Research Article

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Green synthesis, characterization, and application of iron and molybdenum nanoparticles and their composites for enhancing the growth of *Solanum lycopersicum*

https://doi.org/10.1515/chem-2023-0196
received August 12, 2023; accepted January 24, 2024

Abstract: Nanomaterials have become integral in various aspects of agricultural practices, including the development of nano-fertilizers for optimized crop nutrition. This study explores the application of green-synthesized iron (Fe) and molybdenum (Mo) nanoparticles, as well as their composites, using a guava leaf extract (GLE). The focus is on assessing their impact on nitrogen fixation and growth in tomato plants (*Solanum lycopersicum*). The nanoparticles were characterized through Fourier Transform Infrared Spectroscopy, Ultraviolet Diffused Reflectance Spectroscopy, Raman Spectroscopy, and X-ray diffraction analysis. The experiment involved two application methods (soil and direct plant spraying) with varying nanoparticle concentrations. Results indicate that the 1% composite nanoparticles applied to the soil and 3% Mo directly on plants yield the most favorable growth and nitrogen uptake in *S. lycopersicum*. Notably, the 1% composite treatment demonstrated significant enhancement in shoot length, number of branches, and shoot diameter at all three growth stages. Conversely, the 3% Mo treatment when applied directly to plants exhibited optimal results showing substantial shoot length, number of branches, and shoot diameter. Post-experimental soil nutrient analysis further revealed the nuanced effects of nanoparticle applications with 1% composite treatments enhancing nutrient availability compared to control and other concentrations. This research contributes to the evolving field of agri-nanotechnology emphasizing the importance of nanoparticle concentration and application method in influencing plant development and nutrient uptake, paving the way for sustainable agricultural practices.

Keywords: agri-nanotechnology, iron and molybdenum nanoparticles, green synthesis, micronutrients, plant growth parameters, growth analysis

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1 Introduction

Nanomaterials are used in a wide variety of applications throughout the entire agricultural production process, including nano-fertilizers for balanced crop nutrition [1–3]. Significant progress has been made in the previous two decades in the study of nanotechnology for use in agriculture [4–7]. Most biological species, including plants and animals, require the trace metals iron and molybdenum to grow. These elements can be found in soil. The transitional element molybdenum can exist in several oxidation states, ranging from zero to VI. The most prevalent form of VI in agricultural soils is the oxidation form. Specific plant enzymes have been used to take part in oxidative and reduction processes [8,9]. Some phenotypes that interfere with the growth of the plant result from the lack of Mo in plants [10–12]. Most biological species, including plants, need molybdenum to grow [13].

In numerous enzyme systems where haem or haemin serves as the prosthetic group, iron is important. These haem enzyme systems include several cytochromes, peroxidases, and catalases. A live cell's respiratory metabolism is controlled by cytochromes. Ferredoxin, a member of the haem family of iron enzymes, controls oxidation–reduction reactions. Its participation in photosynthesis, NO^{2-} and SO_4^{2-} reduction, and nitrogen assimilation highlight the critical roles iron plays in plant metabolism. Yellow leaves are the main sign of iron deficiency because there is not enough chlorophyll in the environment. The younger top leaves in interveinal tissues are the first to yellow. Leaves that are severely iron deficient turn entirely yellow or practically white before dying and turning brown. The enzyme nitrogenase contains two types of proteins: Mo–Fe protein, which contains molybdenum, iron, and protein, and Fe protein, which contains iron and protein. Iron and Molybdenum are therefore necessary for the nitrogen fixation process. According to the concentration, Mo nanoparticles (NPs) can affect the antioxidant system, mineral uptake, and growth of the pea plant in both favorable and unfavorable ways [14–18]. It has been found that NPs of Mo have both positive and negative effects on the growth of the Pea plant, antioxidant system, and mineral uptake depending on the concentration [19]. Spraying NPs of ZnO increased the growth of tomato plants by increasing their chlorophyll content and Photosystem-II activity. They also increase Iron Fe accumulation (by 12.2%) and Fe deficiency tolerance in tomato plants [20]. ZnONP-treated tomato plants significantly increased plant height, stem diameter, and plant organs (leaves, stem, and roots) dry weight compared to plants without NP treatment [21–23].

Iron and molybdenum play pivotal roles in various enzymatic processes within plants, influencing crucial metabolic pathways such as nitrogen fixation. The intricate interplay of these trace elements contributes significantly to plant development and overall health. This research seeks to bridge the gap between nanotechnology and agriculture, exploring the multifaceted roles Iron and molybdenum nanoparticles can play in enhancing tomato plant growth. In this study, the green synthesis approach was used to create Fe, Mo, and their nanocomposites utilizing an aqueous extract of *P. guajava* as a reducing agent [24].

