review articles and primary studies that emphasize soil Mo chemistry, molybdoenzyme physiology, deficiency correction, fertilization routes, legume symbiosis, and emerging Mo-based materials[5,6,14,18,54,108]. Table 8 therefore compares the present synthesis with the major emphases identified across the broader Mo-related literature, rather than limiting the comparison solely to previous review articles. The present synthesis differs by explicitly integrating these components into a diagnostic chain: soil and rhizosphere constraints regulate Mo availability; Mo availability and uptake govern Mo-dependent enzyme function; enzyme function affects N assimilation or biological N fixation; and agronomic benefits arise only when these processes limit crop performance. Within this framework, route selection is secondary to constraint identification.

The potential contribution of Mo should be interpreted in relation to the broader gains that can be achieved through optimized nutrient, crop, and soil management practices[4] based on a global meta-analysis of 1065 studies and 6753 paired observations, estimated that optimized management reduced N_2O emissions by 31%, NH_3 emissions by 23%, N runoff by 18%, and N leaching by 17% after accounting for local conditions and prevailing practices. These reductions reflect changes in specific N-loss pathways and therefore cannot be directly interpreted as equivalent percentage-point increases in crop NUE. In contrast, the current Mo evidence map lacks

Table 8 Conceptual novelty of the present synthesis relative to major emphases in Mo-related literature

Common emphasis in previous Mo-focused literature	Illustrative source example	Typical limitation for NUE interpretation	What the present synthesis adds
Soil Mo chemistry and availability	[9,10,13,18]	Often explains molybdate behavior or soil availability without consistently linking it to crop-level NUE endpoints	Links soil pH, sorption, liming, amendment effects, and baseline Mo status to Mo uptake, N metabolism, and agronomic response
Plant molybdoenzymes and physiology	[5,6,14,54]	Strong mechanistic detail but often relies on enzyme or N-status proxies	Separates mechanistic capacity from direct agronomic NUE evidence
Mo fertilization or application route	[16,17,21,44]	Can imply route-based management decisions without diagnosing the underlying constraint	Reframes route choice as a way to address root-zone availability, plant deficiency, early establishment, or mechanistic testing
Legume Mo nutrition and BNF	[17,22,23,123]	Often crop- or symbiosis-specific	Integrates legume BNF responses with non-legume nitrate-assimilation pathways
Nano-Mo and MoS_2 materials	[14,21,64,108]	Often emphasizes material behavior or stress physiology more than field-ready NUE outcomes	Evaluates agronomic readiness and identifies nano-Mo as an evidence gap rather than a recommendation-ready technology

sufficiently standardized effect sizes to determine whether diagnosis-based Mo correction delivers a 2%, 5%, or 10% incremental gain in NUE. Mo should therefore not be presented as a substitute for N-rate, timing, placement, crop, or soil management, or as a stand-alone intervention capable of delivering system-wide reductions comparable to those reported by[4]. Rather, Mo is best regarded as a complementary, site-specific intervention that may help realize the benefits of optimized N management when low Mo availability or impaired Mo-dependent N metabolism remains a limiting factor. Factorial field trials comparing optimized N management with and without diagnosis-based Mo correction are needed to quantify this incremental contribution.

A second contribution is the explicit distinction between direct agronomic outcomes and mechanistic proxies. Many studies reported physiological or biochemical responses, including nitrate reductase (NR), glutamine synthetase (GS), glutamate synthase (GOGAT), nitrogenase, chlorophyll, protein content, antioxidant activity, or stress-related markers, without directly assessing NUE. These variables are mechanistically informative, but they are not equivalent to yield-based or fertilizer-recovery NUE. The strongest conclusion, therefore, is that Mo frequently enhances the functional capacity for N assimilation or biological N fixation under specific constraints, whereas direct improvements in NUE must be demonstrated through yield, biomass, N uptake, agronomic efficiency, recovery efficiency, or other related NUE indices.

The constraint-dependent interpretation was not driven solely by lower-support studies. After excluding lower-support evidence, mixed responses remained common among higher- and moderate-support observations (97/215; 45.1%), whereas higher-support studies alone exhibited a greater proportion of clearly positive responses (36/73; 49.3%). This pattern suggests that better-reported studies may more effectively identify beneficial contexts, but they do not remove the need for diagnosis-driven interpretation. In other words, improved study quality helps clarify the conditions under which Mo is effective; it does not render Mo universally effective.

