

A Comprehensive Review on Plant-Mediated Synthesis of Molybdenum-Based Nanoparticles

Mohini Upadhye*, Sakshi Shitole, Roshni Kolse, Vaishnavi Auti, Payal Pomane, Meher Inamdar, Nikita Pardeshi

Department of Pharmacognosy, PES Modern College of Pharmacy, Moshi, Pune, Maharashtra, India

Corresponding Author: Mohini Upadhye (mohiniketh@rediffmail.com)

DOI: <https://doi.org/10.63001/tbs.2026.v21.i04.pp237-257>

KEYWORDS

*Molybdenum oxide nanoparticles;
Green nanotechnology;
Phytochemical mechanisms;
Material characterization;
Antimicrobial activity;
Nanotoxicology;
Quality by Design.*

Article Info

Received: 25.09.2026

Accepted: 11.10.2026

Published: 23.10.2026

Abstract

Molybdenum-based nanoparticles (Mo-based NPs) represent a versatile class of inorganic nanomaterials with applications spanning catalysis, optoelectronics, environmental remediation, and nanomedicine. While physical and chemical synthesis routes offer precise dimensional control, they often require toxic reducing agents, high thermal budgets, or hazardous organic solvents. Consequently, plant-mediated "green" synthesis using phytochemical-rich extracts has emerged as a promising alternative. However, the literature concerning plant-mediated Mo-based NPs remains fragmented, methodologically inconsistent, and characterized by imprecise nomenclature—frequently grouping metallic molybdenum (Mo^0), molybdenum dioxide (MoO_2), molybdenum trioxide (MoO_3), substoichiometric oxides (MoO_x), and molybdenum disulfide (MoS_2) under the generic label "molybdenum nanoparticles."

This review provides a critical evaluation of plant-mediated Mo-based NP synthesis. We present a transparent search strategy, clarify precursor speciation chemistry (MoO_4^{2-} vs. $\text{Mo}_7\text{O}_{24}^{6-}$), detail phytochemical complexation/reduction mechanisms, and establish a rigorous characterization framework combining X-ray diffraction (XRD), X-ray photoelectron spectroscopy (XPS), transmission electron microscopy (TEM), dynamic light scattering (DLS), and zeta potential. Furthermore, biological activities (antimicrobial, antioxidant, seed-priming) are critically evaluated using an evidence-level grading scheme (Levels I–V) to separate demonstrated particle-specific efficacy from phytochemical carryover artifacts. Finally, we propose a Quality-by-Design (QbD) development framework, toxicological guidelines, and a standardized reporting checklist to facilitate the translational development of phytogetic molybdenum nanomaterials.

1. Introduction

Nanotechnology has brought significant advances to pharmaceutical and biomedical research by making it possible to develop materials at the nanoscale with unique optical, electronic, catalytic, and biological properties. Among these materials, transition-metal and transition-metal-oxide nanoparticles have received considerable attention because of their variable oxidation states, tunable surface properties, and ability to interact with biological molecules. Molybdenum (Mo) is an essential trace element that plays an important role in several biological processes. It is present in the active sites of

important enzymes in humans, plants, and microorganisms, including nitrate reductase, xanthine oxidase, and sulfite oxidase.

In recent years, biological methods of nanoparticle synthesis, particularly those using plant extracts, have emerged as promising alternatives to conventional physical and chemical synthesis methods. Plants contain a wide range of naturally occurring compounds, such as phenolic acids, flavonoids, tannins, terpenoids, proteins, and other metabolites. These compounds can participate in nanoparticle

formation by acting as reducing or complexing agents and can also help stabilize the newly formed nanoparticles by serving as surface-capping agents. As a result, plant-mediated synthesis is often considered a relatively simple, environmentally friendly, and potentially cost-effective approach.

However, the synthesis of phytogenic Mo-based nanoparticles involves several important challenges. First, molybdenum has complex aqueous chemistry and can exist in different oxidation states, particularly Mo(V) and Mo(VI), depending on the reaction conditions. It can also form a variety of molybdenum oxides, including crystalline and substoichiometric phases, as well as molybdenum dichalcogenides. Therefore, controlling and accurately identifying the chemical phase of the final nanomaterial is essential.

Second, the terminology used in the literature is not always consistent. Some studies describe their products simply as “molybdenum nanoparticles” without providing sufficient evidence to establish the exact composition, oxidation state, or crystalline phase of the material. This can make it difficult to compare findings between different studies and to understand the actual properties of the synthesized nanoparticles.

Another important concern is the interpretation of biological activity. Several studies evaluate nanoparticles using simple *in vitro* assays, but the nanoparticles are not always adequately separated and purified from the original plant extract. Since plant extracts themselves contain biologically active compounds, it can be difficult to determine whether the observed activity is caused by the nanoparticles, residual

phytochemicals, or a combination of both. Appropriate controls and thorough nanoparticle characterization are therefore essential.

Considering these issues, this review critically examines the current progress in plant-mediated synthesis of Mo-based nanoparticles. Particular attention is given to the available literature, precursor chemistry, formation mechanisms, structural and physicochemical characterization, biological activity, toxicity, and the challenges associated with their potential agricultural, pharmaceutical, and biomedical applications. The review also highlights important gaps in the existing research and discusses the factors that should be considered for the reliable and reproducible development of phytogenic Mo-based nanomaterials.

2. Literature Search Methodology and Evidence Classification

2.1 Literature Search Strategy

A comprehensive literature search was conducted using major scientific databases, including Scopus, Web of Science, PubMed, and Google Scholar. The search covered relevant literature published up to September 2026. The search focused on studies describing the plant-mediated or phytogenic synthesis of molybdenum-based nanomaterials and their subsequent characterization and biological or functional evaluation.

Inclusion criteria:

- Primary research articles reporting the plant-mediated or phytogenic synthesis of Mo, MoO_x, or MoS₂ nanoparticles.

- Studies providing adequate physicochemical or structural characterization of the synthesized nanomaterials.
- Studies reporting biological, agricultural, catalytic, or other functional applications of the synthesized nanoparticles.
- Studies describing the plant material, precursor, synthesis conditions, and relevant experimental procedures.