The selection of guava plants for green synthesis of nanoparticles is attributed to the rich phytochemical composition of guava leaves. Guava (*Psidium guajava*) is known to contain bioactive compounds such as flavonoids, polyphenols, and tannins. These phytochemicals not only act as reducing agents but also stabilize and functionalize the synthesized nanoparticles. The antioxidant properties of guava extracts play a crucial role in preventing the oxidation of nanoparticles during the synthesis process [25]. Additionally, the abundance and accessibility of guava plants in various regions make them a sustainable and cost-effective choice for nanoparticle synthesis. The specific chemical constituents present in guava extracts contribute to the effectiveness and eco-friendliness of the green synthesis approach, making it a popular choice in nanomaterial research.

In the ever-evolving realm of nanotechnology, the green synthesis of nanoparticles has emerged as an eco-friendly and sustainable approach, leveraging natural resources to create novel materials with diverse applications [1]. Among these applications, the utilization of nanomaterials in agriculture has garnered significant attention for its potential to revolutionize plant growth and enhance crop yield. This study explores the green synthesis and characterization of iron and molybdenum nanoparticles, exploring their subsequent application in fostering the growth of *Solanum lycopersicum*, commonly known as tomato plants. Nanoparticles, at the nanoscale dimension, exhibit unique physicochemical properties that distinguish them from bulk materials. The green synthesis methodology employed in this study involves the use of *Psidium guajava* (guava) leaf extract as a reducing agent, reflecting an environmentally friendly approach to nanoparticle production. Understanding the distinctive characteristics of these nanoparticles, particularly those of iron and molybdenum, is crucial for unraveling their potential impact on plant physiology. By elucidating the green synthesis process, thoroughly characterizing the synthesized nanoparticles, and investigating their effects on the growth of *Solanum lycopersicum*, this study endeavors to contribute valuable insights to the expanding field of nanotechnology in agriculture. The outcomes of this research could pave the way for sustainable and eco-friendly strategies to optimize agricultural practices, ensuring a greener and more productive future for crop cultivation.

2 Materials and methods

2.1 Preparation of *Psidium guajava* leaf extract

P. guajava leaves were collected from the main campus of Allama Iqbal Open University, Islamabad, Pakistan.

Freshly collected leaves were washed to remove dust and other impurities. Leaves were shade-dried and ground in the electric grinder to turn them into powder. About 10 g leaves powder was added to the 100 mL of distilled water. The suspension was placed on a hot plate with a magnetic stirrer for 30 min at 600°C. The mixture was then filtered to get plant extract.

2.2 Green synthesis of iron oxide and ammonium hepta molybdate nanoparticles

To produce NPs of Fe and Mo, Iron chloride ($FeCl_3$) and Ammonium Hepta Molybdate ($(NH_4)_6MO_7O_{24}$) were used; 1.4 g of $FeCl_3$ and 1.1 g of $(NH_4)_6Mo_7O_{24}$ were dissolved in 100 mL of distilled water separately. For preparing the composite, we added the same amount of both salts in 100 mL of distilled water (DW). After stirring for 1 h, 50 mL of GE was added to the homogenous solution making a 2:1 ratio and stirred for 1 h. The solution was heated at 80°C while stirring for 2 h. The mixture was then transferred to the oven for drying at 80°C. The mixture was washed with ethanol and distilled water three–four times. The mixture was annealed at 400°C for 2 h.

2.3 Structural analysis of Fe and Mo NPs

The structural analysis of the samples was conducted through a multi-technique approach. Powder X-ray diffraction (XRD) was performed using a Shimadzu LabX 6100 diffractometer equipped with Cu–Kα radiation (wavelength: 1.5418 Å). This method allowed for a detailed examination of the crystalline structure and identification of phases present in the synthesized samples. For investigating the optical properties, Ultraviolet Diffused Reflectance Spectroscopy (UV-DRS) was employed. The characteristic reflectance spectrum, arising from the interaction of light with the synthesized sample, was measured using a Cary100 UV–visible spectrophotometer, providing valuable insights into the material's absorbance and bandgap features. Fourier Transform Infrared Spectroscopy (FTIR) was employed to explore the chemical nature and identify various bonds and functional groups within the samples. This technique allowed for a detailed analysis of the molecular composition and surface chemistry of the synthesized nanoparticles. Additionally, Raman spectroscopy was employed to delve into the vibrational, rotational, and low-frequency modes of the samples. Serving as a structural fingerprint, Raman analysis was carried out using the DV420-OE model from Japan, operating at a frequency of 1,470 Hz and identified by serial number 13969. This technique provided crucial information for the identification of molecules and further characterization of the structural features of the synthesized nanoparticles. The integration of XRD, UV-DRS, FTIR, and Raman spectroscopy in this study allowed for a comprehensive understanding of the structural, optical, and chemical properties of the synthesized samples, facilitating a nuanced analysis of their composition and potential applications.