4.2 Mechanistic synthesis: why Mo responses become positive, mixed, or negative

The biochemical basis of Mo responsiveness is well established: Mo is essential for Mo-dependent enzymes involved in nitrate reduction and biological N fixation. The reviewed studies consistently linked Mo sufficiency or supplementation with increased NR activity, enhanced N-assimilation capacity, improved leaf N or protein status, and, in legumes, greater nodulation or enhanced nitrogenase-related indicators[14,15,22,23,110]. However, this mechanistic plausibility does not guarantee agronomic benefit. Mo responses become positive only when Mo availability, uptake, or enzyme function is actually limiting relative to crop N demand.

This helps explain the predominance of mixed responses. In some studies, Mo likely alleviated a genuine constraint in nitrate assimilation, nodulation, or stress-disrupted N metabolism. In other cases, Mo was probably not limiting, the

applied dose was inappropriate, the measured outcome represented only a biochemical proxy, or the response was influenced by co-applied nutrients or soil amendments. Mixed responses should therefore not be viewed merely as statistical noise; rather, they indicate that Mo responsiveness depends on the alignment among the underlying constraint, application route, dose, crop type, and measured endpoint.

Several causal failure points help explain why mechanistic responses did not consistently translate into agronomic NUE gains. NR activity may increase without a corresponding yield response when N is not the primary limiting factor or when carbon supply, water stress, or sink capacity constrains plant growth. Mo may be available but agronomically ineffective when baseline soil or tissue Mo is already sufficient. Foliar Mo may fail when application timing misses the period of highest Mo demand or when leaf uptake is constrained. Seed-applied Mo may become inhibitory when the applied dose exceeds the tolerance threshold during germination or early root development. Likewise, stress-related markers may improve without corresponding gains in yield or NUE when stress severity is excessive, recovery remains primarily vegetative, or final productivity is not evaluated in the study. These failure points are central to interpreting Mo as a conditional regulator rather than a universally reliable NUE input.

The strength of evidence also varies across pathways. The evidence supporting Mo as a regulator of N-assimilation capacity is stronger than that supporting its universal role in improving fertilizer recovery. Responses involving NR, GS/GOGAT, nitrogenase, nodulation, N status, and stress buffering were frequently reported; however, fewer studies linked these mechanisms to final yield, N uptake, or NUE indices. Thus, the evidence is strongest for Mo as a micronutrient that supports underlying mechanisms and more conditional for its role as an agronomic input for enhancing NUE.

Crop functional type further influences interpretation. In non-leguminous crops, the principal Mo-linked pathway involves nitrate reduction and subsequent N assimilation. In legumes, Mo may additionally support symbiotic N fixation through its roles in nitrogenase activity and nodulation. Legume-based evidence is therefore mechanistically compelling when nodulation or biological N fixation is a limiting factor; however, confirmation through yield and N-accumulation responses remains necessary before it can be generalized as an NUE management recommendation. Non-legume evidence is more dependent on nitrate supply, NR limitation, tissue Mo status, and whether biochemical changes translate into biomass or yield.

Mo-mediated responses were also influenced by cross-nutrient and soil-chemical interactions. Interactions involving P, S, Fe, and Ca chemistry, as well as liming, organic amendments, and rhizosphere processes, were repeatedly observed or mechanistically implicated[18], for example, highlighted how powellite ($CaMoO_4$) solubility and pH/Ca chemistry regulate Mo availability, while broader Mo–N syntheses and empirical studies placed Mo within cross-nutrient frameworks involving anion competition, pH-dependent sorption, and co-applied amendments[10,13]. These interactions explain why Mo cannot be interpreted in isolation from the surrounding soil chemical environment.

4.3 Application route as a constraint-specific delivery pathway

Application routes should be interpreted according to the specific constraints they are intended to address. Soil application targets root-zone Mo availability; foliar application addresses short-term plant Mo deficiency; seed priming or coating targets early establishment and nodulation phases; nutrient-solution delivery evaluates mechanistic capacity under controlled exposure; and nano-Mo remains exploratory until its formulation behavior and field performance are better understood. This framework avoids interpreting route-level response shares as a direct ranking of effectiveness.