Exclusion criteria:

- Studies involving only conventional chemical or physical synthesis methods without a plant-mediated component.
- Studies based exclusively on microbial or fungal synthesis without the involvement of plant extracts or plant-derived materials.
- Articles that did not provide adequate structural or physicochemical characterization of the synthesized material.
- Review articles, conference abstracts, and studies where the nanoparticle composition or synthesis approach could not be clearly established.

The selected studies were subsequently examined with emphasis on the plant species used, major phytoconstituents involved in nanoparticle formation, molybdenum precursor, synthesis conditions, nanoparticle characteristics, analytical techniques, proposed formation mechanisms, and reported biological or functional activities. Particular attention

was given to the reliability of nanoparticle identification and to whether appropriate controls were included to distinguish nanoparticle-associated effects from the activity of residual plant-derived compounds.

3. Chemical Identity, Classification, and Physicochemical Properties

Molybdenum-based nanomaterials comprise a diverse group of materials whose physicochemical and biological properties depend strongly on their chemical composition, oxidation state, crystal structure, particle size, and surface characteristics. Although these materials are often collectively described as “molybdenum nanoparticles,” metallic molybdenum, molybdenum oxides, oxygen-deficient molybdenum oxides, and molybdenum disulfide are chemically distinct materials and should not be considered interchangeable.

The oxidation state of molybdenum is particularly important because it influences the material's electronic structure, aqueous stability, surface reactivity, dissolution behavior, and biological interactions. For example, metallic Mo primarily exists in the zero oxidation state, whereas MoO₂ contains Mo(IV) and MoO₃ predominantly contains Mo(VI). In MoO_{3-x}, mixed oxidation states can occur because of oxygen vacancies, which can substantially alter the optical and electronic properties of the material. MoS₂ is chemically different from the oxide phases and is characterized by a layered structure with Mo in the +4 oxidation state.

The major classes of Mo-based nanomaterials relevant to plant-mediated synthesis and their distinguishing

physicochemical and biological characteristics are summarized in Table 1.

Table 1. Physicochemical and biological comparison of representative molybdenum-based nanomaterials

Parameter	Metallic molybdenum (Mo ⁰)	Molybdenum dioxide (MoO ₂)	α -Molybdenum trioxide (α -MoO ₃)	Substoichiometric molybdenum oxide (MoO _{3-x})	Molybdenum disulfide (MoS ₂)
Oxidation state(s)	Mo ⁰	Mo ⁴⁺	Mo ⁶⁺	Mixed Mo ⁵⁺ /Mo ⁶⁺ states may occur	Mo ⁴⁺
Crystal system	Body-centered cubic (BCC)	Monoclinic	Orthorhombic, layered	Defect-containing structures; may vary with oxygen deficiency	Layered hexagonal (2H phase)
Aqueous stability and dissolution	Relatively stable under controlled conditions but can undergo surface oxidation	Sparingly soluble and comparatively stable in neutral aqueous media	Can undergo hydration/dissolution under suitable conditions, producing molybdate species	Stability and dissolution are strongly influenced by oxygen vacancies, pH, and redox conditions	Highly stable and poorly soluble in neutral aqueous media; surface oxidation may occur under certain conditions
Optical/electronic properties	Metallic conductivity with broad optical extinction	Metallic or highly conductive behavior	Semiconductor with a band gap of approximately 3 eV; strong UV absorption	Oxygen vacancies can introduce additional electronic states and NIR absorption	Semiconductor; monolayer MoS ₂ has a direct band gap, whereas bulk MoS ₂ has an indirect band gap
Definitive characterization	XRD for BCC structure; XPS for Mo ⁰	XRD for phase identification; XPS for Mo ⁴⁺	XRD for characteristic α -MoO ₃ reflections; XPS for Mo ⁶⁺	XPS to identify mixed Mo oxidation states and oxygen vacancies; EPR can provide supporting evidence	Raman spectroscopy for characteristic MoS ₂ vibrational modes; XRD for layered structure; XPS for Mo ⁴⁺ and S ²⁻

Potential biological impact	Generally associated with relatively low acute toxicity, although surface oxidation and particle size can influence cellular effects	Biological effects may involve intracellular oxidative stress and surface interactions	Biological effects may depend on particle dissolution, Mo-ion release, particle size, and exposure conditions	Oxygen vacancies can enhance redox activity and photothermal/photocatalytic responses; biological effects depend strongly on composition and exposure conditions	Biological effects depend on particle size, layer thickness, surface chemistry, dose, and degradation/oxidation behavior
------------------------------------	--	--	---	--	--

3.1 Importance of distinguishing Mo-based nanomaterials

A major issue in the existing literature is the use of the broad term “**molybdenum nanoparticles**” without clearly defining the chemical identity of the synthesized product. This terminology can be misleading because metallic Mo, MoO₂, MoO₃, MoO_{3-x}, and MoS₂ have substantially different structures and properties.

Therefore, reporting the synthesis of a Mo-containing nanomaterial should ideally include evidence for its **chemical composition, oxidation state, crystal phase, morphology, particle size, and surface chemistry**. Techniques such as X-ray diffraction (XRD), X-ray photoelectron spectroscopy (XPS), Raman spectroscopy, transmission electron microscopy (TEM), scanning electron microscopy (SEM), energy-dispersive X-ray spectroscopy (EDS), and, where appropriate, electron paramagnetic resonance (EPR) can provide complementary information.

This distinction is particularly important for **plant-mediated synthesis**. Plant extracts contain multiple reducing, chelating, and capping compounds, and their interaction with molybdenum precursors can produce different Mo-containing phases depending on the precursor concentration, pH, temperature, reaction time, atmosphere, and phytochemical composition of the extract. Consequently, the final product cannot be reliably identified solely from a visible color change or from a single characterization technique.