2.4 Preparation of soil sample for analysis

To check the nutrient status of soil, soil analysis was performed at the National Agriculture Research Centre, Islamabad, by using AB-DTPA. For this analysis sample was prepared by collecting, grinding, and sieving of soil. Two-thirds of the pots were filled with the prepared soil (organic matter in the form of animal dung and soil in a 1:1 ratio) without unnecessarily compressing the soil.

2.5 Experimental application of NPs on tomato plants

Seedlings were purchased from a nursery at the main campus of Allama Iqbal Open University, Islamabad at the age of 15 days after germination. Seedlings were shifted to the prepared pots. Different concentrations of molybdenum at the rate of 0, 1, and 3 and iron at 0, 1, and 3 and composite at 0, 1, and 3 ppm L^{-1} were applied in the form of ammonium heptamolybdate, iron chloride, and their combination (Table 1). Nanoparticles were applied to the soil and sprayed directly on the plants. Nanoparticles were applied at two stages of the plant's growth. After 2 days of reporting the seedlings when they became stable, the first application of nanoparticles took place. At this stage, seedlings were about 10–12 cm in height. The second application takes place 1 month after the first application

Table 1: Treatments summary of nanoparticles in soil and direct application to plants

Fe (Iron)		Molybdenum (Mo)		Fe (Iron) + Molybdenum (Mo)	
In soil	To plans	In soil	To plants	In soil	To plants
1%	1%	1%	1%	1%	1%
3%	3%	3%	3%	3%	3%

when plants just started budding. Two replicas of each combination were planted in the pot with a gap of 10 inches.

3 Results and discussion

3.1 Pre-experimental soil analysis

Soil analysis was performed before the experiment for physiochemical properties such as soil texture, soil pH, electrical conductivity, and organic matter (Table 2). Another analysis was conducted to check the amount of iron (Fe) and molybdenum (Mo) in the soil. This analysis was performed at the NPSL (National Physical and Standards Laboratory). The analysis was performed by the Atomic Absorption Spectrometer, Analyst 100, Perkin Elmer, USA.

The soil used for the experiment was pretested before sowing (Table 2). The results revealed that the soil textural class was silty clay loam with a percentage of clay at 30.4, silt at 51.6, and sand was 18. The organic content of the soil was 0.24 % with a pH of 8.3. In alkaline soils, molybdenum becomes more soluble and is accessible to plants mainly in its anion form as MoO^- the electrical conductance 0.40. The amount of nutrients like nitrogen (N) was 1.54 mg kg^{-1}, phosphorous (P) was 4.9754 mg kg^{-1}, and potassium (K) was 11.654 mg kg^{-1}.

3.2 Green synthesis of NPs

Guava leaf extract (GLE) was prepared in the distilled water. GLE was then added to the salt solution. There was a change in color from light brown to dark brown in the case of iron (Fe) and from colorless to black in the case of molybdenum.

$$3FeCl_3 + \textit{Psidium guajava}\ \text{leaf extract} \xrightarrow[\text{reduction}]{} \text{Fe nanoparticles} + 3Cl^- + 3H^+$$

Iron chloride is reduced to elemental iron (Fe) by the bioactivecomponents present in the *P. guajava* leaf extract. The aqueous leaf extract acts as a reducing agent, facilitating the formation of iron nanoparticles.

$$2(NH_4)_6Mo_7O_{24} + \textit{Psidium guajava}\ \text{leaf extract} \xrightarrow[\text{reduction}]{} \text{Mo nanoparticles} + 14NH_4^+ + 24H^+ + 42O^{2-}$$

ammonium hepta molybdate is reduced to elemental molybdenum (Mo) nanoparticles by the *P. guajava* leaf extract. The reduction process involves the transfer of electrons from the leaf extract to molybdenum ions, resulting in the formation of molybdenum nanoparticles.