The cleaned route-assigned dataset supports this constraint-specific interpretation. Positive response shares were 35.7% for soil application, 38.1% for foliar application, 40.8% for nutrient-solution delivery, and 31.6% for seed priming or coating, whereas nano-Mo showed no clearly positive route-assigned observations and was predominantly characterized by mixed responses (11/13; 84.6%). These descriptive shares were used solely to guide the interpretation of the evidence map and were not intended for inferential comparisons among application routes. Accordingly, they should not be interpreted as effect sizes, probabilities of success, or direct measures of relative effectiveness.

Each application route serves a distinct interpretive role. Soil application functions primarily as a root-zone availability intervention. It is most relevant where soil acidity, Fe/Al oxide

sorption, low baseline Mo status, or amendment history restricts plant-available molybdate; however, it may be ineffective when Mo is already sufficient or when soil chemistry limits its availability following application. Foliar application functions as a tactical plant-correction route. It can partially circumvent root-zone constraints; however, its effectiveness depends on whether the crop is Mo-deficient at the time of application, whether spraying coincides with periods of high N-metabolic demand, and whether foliar uptake is sufficiently effective. Seed priming or coating serves as an early-development intervention, particularly for legume establishment and nodulation. However, this route exhibited the highest proportion of negative responses among the conventional application routes (6/38; 15.8%), highlighting the importance of careful dose and formulation calibration. Soluble micronutrient coatings can release nutrients rapidly and create high local exposure around the embryo and emerging radicle during a physiologically sensitive developmental window. This risk is influenced by the applied dose, coating composition, release behavior, and interactions with co-applied micronutrients or inoculants. Because many seed treatments involve multi-element formulations, negative responses cannot always be attributed solely to Mo. Seed-based recommendations should therefore report the Mo dose per unit seed mass, coating composition and release characteristics, and germination or emergence safety endpoints[124]. Evidence derived from nutrient-solution systems primarily serves as mechanistic proof-of-concept. Such systems can reveal the effects of Mo on nutrient uptake, enzyme activity, and stress physiology under controlled exposure; however, they may also introduce artefacts because hydroponic availability does not accurately replicate soil sorption processes, rhizosphere heterogeneity, or variability in field weather conditions. Nano-Mo and MoS_2-based formulations currently provide exploratory mechanistic and material-level evidence rather than a sufficient basis for agronomic recommendations. At the individual-study level[125,126], reported that a low-dose MoS_2 nanoparticle treatment enhanced biological N fixation and grain yield in soybean, demonstrating the potential of nano-enabled Mo delivery within a specific crop and treatment context. However, this promising finding does not establish route-level reliability or agronomic superiority, as none of the 13 route-assigned nano-Mo observations in the present evidence map was classified as clearly positive, whereas 11 observations (84.6%) were categorized as mixed. Accordingly, the current evidence remains insufficient to support generalized field use or superiority claims over conventional Mo sources. Field-scale recommendations would require standardized particle characterization, dissolution and transformation data, clearly defined dose–response and toxicity thresholds, and direct multi-location comparisons with conventional Mo fertilizers using yield, N uptake, and harmonized NUE endpoints[34].

4.4 Environmental, stress, and genotype moderators

Soil pH and acidity emerged as recurring mechanistic moderators, although they could not be evaluated as pooled quantitative moderators because pH was reported incompletely and selectively across the evidence base. Studies in which acidity, liming, Mo deficiency, or molybdate sorption constituted part of the original hypothesis were more likely to report exact pH values and provide detailed soil characterization. Acid-soil studies may therefore be overrepresented among pH-classifiable observations, whereas neutral–alkaline, foliar, hydroponic, stress-focused, and nanomaterial studies were more likely to remain unclassified.

This differential reporting may inflate the apparent association between acidic soil conditions and favorable responses to Mo. Accordingly, the synthesis supports pH as a mechanistically plausible moderator through its effects on molybdate availability, Fe/Al oxide sorption, and liming response, but not as a quantitatively ranked predictor of agronomic response. Positive responses were reported in several acidic or Mo-limited systems; however, Mo responsiveness was not restricted to acidic soils and was also observed under other limiting conditions, including saline–alkaline environments. Positive responses were reported in several acidic or Mo-limited systems[11,12], but Mo responsiveness was not confined to acidic soils[22]; indicated that Mo could enhance soybean performance under saline–alkaline conditions when the primary constraint was associated with stress physiology and N metabolism.

