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Assessing the Impact of Nano Chelates on Enhancing Physiological, Biochemical and Yield Characteristics in Pulses and Oilseeds: A Comprehensive Review

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ABSTRACT

Pulses and oilseeds are essential elements of global nutrition and agriculture; however, micronutrient deficiencies and environmental stresses frequently limit their productivity. Conventional nutrient delivery methods often do not effectively provide crucial micronutrients such as iron, zinc, manganese and copper, particularly in difficult soil conditions. Nanotechnology, especially nano chelates, presents a promising solution by improving nutrient solubility, stability and bioavailability, which in turn enhances plant growth and resilience. This review compiles recent advancements in the application of nano chelates for pulses and oilseeds, emphasizing their beneficial effects on germination, vegetative growth parameters, physiological traits and biochemical processes. Nano chelates significantly boost the synthesis of chlorophyll a and b, increase soluble protein content, enhance antioxidant enzyme activities (SOD, CAT, POD) and promote proline accumulation, all of which contribute to improved photosynthesis, stress tolerance and yield. Despite positive experimental findings that show increased biomass, canopy development and nutrient use efficiency in crops such as chickpea, mung bean, soybean, mustard and groundnut, challenges persist regarding field-scale implementation and long-term environmental interactions.

Key words: Foliar nutrition, Legumes, Nano chelates, Oilseed.

Pulses and oilseeds play a crucial role in global diets and agricultural sustainability, providing both nutrition and economic stability for millions of farmers. Protein-rich legumes, such as chickpea (*Cicer arietinum*), mung bean (*Vigna radiata*) and pigeon pea (*Cajanus cajan*), deliver essential amino acids and dietary fiber. In contrast, crops like soybean (*Glycine max*), mustard (*Brassica juncea*) and groundnut (*Arachis hypogaea*) serve as key sources of edible oils and healthy fats (Lithourgidis *et al*., 2011; Martin-Guay *et al*., 2018; Nassary *et al*., 2020). Nevertheless, in numerous farming systems, yields are significantly below potential levels, primarily due to nutrient imbalances in the soil, decreasing fertility and stress caused by unfavorable environmental conditions (Krishnasree *et al*., 2022). Micronutrients especially iron (Fe), zinc (Zn), manganese (Mn) and copper (Cu) are indispensable for processes like chlorophyll synthesis, enzymatic regulation and reproductive development in plants (Kanwal *et al*., 2020; Krishnasree *et al*., 2022). Unfortunately, conventional fertilizer and foliar formulations often fail to deliver these nutrients effectively, particularly in alkaline or degraded soils, leading to reduced uptake efficiency and significant nutrient losses through leaching (López-Valdez *et al*., 2018). This inefficiency has accelerated interest in advanced nutrient delivery technologies capable of improving availability and absorption (Ma *et al*., 2018).

Agriculture has benefited from new opportunities brought about by nanotechnology, which manipulates materials at scales ranging from 1 to 100 nanometers

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(Monica and Cremonini, 2009; Kah *et al*., 2018). The creation of nano chelates-micronutrients attached to nanoparticles-is one exciting advancement. These particles have improved stability, increased solubility and the capacity to move nutrients across plant tissues more effectively (Kah *et al*., 2018; López-Valdez *et al*., 2018). Nano chelates have been demonstrated to enhance improved vegetative growth, maintain stronger physiological activity and raise yield potential in a range of crops by enhancing nutrient mobility (Marzouk *et al*., 2019).

Recent experimental evidence indicates that the application of targeted nano chelates can enhance productivity in both pulses and oilseeds. For example, foliar sprays that include nano-Fe and nano-Zn have been shown to improve seed composition, photosynthetic rates and vegetative growth in chickpeas and soybeans (Kanwal *et al*., 2020; Marzouk *et al*., 2019). Mung beans treated with nano-chelated iron exhibited increased biomass, a larger leaf area index and superior grain yield compared to traditional treatments (Kanwal *et al*., 2020). In mustard, the use of nano-ZnO resulted in higher oil yield and increased chlorophyll content (Marzouk *et al*., 2019), whereas in groundnuts, nano-micronutrient complexes enhanced drought resilience and oil concentration (Kah *et al*., 2018). The application of multi-element nano chelates across various pulse and oilseed crops has also been associated with concurrent improvements in protein content, oil yield and resistance to abiotic stresses (Kah *et al*., 2018).