3.2 Metallic molybdenum (Mo⁰)

Metallic molybdenum contains molybdenum in the zero oxidation state and normally adopts a body-centered cubic crystal structure. At the nanoscale, its properties can differ considerably from bulk molybdenum because of the increased surface-to-volume ratio. Surface oxidation can also occur depending on the reaction and storage conditions. XRD can be used to confirm the BCC crystal structure, while

XPS is particularly useful for distinguishing metallic Mo from oxidized molybdenum species.

3.3 Molybdenum dioxide (MoO_2)

MoO_2 contains molybdenum predominantly in the +4 oxidation state and has a monoclinic crystal structure. Compared with highly oxidized Mo(VI) oxides, MoO_2 exhibits different electronic and chemical behavior and can show relatively high electrical conductivity. XRD and XPS are useful for confirming the MoO_2 phase and its oxidation state.

3.4 Molybdenum trioxide ($\alpha\text{-MoO}_3$)

$\alpha\text{-MoO}_3$ is one of the most extensively investigated molybdenum oxide phases. It has an orthorhombic layered structure in which Mo(VI) is coordinated with oxygen. The material exhibits semiconducting behavior and strong absorption in the ultraviolet region. Because different molybdenum oxide phases can have overlapping or closely related characteristics, phase identification should preferably be supported by XRD together with XPS rather than inferred from a single analytical result.

3.5 Substoichiometric molybdenum oxide (MoO_{3-x})

MoO_{3-x} represents oxygen-deficient molybdenum oxide rather than a single perfectly defined stoichiometric compound. The presence of oxygen vacancies can lead to mixed oxidation states and substantially modify the electronic and optical properties of the material. These oxygen vacancies may also contribute to enhanced absorption in the near-infrared (NIR) region and increased redox activity.

Because oxygen deficiency is central to the identity of MoO_{3-x} , XPS analysis is particularly important for demonstrating the presence of different molybdenum oxidation states. EPR may provide additional evidence for paramagnetic defect centers associated with oxygen vacancies.

3.6 Molybdenum disulfide (MoS_2)

MoS_2 is chemically distinct from molybdenum oxides and consists of layered sheets of molybdenum and sulfur. Its layered structure and thickness-dependent electronic properties have made it an important two-dimensional nanomaterial. Bulk MoS_2 behaves as an indirect-band-gap semiconductor, whereas monolayer MoS_2 exhibits a direct band gap.

Raman spectroscopy is widely used to identify MoS_2 through its characteristic vibrational modes, while XRD can provide information about its crystalline structure. XPS can further confirm the chemical states of Mo and S.

Overall, the term “**Mo-based nanoparticles**” should be used carefully, with the specific chemical phase reported whenever sufficient characterization is available. Accurate identification is essential because the physicochemical properties, biological interactions, toxicity, and potential applications of these materials can vary substantially with oxidation state and crystal phase.

4. Phytochemical Synthesis Mechanisms and Precursor Speciation

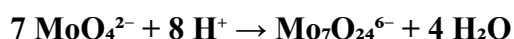
Plant-mediated synthesis of molybdenum-based nanoparticles is a complex process involving several steps, including precursor speciation, interaction of molybdenum species with plant phytochemicals,

nucleation, particle growth, and surface stabilization. Unlike conventional chemical synthesis, plant extracts contain a mixture of biomolecules that can simultaneously participate in reduction, complex formation, and stabilization. Therefore, understanding the chemistry of the molybdenum precursor as well as the role of individual phytochemicals is important for explaining how the nanoparticles are formed.

4.1 Aqueous Precursor Speciation

The chemical form of molybdenum in an aqueous solution is strongly influenced by **pH, precursor concentration, temperature, and ionic conditions**. In mildly alkaline aqueous media, molybdenum(VI) is generally present predominantly as the monomeric molybdate ion, MoO_4^{2-} .

As the pH decreases, particularly below approximately pH 6, molybdate species can undergo protonation and condensation. This may result in the formation of different **polymolybdate or polyoxomolybdate species**. The exact distribution of these species depends on the pH and concentration of the precursor. For example, simplified condensation reactions can be represented as:



and, under more acidic conditions:



These reactions illustrate that molybdenum does not necessarily remain as a single chemical species during nanoparticle synthesis. Instead, a dynamic equilibrium can exist between monomeric molybdate and condensed molybdenum-oxo species.

This speciation is important because different molybdenum species can interact differently with organic molecules present in plant extracts. Monomeric MoO_4^{2-} , for example, may interact differently with phenolic compounds and proteins than larger polymolybdate species. Consequently, changes in pH during plant-mediated synthesis can influence precursor-phytochemical interactions, nucleation, particle growth, and ultimately the chemical phase of the synthesized material.

4.2 Roles of Phytochemical Metabolites

Plant extracts contain several classes of phytochemicals that can contribute to the formation and stabilization of Mo-based nanoparticles. Their exact role depends on their chemical structure, concentration, and interaction with the molybdenum precursor.

1. Flavonoids and Phenolic Acids

Flavonoids and phenolic acids are among the most important phytochemicals involved in plant-mediated nanoparticle synthesis. Compounds containing adjacent hydroxyl groups, such as **catechol- or pyrogallol-type structures**, can interact with molybdenum species through oxygen-containing functional groups. These interactions can lead to the formation of metal-organic complexes and may influence the subsequent nucleation and growth of nanoparticles.

Under heating or mild reflux conditions, some phenolic compounds can undergo oxidation to quinone-like structures. Depending on the precursor and reaction environment, electron transfer during this process may contribute to the reduction of molybdenum species or to changes in their coordination environment. However, the

exact reduction pathway should be experimentally demonstrated rather than assumed solely from the presence of phenolic compounds.

2. Tannins

Tannins are high-molecular-weight polyphenolic compounds containing multiple hydroxyl and other oxygen-containing functional groups. Their multiple binding sites allow them to interact with metal-containing species and provide a relatively strong organic environment around developing nanoparticles.

During synthesis, tannins may therefore contribute to **complexation, nucleation control, and surface stabilization**. Their bulky molecular structure can also provide steric protection around newly formed particles, which may reduce particle aggregation and uncontrolled crystal growth.