Stress-related conditions explain another major source of mixed responses. Under salinity, drought, heavy metal exposure, or redox imbalance, Mo may help stabilize N metabolism and stress-related physiological processes. This was reflected in studies reporting changes in NR, GS/GOGAT, antioxidant systems, growth recovery, or N-related traits under arsenic, nickel, and saline–alkaline conditions[14]. However, stress-related studies often emphasize biochemical or vegetative endpoints. Although these findings identify potential pathways that may support NUE-related resilience, they do not

always demonstrate improvements in fertilizer recovery or yield-based NUE.

Genotype-specific evidence remains limited but nonetheless important. Most studies evaluated only a single cultivar or genotype, thereby restricting inference regarding genotype × environment × management interactions. Where genotype comparisons were included, the magnitude of response often varied among cultivars or among groups differing in stress sensitivity. This suggests that Mo responsiveness may depend on genotype-specific differences in Mo uptake, Mo allocation, nitrate reduction, nitrogenase activity, stress tolerance, or root-zone adaptation. Future studies designed to inform recommendations should therefore include contrasting genotypes rather than assuming that a single cultivar adequately represents an entire crop species.

4.5 Limitations and methodological implications

Several limitations affect the strength and generalizability of this synthesis. First, the formal evidence base was derived exclusively from Scopus-indexed records, and the 141 retained reports represent a Scopus-indexed body of evidence rather than the entirety of the global literature on Mo-mediated crop NUE. Although Scopus provides standardized metadata suitable for reproducible screening and bibliometric mapping, relevant studies indexed only in Web of Science, CAB Abstracts, AGRICOLA, regional databases, or non-English literature may have been missed. This limitation may influence not only study coverage but also the observed distribution of effect directions. The predominance of mixed responses could change if the omitted literature differs systematically in crop type, geographic region, soil conditions, experimental setting, or publication outcomes. In particular, a greater representation of deficiency-correction field trials conducted on tropical acidic soils could increase the proportion of positive responses, although this possibility remains untested and the opposite trend cannot be ruled out. The reported proportions should therefore be interpreted as patterns within the Scopus-indexed evidence map rather than as estimates of global prevalence.

Second, the synthesis relied on accessible full texts, which may introduce availability bias. Third, no formal effect-size meta-analysis was performed because the included studies differed substantially in Mo dose units, application routes, formulations, crop species, experimental conditions, stress contexts, NUE definitions, and statistical reporting practices. Quantitative pooling would risk producing biologically misleading estimates.

Fourth, observation-level frequencies should not be interpreted as independent effect estimates. Several studies contributed multiple coded observations because they evaluated different application routes, doses, stress conditions, or outcome domains. Although this preserves information from complex experiments, it creates dependency among observations. For this reason, the response shares reported here should be interpreted as patterns within the evidence map rather than as prevalence estimates of true agronomic effects.

Fifth, publication bias remains a possibility. Studies reporting positive micronutrient responses may be more likely to be published than those reporting neutral or inconsistent outcomes, whereas stress and toxicity studies may disproportionately represent negative or mixed physiological responses. Therefore, the positive, mixed, neutral, and negative proportions should be used to identify research patterns and uncertainties, not to estimate the probability that Mo application will succeed in a given field.

Sixth, direction-of-effect coding inevitably simplifies complex dose–response relationships. Mo may produce beneficial effects within a narrow sufficiency range but become inhibitory at higher doses, depending on the crop species, soil pH, application route, and baseline Mo status. Retaining mixed responses reduced the risk of forcing complex evidence into positive or negative categories, but it could not fully capture effect magnitude or nonlinear response thresholds.

Nano-Mo evidence warrants particular caution. Claims appearing in the popular and promotional literature seem to outpace the coded evidence, as the available evidence base was limited in size, predominantly characterized by mixed responses, and did not include any clearly positive route-assigned observations under the predefined coding criteria. This review therefore cannot support generalized claims of field readiness or agronomic superiority for nano-Mo formulations.