Despite the promising findings, the adoption of these technologies at the field scale remains limited. Significant uncertainties persist concerning the long-term interactions of nano chelates with soil ecosystems, their longevity and their cumulative impacts on the health and quality of crops (Kah *et al*., 2018; Ma *et al*., 2018). This review consolidates recent research to evaluate the effects of nano chelates on growth performance, physiological functions, biochemical alterations and yield results in pulses and oilseeds. Furthermore, the discussion highlights essential research gaps that must be addressed to promote sustainable nutrient management strategies and mechanism of nano chelates is given in Fig 1.

Growth parameters influenced by nanochelates

Nano chelates enhance solubility, mobility and the regulated distribution of essential micronutrients because of their chelated nutritional content and incredibly small particle size. In both oilseeds (like soybean, mustard and peanut) and pulses (like chickpea, mung bean, lentil and black gram), this increased nutritional efficiency leads to notable gains in germination, vegetative growth and branching. Nano-formulations perform better than conventional fertilizers in promoting early seedling establishment, enhancing canopy growth and raising biomass production, laying a strong basis for higher yield potential (Abdelmonem, 2020).

Days to germination and emergence

Priming seeds or applying nano-Zn, nano-Fe and multi-nutrient nano chelates at the early growth stage accelerates germination and ensures more uniform seedling establishment in pulses and oilseeds. In trials with mung bean and mustard, Abdelmonem (2020) noted that nano-Zn priming reduced sprouting time by two to three days compared with conventional $ZnSO_4$. Mallikarjuna (2021) showed that treating chickpea and soybean seeds with nano chelates enhanced amylase activity, which sped up starch breakdown, encouraged faster root and shoot emergence and improved seed vigour index values. Similarly, Rajput *et al*. (2022) recorded a 15-18% improvement in germination rate in lentil after nano-Fe application, while Jadhav *et al*. (2023) observed comparable gains in groundnut and black gram through the use of multi-micronutrient nano chelates. Li *et al*. (2018) also reported that nanoscale nutrient delivery promoted stronger and more synchronized seedling emergence under varying field conditions.

Plant height

The enhanced absorption of micronutrients from nano-Zn and nano-Fe results in improved stem elongation, increased shoot biomass and a taller plant canopy. In their

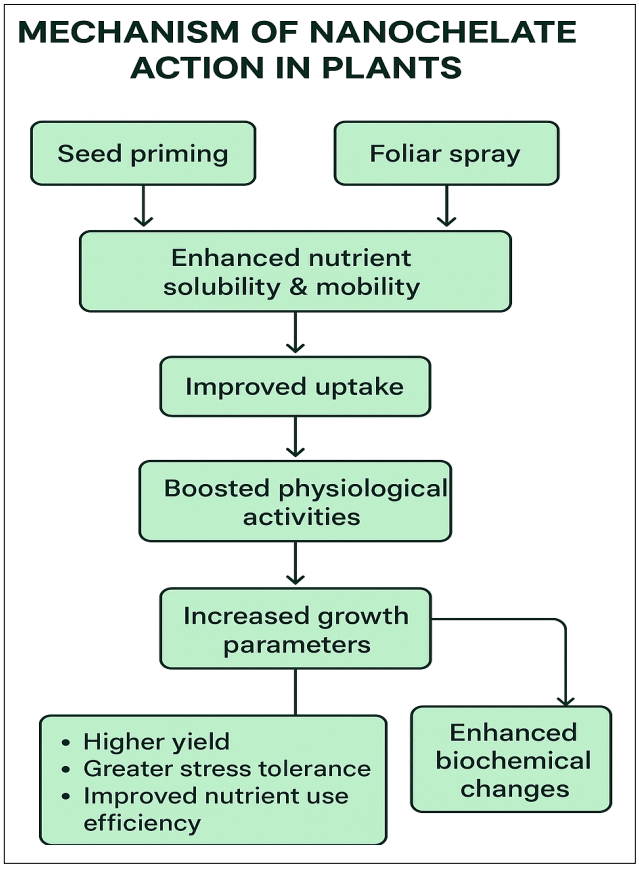


Fig 1: Mechanism of nano chelate action in plants.