3. Proteins and Polysaccharides

Proteins and polysaccharides present in plant extracts can act primarily as **natural stabilizing and capping agents**. Functional groups such as carboxyl ($-\text{COOH}/-\text{COO}^-$), amino ($-\text{NH}_2$), and hydroxyl ($-\text{OH}$) groups can interact with the surface of developing Mo-based particles.

Adsorption of these biomolecules onto the nanoparticle surface can create an organic layer around the particles. This layer may help prevent particle-particle contact, thereby reducing aggregation and improving colloidal stability. Proteins and polysaccharides can also influence particle size and morphology by limiting further crystal growth.

5. Methods:-

1. Green Synthesis Using Plant Extract

Green synthesis of molybdenum-based nanoparticles is a simple and eco-friendly method that uses plant extracts as natural sources of reducing, coordinating, and stabilizing compounds. Phytochemicals such as polyphenols, flavonoids, proteins, sugars, and organic acids interact with the molybdenum precursor and assist in nanoparticle formation and stabilization. In a typical process, the plant material is washed, cut, heated with distilled water, cooled, and filtered to obtain the extract. A molybdenum precursor such as ammonium heptamolybdate is then mixed with the extract under controlled stirring and temperature. The resulting material is separated, washed, and dried. When MoO_3 is the desired product, controlled calcination may be carried out to obtain the crystalline oxide. Finally, the synthesized material is characterized using techniques such as XRD, XPS, FTIR, SEM/TEM, and EDS to confirm its composition, structure, and morphology.

2. Sol-Gel Method

The sol-gel method is a commonly used approach for preparing molybdenum oxide nanoparticles. In this method, a molybdenum precursor is first dissolved in a suitable solvent, followed by pH adjustment, hydrolysis, and condensation to form a colloidal **sol**. With further reaction, the sol develops into a three-dimensional **gel** network. The gel is then dried and calcined to remove volatile and organic components and promote the formation of crystalline **MoO_3 nanoparticles**.

3. Hydrothermal Method

The hydrothermal method is a widely used conventional technique for preparing **MoO₃ nanoparticles and other molybdenum-oxide nanostructures**. In this method, a molybdenum precursor is dissolved in water and the solution is transferred into a **Teflon-lined sealed autoclave**. On heating, the increased temperature and pressure promote nucleation and controlled crystal growth. After the reaction, the autoclave is allowed to cool naturally, and the resulting material is collected by centrifugation or filtration, washed, and dried.

4. Solvothermal Method

The solvothermal method is similar to hydrothermal synthesis, but it uses an organic solvent instead of water. In this method, a molybdenum precursor is mixed with a suitable organic solvent and chemical modifiers, followed by transfer into a sealed autoclave. The mixture is heated under controlled temperature and pressure, allowing nucleation and crystal growth to occur. After cooling, the product is separated, washed, and dried to obtain the desired molybdenum oxide nanostructure. This method is particularly useful for controlling the particle size, morphology, and crystal phase by changing the solvent and reaction conditions.

5. Chemical Precipitation / Co-precipitation Method

Chemical precipitation is one of the simplest conventional methods for preparing molybdenum oxide nanoparticles. In this method, a molybdenum salt solution is reacted with a suitable precipitating agent such as **NaOH**, **NH₄OH**, or **urea**, causing a molybdenum-containing precipitate to form. The precipitate is then separated by filtration or

centrifugation, washed to remove impurities, and dried. Finally, **calcination or annealing** is carried out to convert the precursor into crystalline **MoO₃ nanoparticles**.

6. Microwave-Assisted Synthesis

Microwave-assisted synthesis is a rapid method for preparing **MoO₃ nanoparticles** in which microwave energy is used to heat the reaction mixture quickly and uniformly. A molybdenum precursor is mixed with a suitable solvent or reducing agent and exposed to microwave irradiation, which promotes rapid nucleation and particle growth. The formed material is then separated, washed, dried, and, when required, calcined to obtain crystalline MoO₃ nanoparticles. The method can significantly reduce reaction time and may help control particle size and morphology compared with conventional heating.

7. Thermal Decomposition Method

Thermal decomposition is a simple method in which a **molybdenum-containing precursor is heated at a controlled temperature** until it decomposes and forms the desired molybdenum oxide. During heating, the precursor gradually loses volatile components and transforms into a molybdenum oxide phase, which can form **MoO₃ nanoparticles** under suitable conditions. The final particle size, morphology, and crystal phase depend mainly on the **heating temperature, heating time, and surrounding atmosphere**.

6. Critical Synthesis Parameters and Quality by Design (QbD) Framework

The properties of plant-mediated Mo-based nanoparticles can vary considerably depending on the conditions used during synthesis. Parameters such as **pH, plant-extract concentration, precursor ratio, temperature, reaction time, agitation, and purification** can influence particle size, morphology, crystallinity, surface

chemistry, and stability. Therefore, applying a **Quality by Design (QbD)** approach can help identify and systematically optimize the critical process parameters (CPPs) that control the critical material attributes (CMAs) and ultimately affect the performance of the nanoparticles.

Table 2. Quality by Design (QbD) Matrix for Phytogetic Molybdenum Nanoparticles

Critical Process Parameter (CPP)	Typical Variable	Effect on Critical Material Attributes (CMAs)	Impact on Critical Performance Attributes (CPAs)
pH of reaction mixture	Approximately 4–10, depending on the precursor and target phase	Influences molybdenum speciation, phytochemical ionization, surface charge, and nucleation	Affects particle size, phase formation, aggregation, and colloidal stability
Extract-to-precursor ratio	Optimized according to plant extract and precursor concentration	Influences reduction/complexation behavior and the amount of phytochemical capping on the particle surface	Affects particle size, aggregation, surface chemistry, and residual organic content
Reaction temperature	Depends on the synthesis method	Influences dehydration, nucleation rate, crystal growth, and crystallinity	Affects crystallite size, phase purity, defect density, and dissolution behavior
Reaction time / agitation	Optimized according to the synthesis system	Influences precursor–phytochemical interactions, nucleation, particle growth, and possible Ostwald ripening	Can affect particle-size distribution, morphology, and uniformity
Purification/washing cycles	Water, ethanol, or other suitable washing media	Helps remove unreacted precursor salts and loosely bound phytochemicals	Reduces residual impurities and helps prevent interference in biological assays

A QbD-based approach is particularly useful for phytogetic synthesis because plant extracts naturally contain multiple compounds whose concentrations can vary with **plant species, plant part, harvesting conditions, extraction method, and storage**. Identifying the important process variables and establishing suitable

operating ranges can therefore improve the reproducibility and quality of the final Mo-based nanoparticles.