Finally, several diagnostic moderators were reported inconsistently, including baseline soil Mo status, tissue Mo concentration, Fe/Al oxide indicators, liming history, soil pH, co-applied nutrients, inoculation status, and genotype-specific Mo-use efficiency. These gaps constrain causal interpretation

and indicate that future Mo–NUE research will require more standardized reporting practices.

4.6 Agronomic and advisory implications

The practical implication of this synthesis is that Mo recommendations should be based on evidence of at least one of three constraints: low plant-available Mo, impaired Mo-dependent N metabolism, or limitations in biological N fixation. Without evidence of at least one of these constraints, routine Mo application is difficult to justify based on the current evidence map. Table 9 translates this principle into an operational decision-making framework.

From an agricultural engineering perspective, the constraint-diagnosis framework can guide both fertilizer formulation and site-specific delivery strategies. Sparingly soluble powellite ($CaMoO_4$) and related slow-release carriers offer a potential formulation pathway for regulating Mo release, whereas sensor- or soil map-guided diagnostics could help identify fields where variable-rate liming and targeted Mo co-application warrant evaluation[18]. From a policy and extension perspective, Mo should be incorporated into integrated acid-soil management packages rather than promoted as a stand-alone micronutrient input, with recommendations guided by soil pH, baseline soil or tissue Mo status, crop functional type, and locally validated responses in yield or NUE.

The recent concentration of soybean, *Glycine max*, nodulation, and biological N fixation terms in the Fig. 3(b) overlay highlights a potential translational pathway for the development of integrated rhizobia–Mo packages. Such packages could combine strain-specific inoculation, seed-compatible Mo formulation and dose, application timing, and site diagnosis to improve nodulation and biological N fixation where these processes are limiting. However, the overlay reflects research attention rather than demonstrated agronomic effectiveness; therefore, compatibility testing and factorial field trials remain necessary to determine whether combined rhizobia–Mo delivery can provide reproducible improvements in N accumulation, yield, and NUE beyond those achieved through inoculation or Mo application alone.

At advisory level, Mo should be incorporated into precision nutrient management as a conditional micronutrient lever. For acidic or potentially Mo-limited soils, soil diagnosis should precede soil Mo application. For legumes, Mo should be prioritized when nodulation, nitrogenase activity, or biological N fixation is suspected to be limiting crop performance. Foliar Mo application should be regarded as a targeted corrective measure rather than a blanket spraying strategy, whereas seed priming or coating should be employed only with careful dose calibration because early-stage exposure can produce inconsistent responses. Evidence derived from nutrient-solution systems should be translated to field conditions with caution, and recommendations regarding nano-Mo remain premature in the absence of standardized characterization and robust field validation. Consequently, broad recommendations

Table 9 Constraint-diagnosis framework for Mo management in crop NUE systems

Constraint to diagnose	Minimum diagnostic evidence	Most plausible management route	Required agronomic confirmation
Low plant-available Mo	Soil Mo status, soil pH, liming history, Fe/Al oxide or sorption indicators where available	Soil application or foliar correction	Yield or N-uptake response after Mo correction, supported by NUE or biomass where available
Impaired Mo-dependent N metabolism	Tissue Mo, NR activity, plant N status, protein or chlorophyll indicators	Foliar or soil application, depending on root-zone constraint	Improvement in NR/tissue N status followed by biomass, N uptake, yield, or NUE response
Biological N fixation limitation	Nodulation, nodule biomass, nitrogenase activity, inoculation status, legume performance	Seed treatment, foliar application, or soil application depending on timing and soil context	Nodulation or nitrogenase improvement followed by N accumulation, biomass, or yield response
Stress-disrupted N metabolism	Salinity, heavy metal, drought, or redox-stress indicators linked to NR, GS/GOGAT, N status, or growth	Context-specific; foliar, soil, or seed route depending on constraint	Stress recovery that persists to final biomass, yield, N uptake, or NUE outcome
Nano-Mo uncertainty	Particle size, coating, dissolution, transformation, release kinetics, plant-available Mo fraction, toxicity threshold	Not recommendation-ready; research-use only until field validation	Superiority or equivalence to conventional Mo sources under field conditions using yield, N uptake, and NUE endpoints

should be preceded by small-plot validation trials, local dose optimization, and careful monitoring of yield, N uptake, and NUE-related outcomes.