research, Li *et al*. (2018) observed height increases of 20-25% in chickpea and soybean following the application of nano-Zn, while Abdelmonem (2020) reported comparable results in mustard when foliar nano-Zn was applied during the vegetative growth phase. Meng *et al*. (2018) indicated that nano-Fe promoted stem growth in lentil by stimulating both cell division and elongation in the shoot meristems. Jashni and Aynehband (2017) discovered that mung bean and groundnut plants treated with nano chelates not only exhibited increased height but also developed stronger stems, which contributed to enhanced stress tolerance. Rajput *et al*. (2022) associated this response with the activation of auxin and gibberellin pathways, which are known to regulate stem elongation and canopy structure. Additional research on groundnut and canola supports the notion that nano-calcium and foliar micronutrients further improve growth and yield under adverse soil and drought conditions (Kalantar Ahmadi and Shoushi Dezfouli, 2019; Liu *et al*., 2022).

Root length

Nano chelated micronutrients encourage deeper and more branched root systems, increasing the plant's capacity to access water and nutrients. Meng *et al*. (2018) observed a 28% improvement in root length in lentil and groundnut after nano-Fe treatment, attributing it to heightened meristematic activity and lateral root initiation. Kalantar Ahmadi and Shoushi Dezfouli (2019) reported that multi-micronutrient nano chelates in mung bean and mustard enhanced root surface area, improving moisture utilization under limited rainfall. Abdelmonem (2020) found that foliar nano-Zn in chickpea indirectly boosted root growth by improving photosynthetic efficiency and carbohydrate transfer to roots. Mallikarjuna (2021) recorded denser fine root formation in soybean, while Tang *et al*. (1997) noted that pigeon pea treated with nano chelates developed a more fibrous and exploratory root network, supporting stronger plant establishment. Additionally, foliar applications of Zn and Fe micronutrients have been shown to improve root quality and nutrient uptake in rapeseed and canola (Jashni *et al*., 2017; Kalantar Ahmadi and Shoushi Dezfouli, 2019). Wheat treated with NPK foliar sprays also showed improved root traits under water stress (Jadhav *et al*., 2023).

Number of branches

Supplying nano-boron, nano-Zn, or mixed micronutrient nanochelates stimulates lateral branching, which increases the number of reproductive nodes and potential yield sites. In chickpea and pigeon pea, Liu *et al*. (2022) recorded branch numbers 15-20% higher than in conventionally treated plants. Jadhav *et al*. (2023) found similar effects in mustard and groundnut, where greater branching boosted pod and siliqua counts. Abdelmonem (2020) observed that mung bean under nano-Zn treatment formed more pod-bearing branches, enhancing productivity. Rajput *et al*. (2022) reported that nano-Fe in lentil improved carbohydrate flow to developing shoots, while Mallikarjuna (2021) linked increased branching in soybean to better micronutrient translocation and higher cytokinin activity, which promotes axillary bud growth.

Leaf number and leaf area

Application of nano-Zn, nano-Fe, or blended micronutrient nano chelates promotes the production of more leaves and larger leaf blades, increasing light capture and photosynthetic performance. In soybean and black gram, Mallikarjuna (2021) documented significant rises in leaf area index after nano-Zn foliar feeding, supported by higher chlorophyll content and sustained leaf hydration. Abdelmonem (2020) found that groundnut and chickpea treated with nano chelates had 25-30% more leaves, reflecting greater nutrient availability and activation of photosynthetic enzymes. According to Rajput *et al*. (2022), lentil leaves under nano-Fe treatments were thicker and retained activity for a longer duration. Liu *et al*. (2022) noted that mustard plants receiving nano chelates developed broader blades with improved stomatal function, also observed a denser canopy in pigeon pea, translating into higher assimilate production for later reproductive growth also mentioned it in Table 1 and there is a uptake mechanism of nanochelates on plants in Fig 2.