3.3 Structural analysis of NPs

3.3.1 Fourier transform infrared spectroscopy (FTIR)

The absorption bands of samples M1 (iron sample), M2 (molybdenum sample), and M3 (combination sample of iron + molybdenum) were analyzed by FTIR within the wavelength range of 500–3,500 cm^{-1} as shown in Figure 1. The band at 1,579 cm^{-1} (C═O stretching) and 1,052 cm^{-1} (C–C bending) and the stretching vibrations below 700 cm^{-1} are ascribed to the stretching vibrations for FeO [26–28]. The observed differences in the baseline at 3,000 cm^{-1} and variations in the intensities of C–O and C═C bonds among Fe

Table 2: Soil analysis results from the National Physical and Standards Laboratory, Pakistan

Parameter	Unit	Value
N	mg kg^{-1}	1.54
P	mg kg^{-1}	4.97
K	mg kg^{-1}	116
Iron	%	1.22
Molybdenum	%	2.18
Organic matter	%	0.24
Clay	%	30.4
Silt	%	51.6
Sand	%	18
pH	—	8.3
Electric conductivity	dS m^{-1}	0.40
Class	—	Silty clay loam

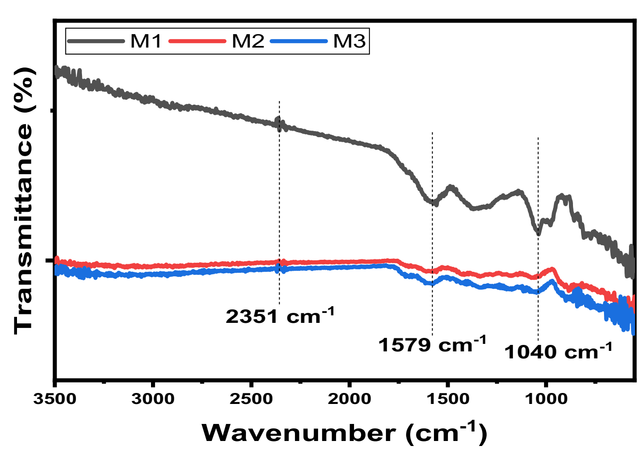

Figure 1: FTIR analysis of M1 (FeNPs), M2 (MoNPs), and M3 (Fe–MoNPs).

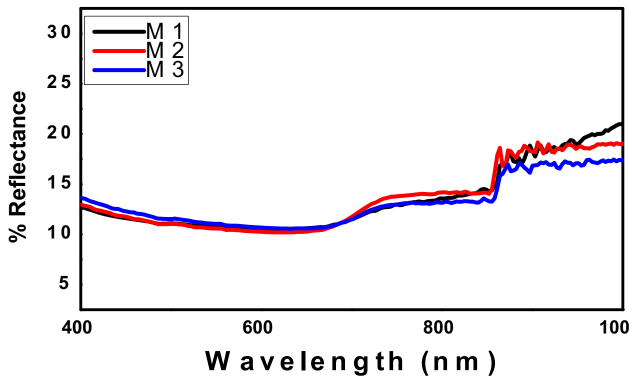

Figure 2: DRS Analysis of M1 (FeNPs), M2 (MoNPs) and M3 (Fe–MoNPs).

and Mo nanoparticles suggest potential disparities in the composition and surface functionalization of the nanoparticles. These variations may be influenced by differences in the reactivity of the plant extract in the green synthesis process.

3.3.2 UV–vis diffuse reflectance spectroscopy

The UV-DRS analysis of samples M1, M2, and M3 as shown in Figure 2 shows the reflectance of the samples in the visible-light range. Different intensity peaks with different colors represent the optical properties of the prepared material as depicted in Figure 2.

3.3.3 X-ray diffraction analysis

The structural analysis of samples M1, M2, and M3 were analyzed using powder XRD analysis, as shown in Figure 3.

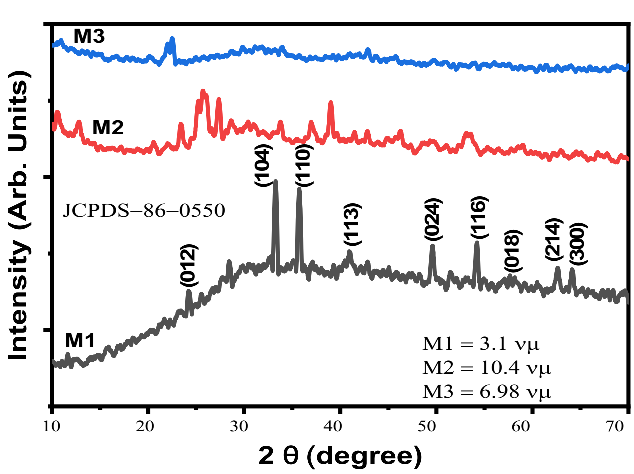

Figure 3: XRD Analysis of M1 (FeNPs), M2 (MoNPs), and M3 (Fe–MoNPs).