4.7 Future research priorities

Future Mo–NUE research should prioritize hypothesis-driven prediction rather than post hoc documentation of responses. The next phase of Mo–NUE research should evaluate whether diagnostic indicators can reliably predict responses before application, rather than simply documenting responses after application.

Three advances are most important. First, diagnostic variables must be standardized, including baseline soil Mo status, tissue Mo concentration, soil pH, Fe/Al oxide or sorption indicators where feasible, liming history, organic amendments, N source and application rate, inoculation status, co-applied nutrients, and crop genotype. Second, field-valid NUE endpoints must be strengthened through yield, biomass, N uptake, and harmonized NUE metrics, including agronomic efficiency, recovery efficiency, physiological efficiency, partial factor productivity, N uptake efficiency, and N utilization efficiency where relevant. Third, the translation of mechanistic findings to field applications must be strengthened by linking NR, GS, GOGAT, NiR, nitrogenase, N transporters, molybdate transporters, tissue Mo allocation, and cross-nutrient interactions to field-level performance. Nano-Mo studies, in particular, require detailed particle characterization, release behavior assessments, toxicity thresholds, and direct comparisons with conventional Mo sources under field conditions.

These priorities would shift Mo research from promising physiological evidence toward reliable, diagnosis-based agronomic recommendations for enhancing crop NUE-related performance. The critical challenge for the next generation of Mo research is to determine whether pre-application diagnostic indicators can reliably predict agronomic responses across diverse crop, soil, and stress conditions.

5 Conclusions

This Scopus-indexed structured evidence synthesis demonstrates that Mo functions as a context-dependent lever for crop NUE-related performance rather than as a consistently positive or route-independent input. Mixed responses constituted the dominant pattern across both the full coded matrix (114/249; 45.8%) and the route-assigned evidence base (109/233; 46.8%), whereas clearly positive responses accounted for 86/249 (34.5%) and 81/233 (34.8%), respectively. These frequencies should not be interpreted as probabilities of agronomic success; rather, they demonstrate that Mo responses depend on whether an intervention alleviates a genuine constraint related to plant-available Mo, Mo-dependent N metabolism, biological N fixation, stress physiology, or genotype × environment × management interactions. Under such limiting conditions, Mo may enhance nitrate reduction, N assimilation, symbiotic N fixation, and crop-level NUE-related performance.

This synthesis reframes Mo management from an application-route paradigm to a constraint-diagnosis paradigm. Soil, foliar, seed-based, nutrient-solution, and nano-Mo evidence should not be interpreted as a straightforward hierarchy of effectiveness. Route-level proportions are evidence-map patterns, not effect-size estimates or success probabilities. Nutrient-solution studies provide mechanistic insight but require field validation. More importantly, the current nano-Mo evidence remains insufficient to support field recommendations: none of the 13 route-assigned observations was clearly positive, and 11 observations (84.6%) were mixed. Nano-Mo should therefore remain a research-stage technology until standardized material characterization, safety assessment, and field comparisons with conventional Mo sources demonstrate consistent improvements in yield, N uptake, and NUE.

The most defensible agronomic use of Mo requires site-specific diagnosis, particularly the assessment of soil pH, baseline soil or tissue Mo status, potential Mo limitation, crop functional type, and stress context, followed by route- and dose-specific calibration. Future research should move beyond documenting Mo responses after application and instead test whether pre-application diagnostic indicators can predict agronomic response across crop, soil, and stress contexts. Standardized diagnostic variables, harmonized NUE metrics, and multi-location genotype × environment × management trials are required to translate promising physiological evidence into reliable micronutrient-informed strategies for improving crop NUE-related performance.

Supplementary materials

The online version of this article at https://doi.org/10.15302/J-FASE-2027737 contains supplementary materials.

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Compliance with ethics guidelines

Ridho Victory Nazara, Nurul Aini, Mochammad Roviq, Andi Kurniawan, Nur Izzatul Maulidah, and Moch Dawam Maghfoer declare that they have no conflicts of interest or financial conflicts to disclose. This article does not contain any studies with human or animal subjects performed by any of the authors.

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