7. Structural and Physicochemical Characterization Framework

Proper characterization is essential for confirming the identity, structure, and

properties of plant-mediated Mo-based nanoparticles. Since different molybdenum phases can show similar features, a combination of analytical techniques is preferred to avoid incorrect phase assignment. **X-ray diffraction (XRD)** is mainly used to determine the crystal structure and phase, while **X-ray photoelectron spectroscopy (XPS)** provides information about the surface composition and oxidation states of molybdenum. Other techniques such as **FTIR, Raman spectroscopy, SEM, TEM, EDS, and DLS** provide complementary information about surface chemistry, morphology, elemental composition, and particle size.

It is also important to distinguish between different measures of particle size. **Crystallite size** is estimated from XRD peak broadening, commonly using the Scherrer equation, and represents the size of an individual crystalline domain rather than the entire particle. **Primary particle size** is generally determined by TEM and

represents the physical dimensions of individual particles observed in the dry state. In contrast, **hydrodynamic diameter** is measured by DLS in suspension and includes the particle core together with its surrounding solvation layer and adsorbed phytochemical molecules. Therefore, DLS measurements are generally larger than TEM measurements.

8. Comparative Analysis of Reviewed Primary Literature

A critical comparison of reported plant-mediated molybdenum-based nanoparticle studies is presented in Table 3. The studies differ considerably in terms of plant material, molybdenum precursor, synthesis conditions, structural characterization, and biological or functional evaluation. This comparison also highlights important gaps in the existing literature, particularly regarding confirmation of the exact molybdenum phase, oxidation state, nanoparticle size, purification, and safety evaluation.

Table 3. Comparative analysis of selected plant-mediated molybdenum-based nanoparticle studies

Plant species and part used	Precursor and synthesis conditions	Assigned phase and morphology	Structural characterization	Application / biological model	Evidence level	Key limitations
<i>Solanum xanthocarpum</i> (leaf)	Molybdenum precursor; aqueous extraction and overnight shaking	"Molybdenum NPs"; exact oxide phase unclear; irregular aggregates	XRD indicated a crystalline product; SEM showed aggregates; TEM/DLS not reported	Antibacterial activity against <i>S. aureus</i> and <i>P. aeruginosa</i> ; DPPH antioxidant assay	Level II	Exact phase and oxidation state were not clearly established; XPS and purification details were lacking

<i>Pterocarpus santalinus</i> (leaf)	Ammonium molybdate with aqueous plant extract followed by calcination	Orthorhombic MoO_3 ; spherical particles	XRD and FE-SEM; DLS and zeta potential not reported	ABTS antioxidant assay; phytopathogenic microorganisms; seed-priming studies	Level II/III	Limited particle-size characterization and lack of detailed cytotoxicity/safety evaluation
<i>Citrus sinensis</i> (leaf)	Ammonium molybdate with aqueous extract and vegetable-oil capping	Reported as molybdenum oxide; cubical morphology	XRD and zeta-potential analysis; TEM not reported	Antifungal activity against <i>Colletotrichum</i> associated with anthracnose	Level II	Limited structural characterization and no XPS or comprehensive safety assessment
<i>Lactuca serriola</i> (leaf)	Ammonium molybdate with ethanolic extract	Reported orthorhombic MoO_3 ; nanorod/spherical morphology	XRD and SEM/EDX; DLS not reported	Photocatalytic degradation of Crystal Violet; pollen morphology evaluation	Level I	Mainly focused on environmental/photocatalytic applications rather than biomedical or pharmaceutical applications
<i>Syzygium aromaticum</i> (flower bud)	Ammonium heptamolybdate with aqueous extract followed by calcination	Orthorhombic MoO_3 ; spherical morphology	XRD and TEM; DLS not reported	Material characterization and optical studies	Level I	High-temperature treatment may remove much of the original phytochemical coating; mainly a synthesis proof-of-concept
<i>Centella asiatica</i> (whole plant)	Molybdenum precursor using combustion-based synthesis	Molybdenum oxide; spherical morphology	XRD and SEM	Photocatalytic dye degradation and electrochemical lead sensing	Level I	Primarily a materials/environmental study; biocompatibility and toxicological evaluation were not extensively investigated

Critical Interpretation

Overall, the available studies demonstrate that plants can be used as sources of biomolecules for the synthesis of Mo-containing nanomaterials. However, the **strength of the evidence varies considerably between studies**. Some reports provide XRD and electron-microscopy data, whereas others lack sufficient evidence to establish the exact chemical phase or oxidation state.

A recurring limitation is the use of the broad term **“molybdenum nanoparticles”** without confirming whether the final material is metallic Mo, MoO₂, MoO₃, MoO_{3-x}, or another Mo-containing phase. Similarly, the absence of XPS in several studies makes it difficult to confidently assign the oxidation state of molybdenum.

Another important issue is purification. Plant extracts contain bioactive compounds that can themselves exhibit antioxidant or antimicrobial activity. Therefore, biological results obtained without adequate washing, purification, and extract-only controls may not necessarily represent the activity of the nanoparticles alone.

Future studies should therefore combine **XRD for phase identification, XPS for oxidation-state analysis, TEM/SEM for morphology, DLS for hydrodynamic size, EDS for elemental composition, and appropriate purification and biological controls**. Such a standardized characterization strategy would improve the reproducibility and reliability of phytogenic Mo-based nanoparticle research.