The formed cubic spinel peaks at 2θ values of 24.3°, 33.2°, 35.6°, 40.8°, 49.6°, 54.2°, 57.6°, 62.7°, and 64.1° are attributed to the (012), (104) (110), (113), (024), (116), and (018) (214) (300) reflection plane based on the JCPDS card no. 86-0550. The average crystallite sizes using all of the reflections of the samples, obtained by Derby Scherer's formula (equation (1)), were 3.1, 10.4, and 6.98 nm for samples M1, M2, and M3, respectively.

$$D_{hkl} = \frac{K\lambda}{\beta \cos\theta}, \quad (1)$$

where h, k, and l are the X-ray wavelength, K represents the Scherrer constant (0.98), λ denotes the wavelength (1.54), and β denotes the full width at half maximum (FWHM).

3.3.4 Raman analysis

Raman spectroscopy analysis is a special technique used for exploring the atomic structure of nanoparticles. The Raman spectroscopy spectra analysis is shown in Figure 4 where prepared samples with the Raman mode ~822, 938, 1,372, and 1,613 cm^{-1} wave number modes, respectively, showed the stretching vibration of Fe–O. The disparities in absorption peaks below 1,000 cm^{-1} between M3 and M1 Raman spectra, both involving Fe, could indicate a distinct chemical environment or coordination state for Fe in the composite M3. The presence of Mo might influence the intensity by modulating the vibrational properties or surface interactions, potentially enhancing the Raman signals for Fe-containing compounds. Further investigation is needed to elucidate the specific molecular interactions contributing to the observed differences in Raman spectra intensity between M1 and M3.

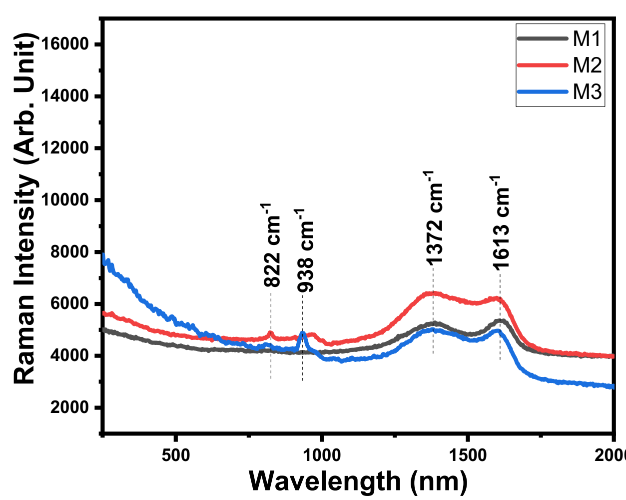

Figure 4: Raman analysis of M1 (FeNPs), M2 (MoNPs), and M3 (Fe–MoNPs).

Figure 5: Effect of NPs on *S. lycopersicum* growth in stages 1, 2, and 3, respectively.

3.4 Impact of nanoparticles on tomato plant growth

The impact of nanoparticle (NP) applications on tomato plant growth was evaluated at three stages (Figure 5) considering two application methods. Table 3 reflects the effects of NPs applied to soil, and Table 4 represents the direct application of NPs to plants.

3.4.1 NP Application to soil

3.4.1.1 Shoot length

The 3% Fe + Mo treatment at Stage 3 shows a significantly higher shoot length (32.5 cm) compared to other treatments, emphasizing the positive impact of the combined iron and molybdenum nanoparticles on vertical plant growth. Notably, the 1% Fe + Mo treatment exhibits an increased shoot length at all stages, indicating a growth-promoting effect.

3.4.1.2 Number of branches

At Stage 2 and Stage 3, the 1% Fe + Mo treatment exhibits the highest number of branches (79 and 90, respectively), highlighting the enhanced branching architecture induced by the combination of iron and molybdenum nanoparticles. The 3% Fe treatment also shows a notable increase in the number of branches at all stages.

3.4.1.3 Shoot diameter

In terms of shoot diameter, the 1% Fe + Mo treatment stands out at Stage 3 (1 cm), emphasizing the combined effect of iron and molybdenum nanoparticles on the overall plant structure. The 3% Fe treatment shows enhanced shoot diameter at all stages, further supporting the positive impact of iron nanoparticles on plant development.

3.4.2 NP Application directly to plants

3.4.2.1 Shoot length

The 3% Mo treatment demonstrates the highest shoot length at all stages, underscoring the positive influence of molybdenum nanoparticles on shoot elongation. The 1% Fe treatment also shows notable shoot length, suggesting a growth-promoting effect of Iron nanoparticles.

Table 3: Impacts on plant growth by NP application to soil

Treatment	Shoot length (cm)			No. of branches			Shoot diameter (cm)		
	Stage 1	Stage 2	Stage 3	Stage 1	Stage 2	Stage 3	Stage 1	Stage 2	Stage 3
1% Fe	26	61	67.3	5.33	10.6	16	0.36	0.46	0.8
3% Fe	26	50	54	3.7	9	9	0.4	0.45	0.55
1% Mo	19.3	52.3	63	3.6	8.3	5.6	0.36	0.43	0.4
3% Mo	16.5	16	23.5	4	7	7.5	0.4	0.5	0.5
1% (Fe + Mo)	24.5	79	90	3.6	11	22	0.4	0.6	1
3% (Fe + Mo)	32.5	70.6	79.3	6	11	19.3	0.43	0.6	0.93
Control	27	44.5	58.5	6	8.5	12	0.4	0.5	0.7

Table 4: Impacts on plant growth by NP application directly to plants

Treatment	Shoot length (cm)			No. of branches			Shoot diameter (cm)		
	Stage 1	Stage 2	Stage 3	Stage 1	Stage 2	Stage 3	Stage 1	Stage 2	Stage 3
1% Fe	22.3	24.5	56.3	4.6	12.3	16	0.36	0.43	0.6
3% Fe	13.6	41	42	4	9	10.5	0.3	0.45	0.55
1% Mo	16.5	26	28	3.6	9	6.5	0.35	0.45	0.55
3% Mo	34	60.5	71.5	5	12	15.5	0.3	0.55	1.1
1% (Fe + Mo)	22.6	47.6	49	5.3	9	11.6	0.4	0.5	0.6
3% (Fe + Mo)	23.6	55	62.6	5.3	8.6	9.3	0.43	0.5	1
Control	27	44.5	58.5	6	8.5	12	0.4	0.5	0.7

3.4.2.2 Number of branches

The 3% Fe treatment leads to the highest number of branches at all stages, indicating a branching stimulatory effect of Iron nanoparticles on tomato plants.

3.4.2.3 Shoot diameter

At Stage 3, the 3% Mo treatment exhibits the highest shoot diameter (1.1 cm), emphasizing the positive impact of molybdenum nanoparticles on the overall plant structure. The 1% Fe + Mo treatment also shows increased shoot diameter, supporting the notion of a synergistic effect of combined iron and molybdenum nanoparticles.

The combined application of Iron and Molybdenum nanoparticles appears to have a synergistic effect on various growth parameters, including shoot length, number of branches, and shoot diameter. Iron nanoparticles, when applied alone, also demonstrate positive effects on plant growth, especially in terms of branching architecture. Molybdenum nanoparticles exhibit a distinct influence on shoot length and diameter when applied directly to plants, suggesting a specific role in enhancing vertical growth and structural development. The results indicate that the application of Iron and Molybdenum nanoparticles, both individually and in combination, can positively influence tomato plant growth. The observed effects on shoot length, branching, and shoot diameter suggest the potential use of these nanoparticles as growth-promoting agents in agricultural practices. Further investigations into the underlying mechanisms and long-term impacts are warranted for a comprehensive understanding of their applicability in sustainable agriculture.

3.5 Post-experimental nutrient analysis soil

Analysis was carried out after the experiment was completed. The parameters included for analysis were potassium (K), phosphorus (P), and nitrogen (N). The amount of nutrients present in the soil samples to which NPs were applied to soil is discussed below. The highest amounts of potassium and phosphorus were 500 and 12.80 mg kg^{-1}, respectively, present in treatment no. 3 (1% Mo) and 5 (1% Fe + Mo) while nitrogen (N) was 2.35 mg kg^{-1} in control (Tables 5 and 6). Comparing Tables 5–7, the plants grown with a 1% Mo–Fe composite showed the most vital growth

Table 5: Post-experimental nutrient analysis of soil (NP treatments applied to soil)

Treatments to soil	Amount of potassium (mg kg^{-1})	Amount of phosphorous (mg kg^{-1})	Amount of nitrogen as NO_3-N (mg kg^{-1})
1% Fe	468	7.00	1.05
3% Fe	400	7.30	1.19
1% Mo	500	6.30	1.12
3% Mo	442	5.90	1.77
1% (Fe + Mo)	360	12.80	0.77
3% (Fe + Mo)	346	8.00	2.12
Control	386	5.90	2.35