9. Critical Evaluation of Biological Activities and Experimental Controls

9.1 Antimicrobial Mechanisms and Assay Rigor

Mo-based nanoparticles may show antimicrobial activity through several mechanisms, including disruption of the bacterial membrane, generation of reactive oxygen species (ROS), inhibition of cellular enzymes, and changes associated with molybdenum ion release. However, many studies rely mainly on qualitative disc-diffusion or zone-of-inhibition tests. These assays are useful for preliminary screening but do not provide detailed information about antimicrobial potency or mechanism.

For more reliable evaluation, future studies should include **minimum inhibitory concentration (MIC)** and **minimum bactericidal concentration (MBC)** using broth microdilution methods. **Time-kill studies** and membrane-permeability assays, such as propidium iodide uptake or crystal violet leakage, can provide additional information about bacterial damage. Intracellular ROS can be evaluated using fluorescent probes such as **DCFH-DA**. Testing against both susceptible strains and **multidrug-resistant (MDR) clinical isolates** would also provide a better understanding of the practical antimicrobial potential of these nanoparticles.

9.2 Antioxidant Activity and Control Validation

Plant-mediated nanoparticles often show strong antioxidant activity in **DPPH and ABTS assays**. However, the measured activity may not come entirely from the nanoparticles themselves. It can arise from the redox properties of surface-associated

molybdenum species, antioxidant phytochemicals remaining on the nanoparticle surface, or interference caused by nanoparticles during optical measurements.

To distinguish these effects, appropriate control groups should be included:

- **Group A:** Plant extract alone at an equivalent concentration.
- **Group B:** Molybdenum precursor salt alone.
- **Group C:** Crude, unwashed nanoparticle suspension.
- **Group D:** Purified and washed nanoparticle suspension, such as material purified by repeated centrifugation or dialysis.

Comparison of these groups can help determine whether the observed antioxidant activity is mainly due to the nanoparticles, residual phytochemicals, the precursor, or assay interference.

10. Biocompatibility, Toxicology, and Environmental Safety

Safety evaluation is an important part of developing phyto-genic Mo-based nanoparticles for biomedical, pharmaceutical, or agricultural applications. Their interaction with biological systems depends not only on particle size and surface properties but also on dissolution, released molybdenum

species, and interactions with biological molecules.

10.1 Dissolution, Protein Corona, and Cellular Fate

When Mo-based nanoparticles enter biological fluids, proteins and other biomolecules can quickly attach to their surface and form a **protein corona**. Proteins such as serum albumin and fibrinogen may alter the nanoparticle's hydrodynamic size, surface charge, stability, and cellular uptake.

The **pH of the surrounding environment** can also influence nanoparticle dissolution and the release of molybdenum-containing ionic species. Therefore, studies should evaluate nanoparticle stability and dissolution under relevant physiological and intracellular conditions. This is particularly important for distinguishing effects caused by the intact nanoparticles from those caused by released molybdenum ions.

A complete safety assessment should therefore consider **particle properties, dissolution behavior, protein-corona formation, cellular uptake, oxidative stress, cytotoxicity, and ion-mediated effects** rather than evaluating nanoparticle toxicity from a single assay alone.

11. Translational Challenges and Environmental Sustainability

11.1 Quantitative Assessment of “Green” Metrics

Although plant-mediated synthesis can reduce the use of harsh chemical reducing agents such as sodium borohydride and hydrazine, it should not automatically be

considered a completely sustainable process. Its environmental impact depends on the amount of plant material, water, chemicals, solvents, and energy used during synthesis and purification.

Therefore, green synthesis should be evaluated using measurable **green chemistry metrics**, including:

- **Process Mass Intensity (PMI):** Total mass of all materials used, including plant biomass, water, solvents, and precursors, per unit mass of purified nanoparticles produced.
- **Energy Demand:** Energy required for steps such as plant extraction, heating, centrifugation, drying, and high-temperature calcination.
- **E-Factor:** Amount of waste generated per unit mass of the final nanoparticle product.

Reporting these parameters would allow a more realistic comparison between plant-mediated and conventional synthesis methods.

11.2 Extract Reproducibility and Batch-to-Batch Variability

One of the major challenges in translating plant-mediated nanoparticle synthesis into pharmaceutical or industrial applications is the natural variability of plant extracts. The phytochemical composition can change depending on the **geographical location**,

harvesting season, plant age, drying conditions, storage, and extraction method.

To improve reproducibility between batches, researchers should clearly report:

- **Botanical authentication**, including the full plant name and herbarium voucher number.
- **Standardized extraction conditions**, including solvent, temperature, extraction time, and solid-to-liquid ratio.
- **Phytochemical profiling**, preferably using techniques such as HPLC or LC-MS to identify and quantify important marker compounds.

Such standardization can help establish a more consistent relationship between the plant extract composition, synthesis process, and properties of the resulting nanoparticles.

12. Minimum Reporting Checklist for Phytogetic Molybdenum Nanoparticles

To improve reproducibility and scientific reliability, future studies on phytogetic Mo-based nanoparticles should provide sufficient information about the plant material, extraction procedure, synthesis conditions, purification, characterization, and biological testing. A suggested reporting checklist is presented in Table 4.

Table 4. Standardized Reporting Checklist for Phytogetic Mo-NP Research

Section / Category	Required Reporting Item	Checklist Criteria
Botanical Sourcing	Plant species and authentication	Full botanical name, plant part used, collection location, harvest season, and herbarium voucher number

Extract Preparation	Extraction parameters	Drying method, biomass particle size, solvent and purity, extraction temperature and time, solid-to-liquid ratio, and filtration method/pore size
Synthesis Protocol	Reaction variables	Precursor chemical formula and purity, precursor concentration, extract-to-precursor ratio, pH, temperature, stirring speed, and reaction time
Purification Steps	Washing and isolation	Centrifugation speed and time, washing solvent(s), number of washing cycles, drying method and temperature, and calcination conditions
Phase Identification	Structural determination	XRD pattern with appropriate standard reference files and XPS analysis to confirm molybdenum oxidation states
Dimensional Analysis	Particle-size measurements	XRD crystallite size, TEM particle-size distribution, DLS hydrodynamic diameter, PDI, and zeta potential
Control Groups	Biological controls	Parallel testing of plant extract, precursor salt, unwashed nanoparticles, and purified nanoparticles
Toxicity Assessment	Biocompatibility data	Cytotoxicity using relevant mammalian cell models, hemolysis testing, and molybdenum-ion release under physiologically relevant conditions

A standardized reporting approach such as this would make studies easier to compare and reproduce. It would also help distinguish the effects of the **nanoparticle itself, residual plant phytochemicals, and released molybdenum species**, which is important for evaluating the true potential and safety of phytogenic Mo-based nanomaterials.