Table 6: Post-experimental nutrient analysis of soil (NP treatments applied to plants)

Treatment to plants	Amount of potassium (mg kg^{-1})	Amount of phosphorous (mg kg^{-1})	Amount of nitrogen as NO_3-N (mg kg^{-1})
1% Fe	512	5.00	1.51
3% Fe	438	10.00	1.91
1% Mo	378	7.00	1.70
3% Mo	380	9.10	1.13
1% (Fe + Mo)	414	9.53	1.27
3% (Fe + Mo)	498	8.75	1.60
Control	386	5.90	2.35

Table 7: Impacts on plant growth by NP application to soil

S. No.	Treatment	Shoot length (cm)			No. of Branches			Shoot diameter (cm)		
		Stage 1	Stage 2	Stage 3	Stage 1	Stage 2	Stage 3	Stage 1	Stage 2	Stage 3
1.	1% Fe	26	61	67.3	5.33	10.6	16	0.36	0.46	0.8
2.	3% Fe	26	50	54	3.7	9	9	0.4	0.45	0.55
3.	1% Mo	19.3	52.3	63	3.6	8.3	5.6	0.36	0.43	0.4
4.	*3% Mo*	*16.5*	*16*	*23.5*	*4*	*7*	*7.5*	*0.4*	*0.5*	*0.5*
5.	1% (Fe + Mo)	24.5	79	90	3.6	11	22	0.4	0.6	1
6.	3% (Fe + Mo)	32.5	70.6	79.3	6	11	19.3	0.43	0.6	0.93
7.	**Control**	**27**	**44.5**	**58.5**	**6**	**8.5**	**12**	**0.4**	**0.5**	**0.7**

The use of italic signifies emphasis on a specific treatment showing best values, while bold for "Control" highlights it as reference group.

for all selected growth parameters. With the same composite treatment, maximum uptake of plant nutrients was also observed. However, suppressed phosphorus uptake was visibly noticed.

In the treatment where NPs were directly sprayed onto the plant specimens, results varied. For direct leas application, 3% Mo treatment showed the most promising results. Minimum soil potassium and low nitrogen concentrations indicate improved uptake of plant nutrients when compared to control and other experimental concentrations. Phosphorus uptake has, however, reduced when compared to the control treatment. Comparing Tables 6–8, the plants grown with a 3% Mo showed the most vital growth for all selected growth parameters.

Our results support previous studies indicating that the application of metal nanoparticles can positively influence plant growth parameters [29–31]. The observed increase in shoot length, number of branches, and shoot diameter, particularly with the 3% (Fe + Mo) treatment, is consistent with reports in the literature on the growth-promoting effects of certain nanoparticles on various plant species. The variations in soil nutrient content and plant nutrient uptake align with studies emphasizing the role of nanoparticles in influencing soil fertility. Specifically, the elevated phosphorous levels in the 1% (Fe + Mo) treatment corroborate findings that suggest nanoparticles can enhance nutrient availability and uptake in plants, leading to improved growth. Our study adds to the growing evidence supporting the synergistic effects of combined nanoparticle treatments. The 3% (Fe + Mo) treatment consistently outperformed individual Fe and Mo treatments in promoting plant growth. This finding aligns with the literature, suggesting that combining different nanoparticles can have additive or synergistic effects on plant responses. The superior phosphorous uptake efficiency observed in the 1% (Fe + Mo) treatment corresponds with reports emphasizing the importance of specific nanoparticle formulations in enhancing nutrient uptake. This aligns with the notion that the type and concentration of nanoparticles play a critical role in influencing nutrient availability to plants. The control group serves as a valuable reference for assessing the impact of nanoparticle treatments. Our results indicate that while the control group maintains stable nutrient levels, nanoparticle treatments lead to discernible changes in soil and plant nutrient composition.

The results indicated positive effects of iron and molybdenum nanoparticles on various parameters, including shoot length, number of branches, and shoot diameter. The combined application of iron and molybdenum nanoparticles showed a synergistic effect in enhancing growth parameters compared to individual treatments. Notably, the 3% (Fe + Mo)

Table 8: Impacts on plant growth by NP application directly to plants

S. No.	Treatment	Shoot length (cm)			No. of branches			Shoot diameter (cm)		
		Stage 1	Stage 2	Stage 3	Stage 1	Stage 2	Stage 3	Stage 1	Stage 2	Stage 3
1.	1% Fe	22.3	24.5	56.3	4.6	12.3	16	0.36	0.43	0.6
2.	3% Fe	13.6	41	42	4	9	10.5	0.3	0.45	0.55
3.	1% Mo	16.5	26	28	3.6	9	6.5	0.35	0.45	0.55
4.	*3% Mo*	*34*	*60.5*	*71.5*	*5*	*12*	*15.5*	*0.3*	*0.55*	*1.1*
5.	1% (Fe + Mo)	22.6	47.6	49	5.3	9	11.6	0.4	0.5	0.6
6.	3% (Fe + Mo)	23.6	55	62.6	5.3	8.6	9.3	0.43	0.5	1
7.	**Control**	**27**	**44.5**	**58.5**	**6**	**8.5**	**12**	**0.4**	**0.5**	**0.7**

The use of italic signifies emphasis on a specific treatment showing best values, while bold for "Control" highlights it as reference group.

treatment exhibited superior performance in promoting tomato plant growth. Post-experimental nutrient analysis of soil highlighted changes in potassium, phosphorus, and nitrogen content, further supporting the influence of nanoparticle treatments on soil fertility. Comparing the results from direct soil application and direct plant application, variations in nutrient uptake and growth parameters were observed. The 3% Mo treatment showed promising results for direct plant application, emphasizing the importance of the application method in nanoparticle-plant interactions. The findings aligned with previous studies emphasizing the potential of metal nanoparticles in influencing plant growth and soil fertility. However, the study also recognized the complexity of nanoparticle-plant interactions, calling for further research into the underlying mechanisms.

The current study highlights the complexity of nanoparticle-plant interactions, suggesting the need for further investigation into the underlying mechanisms. Our results contribute to the ongoing discourse on the potential benefits and challenges associated with nanoparticle applications in agriculture. Our findings provide valuable insights into the effects of iron and molybdenum nanoparticles on tomato plants and soil nutrient dynamics. The observed trends align with existing literature, emphasizing the need for tailored nanoparticle formulations and comprehensive studies to harness the full potential of nanotechnology in sustainable agriculture. Future research should delve into the molecular and physiological mechanisms underlying these effects for a more nuanced understanding and practical application in agricultural practices.

4 Conclusions

This study has shown promising insights into the use of green-synthesized Fe and Mo nanoparticles for enhancing the growth and nitrogen uptake of tomato plants. The eco-friendly approach employing guava leaf extract showed successful nanoparticle synthesis establishing a sustainable pathway for agricultural nanotechnology. The nuanced effects observed in plant growth parameters during the experimental application of NPs emphasize the need for meticulous consideration of NP types and application methods. Notably, the 1% composite NPs applied to the soil and 3% molybdenum directly on plants emerged as a standout combination showing superior outcomes. Looking ahead, this research opens avenues for future exploration and refinement. Further investigations could explore optimizing NP concentrations, additional green synthesis methods, and assessing the long-term impact of NP applications on soil health. Understanding the underlying mechanisms of how these NPs interact with plant physiology and soil dynamics could provide a deeper comprehension of their agricultural implications. Moreover, the study prompts the exploration of diverse plant species to evaluate the generalizability of the observed effects. Assessing the influence of environmental variables and diverse soil compositions on NP efficacy is crucial for tailoring these approaches to different agricultural contexts. This study provides a foundation for the ongoing dialogue on the sustainable application of nanotechnology in agriculture. As we move forward, a comprehensive understanding of the ecological, economic, and societal implications of nanoparticle use will be imperative for harnessing the full potential of nanotechnology in shaping the future of agriculture.

Acknowledgments: The authors extend their appreciation to the Researchers Supporting Project No. RSP2024R247, King Saud University, Saudi Arabia.

Funding information: This work was supported by the Researchers Supporting Project No. RSP2024R247, King Saud University, Saudi Arabia.

Author contributions: Conceptualization, H. F.,S.O.A.; data curation, M.H.,A.K.; formal analysis, H.Q.,S.A.R.,A.A.A.K.; funding acquisition, S.A.R.,A.A.A.M.A.M.,M.S.E.; investigation, M.H.; methodology, T.A.; project administration, A.M.A.M.,M.S.E.; resources, S.A.R.A.M.A.M.,M.S.E.; software, S.O.A.,I.A.; supervision, H.F.,T.A.; validation, H.Q.,I.A.; visualization, T.A.; writing – original draft, H.F., M.H.; writing – review & editing, T.A.,H.Q.S.A.R.,A.A.

Conflict of interest: The authors declare no conflict of interest.

Ethical approval: The conducted research is not related to either human or animal use.

Data availability statement: All data generated or analyzed during this study are included in this published article.

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