12. Conclusion

Plant-mediated synthesis offers a simple and environmentally friendly approach for producing functionalized molybdenum-based nanoparticles. However, moving these materials from preliminary laboratory studies toward pharmaceutical, biomedical,

or agricultural applications requires better control and stronger scientific evidence.

Future research should clearly establish the **chemical composition, crystal phase, oxidation state, and particle size** of the synthesized materials using complementary techniques such as XRD, XPS, TEM, and DLS. Biological studies should also include proper purification procedures and suitable plant-extract controls to distinguish the actual effects of nanoparticles from those of residual phytochemicals.

Improved standardization of plant extraction, **Quality-by-Design (QbD)** approaches for synthesis optimization, detailed toxicity studies, and consistent reporting practices will help improve the reproducibility and reliability of phytogenic molybdenum-based nanoparticles. These

efforts can support the further development and responsible application of these materials in biomedical, pharmaceutical, and agricultural fields.

Declarations

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

Acknowledgements

The authors sincerely acknowledge **Principal Prof. Dr. S. N. Dhole, Progressive Education Society's Modern College of Pharmacy, Moshi, Pune**, for providing academic guidance and research support.

References

1. Jeevanandam J, Barhoum A, Chan YS, Dufresne A, Danquah MK. Review on nanoparticles and nanostructured materials: history, sources, toxicity and regulations. *Beilstein J Nanotechnol.* 2018;9:1050–1074. https://doi.org/10.3762/bjnano.9.98
2. Nel A, Xia T, Mädler L, Li N. Toxic potential of materials at the nanolevel. *Science.* 2006;311(5761):622–627. https://doi.org/10.1126/science.1114397
3. Buzea C, Pacheco II, Robbie K. Nanomaterials and nanoparticles: sources and toxicity. *Biointerphases.* 2007;2(4):MR17–MR172. https://doi.org/10.1116/1.2815690
4. Yaqoob AA, Ahmad H, Parveen T, et al. Recent advances in metal nanoparticles as alternative therapeutic agents against bacterial pathogens. *Appl Microbiol Biotechnol.* 2020;104(1):219–229. https://doi.org/10.1007/s00253-019-10263-8
5. Wang J, Polleux J, Lim J, Dunn B. Molybdenum-based nanomaterials: synthesis, properties, and applications in energy storage and conversion. *Adv Funct Mater.* 2012;22(10):2133–2144. https://doi.org/10.1002/adfm.201103013
6. Chhowalla M, Shin HS, Eda G, Li LJ, Loh KP, Zhang H. The chemistry of two-dimensional layered transition metal dichalcogenide nanosheets. *Nat Chem.* 2013;5(4):263–275. https://doi.org/10.1038/nchem.1589
7. Iravani S. Green synthesis of metal nanoparticles using plants. *Green Chem.* 2011;13(10):2638–2650. https://doi.org/10.1039/C1GC15386B

8. Mittal AK, Chisti Y, Banerjee UC. Synthesis of metallic nanoparticles using plant extracts. *Biotechnol Adv.* 2013;31(2):346–356. https://doi.org/10.1016/j.biotechadv.2013.01.003
9. Ahmed S, Ahmad M, Swami BL, Ikram S. A review on plants extract mediated synthesis of silver nanoparticles for antimicrobial applications: a green expertise. *J Adv Res.* 2016;7(1):17–28. https://doi.org/10.1016/j.jare.2015.02.007
10. Rai M, Yadav A, Gade A. Silver nanoparticles as a new generation of antimicrobials. *Biotechnol Adv.* 2009;27(1):76–83. https://doi.org/10.1016/j.biotechadv.2008.09.002
11. Das RK, Brar SK. Plant mediated green synthesis: modified approaches. *Nanoscale.* 2013;5(21):10155–10162. https://doi.org/10.1039/C3NR02548A
12. Bharathidasan P, Surya M, Geetha Sravanthy P, Saravanan M. Green synthesis of molybdenum nanoparticles from *Solanum xanthocarpum* and evaluation of their antimicrobial and antioxidant activity against multidrug-resistant wound isolates. *Cureus.* 2024;16(4):e56760. https://doi.org/10.7759/cureus.56760
13. Shaik B, Nakka S, Anday MK, et al. Phyto-genic molybdenum nanoparticles using *Pterocarpus santalinus*: characterisation, antioxidant, antimicrobial, seed priming and nitrogen fixation activities. *Sci Rep.* 2026;16:52544. https://doi.org/10.1038/s41598-026-52544-1
14. Green synthesis of molybdenum-based nanoparticles and their applications in energy conversion and storage: a review. *Int J Hydrogen Energy.* 2022;47(72):31014–31057. https://doi.org/10.1016/j.ijhydene.2021.10.076
15. Zhang XF, Liu ZG, Shen W, Gurunathan S. Silver nanoparticles: synthesis, characterization, properties, applications, and therapeutic approaches. *Int J Mol Sci.* 2016;17(9):1534. https://doi.org/10.3390/ijms17091534
16. Fadeel B, Farcas L, Hardy B, et al. Advanced tools for the safety assessment of nanomaterials. *Nat Nanotechnol.* 2018;13(7):537–543. https://doi.org/10.1038/s41565-018-0185-0
17. Love SA, Maurer-Jones MA, Thompson JW, Lin YS, Haynes CL.

- Assessing nanoparticle toxicity. *Annu Rev Anal Chem.* 2012;5:181–205.
<https://doi.org/10.1146/annurev-anchem-062011-143134>
18. Kinnear C, Moore TL, Rodriguez-Lorenzo L, Rothen-Rutishauser B, Petri-Fink A. Form follows function: nanoparticle shape and its implications for nanomedicine. *Chem Rev.* 2017;117(17):11476–11521.
<https://doi.org/10.1021/acs.chemrev.7b00194>
 19. Yu Z, Lou R, Pan Y, et al. Biogenic molybdenum oxide nanoparticles: synthesis, characterization and prospective biological applications. *J Trace Elem Med Biol.* 2021;68:126833.
<https://doi.org/10.1016/j.jtemb.2021.126833>
 20. Al-Arjan WS, Khan ST. Phyto-genic transition metal oxide nanoparticles: mechanism of synthesis, biological activities, and safety considerations. *Environ Res.* 2023;216:114682.
<https://doi.org/10.1016/j.envres.2022.114682>
 21. Shah A, Rahman L, Khan Z, et al. Biogenic synthesis of MoO₃ nanoparticles using extract of *Lactuca serriola*: characterization and environmental applications. *Arab J Basic Appl Sci.* 2023;30(1):412–425.
<https://doi.org/10.1080/16583655.2023.2292322>
 22. Ramesh M, Anbu S, Sinthiya A. Synthesis and characterization of molybdenum oxide nanoparticles by green method using *Citrus sinensis* leaf extract. *J Nanostruct Chem.* 2022;12(2):189–198.
<https://doi.org/10.1007/s40097-021-00445-3>
 23. Kumar A, Sharma P, Clove-mediated green synthesis of MoO₃ nanoparticles: characterization and evaluation. *Int J Sci Res Dev.* 2014;2(4):220–224.
 24. Mamatha GP, et al. Facile green synthesis of Molybdenum oxide nanoparticles using *Centella asiatica* plant: photocatalytic and electrochemical lead sensor applications. *Mater Today Proc.* 2021;47:3512–3518.
<https://doi.org/10.1016/j.matpr.2021.10.112>
 25. Makarov VV, Love AJ, Sinitsyna OV, et al. "Green" nanotechnologies: synthesis of metal nanoparticles using plants. *Acta Naturae.* 2014;6(1):35–44.
 26. Akhtar MS, Panwar J, Yun YS. Biogenic synthesis of metallic nanoparticles by plant extracts. *ACS Sustain Chem Eng.* 2013;1(6):591–602.
[<https://doi.org/10.1021/sc3001182>]

-](<https://doi.org/10.1021/sc3001182>)
27. Pal SL, Jana U, Manna PK, Mohanta GP, Manavalan R. Nanoparticle: an overview of preparation and characterization methods. *J Appl Pharm Sci.* 2011;1(6):228–234.
 28. Tenzer S, Docter D, Rosff S, et al. Rapid formation of plasma protein corona critically determines nanoparticle pathophysiology. *Nat Nanotechnol.* 2013;8(10):772–781. <https://doi.org/10.1038/nnano.2013.181>
 29. Nel AE, Mädler L, Velegol D, et al. Understanding biophysicochemical interactions at the nano-bio interface. *Nat Mater.* 2009;8(7):543–557. [<https://doi.org/10.1038/nmat2442>] (<https://doi.org/10.1038/nmat2442>)
 30. Yu XR, Unnikrishnan B, Chen YJ, et al. Synthesis and biomedical applications of molybdenum-based nanomaterials. *ACS Biomater Sci Eng.* 2020;6(9):4770–4788. <https://doi.org/10.1021/acsbiomaterials.0c00712>
 31. Doaa E Elsherif, Osama A Alaziz, Eman H Rashed, Aya M Hewidy, Roqia A Abdelazim, Salma A Dabash, Mai A El-Esawy. Green synthesis of MoO₃NPs. *BMC Plant Biol* 2026 May 26;26:918. doi: [10.1186/s12870-026-09007-6](https://doi.org/10.1186/s12870-026-09007-6) (<https://www.sciencedirect.com/science/article/abs/pii/S0360319921040817>)
 32. Shihai Chen, Ping Zhang, Hongmei Bai, Wenhui Yi. nano-molybdenum oxide for photothermal cancer therapy, Sol-gel method. *Nanomedicine (Lond)* 2025 Mar 10;20(8):883–901. (<https://pmc.ncbi.nlm.nih.gov/articles/PMC11988261/>)
 33. Alexej Michailovski Dipl.-Chem., Greta R. Patzke Dr. Hydrothermal Synthesis of Molybdenum Oxide Based Materials. 01 December 2006 <https://doi.org/10.1002/chem.200600977>
 34. Muhammad Kashif, Talha Sharif, Salman Khan, Natasha Shahzad, Jalal Amir, Misbah Gul, Kashif Shahid, Awais Qarni, Ajmal Shah, Nolubabalo Matinise. Synthesis Strategies and Multifaceted Applications of Molybdenum-Based Nanomaterials: A Comprehensive Review 20 March 2026 <https://doi.org/10.1155/sci5/176440> [0Digital Object Identifier \(DOI\)](https://doi.org/10.1155/sci5/176440)
 35. Andreea Mariana Negrescu, Manuela S. Killian, Swathi N. V. Raghu, Patrik Schmuki, Anca Mazare, Anisoara Cimpean. Metal Oxide Nanoparticles: Review of Synthesis, Characterization and Biological Effects. *J. Funct. Biomater.* 2022, 13(4), 274; <https://doi.org/10.3390/jfb13040274>
 36. A.V. Avani, R.B. Chrisma, E.I. Anila. Low temperature synthesis of MoO₃ nanoparticles by

hydrothermal method: Investigation on their structural and optical properties. 26 April 2023.
<https://doi.org/10.1016/j.matpr.2022.11.060>

37. Sham AlZahabi, Wael Mamdouh. Valorization of citrus processing waste into high-performance bionanomaterials: green synthesis, biomedicine, and environmental remediation. *RSC Adv.* (2025) 15 (43): 36534–36595.
<https://doi.org/10.1039/d5ra04307g>