Physiological changes influenced by nano chelates

Nano chelates act as efficient carriers of micronutrients, enhancing their solubility, mobility and bioavailability within the plant system (Poudel *et al*., 2023). The nanoscale size facilitates rapid root uptake and effective translocation through the vascular network, while the chelated form prevents micronutrient fixation in the soil, ensuring sustained delivery even under challenging pH or moisture conditions (Cui *et al*., 2020; Teng *et al*., 2018). This steady nutrient access improves metabolic capacity, bolsters chlorophyll synthesis and supports canopy expansion, thereby strengthening source-sink dynamics and boosting physiological efficiency in pulses and oilseeds (Ponniya *et al*., 2015).

Leaf area (LA)

Leaf area directly determines the photosynthetic surface available for light capture and carbon assimilation.

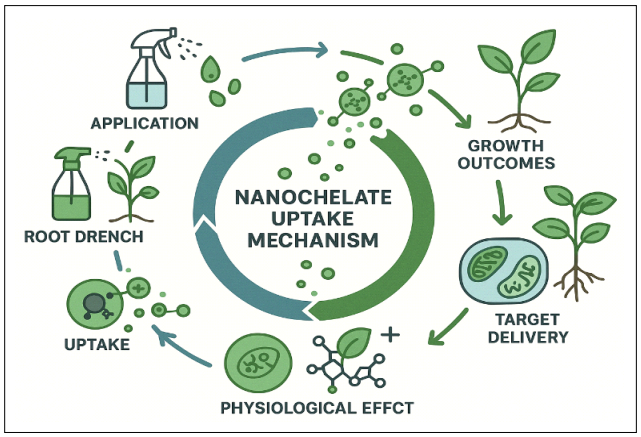


Fig 2: Uptake mechanism of nano chelate on plants.

Application of nanochelated micronutrients such as nano-Zn and nano-Fe has been found to stimulate cell division and expansion in developing leaves (Pandey *et al*., 2006; Fatollahpour *et al*., 2020). These nanoscale formulations provide targeted nutrient delivery to meristematic tissues, ensuring optimal chlorophyll biosynthesis and enhanced metabolic activity (Phan *et al*., 2019). In pulses, foliar nano-Zn application increased LA by over 20%, contributing to improved canopy coverage and greater light interception during the critical vegetative stage (Ashrafuzzaman *et al*., 2000). Larger leaf area also reduces soil evaporation by shading and helps maintain better leaf water status under mild drought conditions (Teng *et al*., 2018).

Leaf area index (LAI)

Leaf area index represents the total leaf surface area per unit ground area, serving as an important indicator of canopy density and light-harvesting potential. Nano chelated micronutrients, particularly nano-Fe and nano-Zn, have been shown to significantly increase LAI by promoting rapid canopy development and delaying leaf senescence (Phan *et al*., 2019; Poudel *et al*., 2023). A higher LAI enhances the interception of photosynthetically active radiation (PAR), leading to improved biomass production efficiency (Dimkpa and Bindraban, 2018). In lentil, zinc supplementation is critical for reproductive success and pollen viability, which indirectly supports sustained canopy health (Pandey *et al*., 2006). In groundnut and lentil, nano-Zn foliar sprays maintained elevated LAI values well into the reproductive phase (Ashrafuzzaman *et al*., 2000).

Crop growth rate (CGR)

Crop growth rate quantifies the increase in plant dry matter per unit area over time. Nanochelates, through improved micronutrient delivery and enhanced physiological activity, significantly raise CGR during both vegetative and reproductive phases (Rajput *et al*., 2022). Their nanoscale properties allow faster nutrient absorption and rapid mobilization to actively growing tissues (Phan *et al*., 2019). In cereals and legumes, foliar nano-fertilizer applications improved canopy photosynthetic rates and biomass conversion efficiency, resulting in higher CGR compared to conventional sources (Ashrafuzzaman *et al*., 2000).

Net assimilation rate (NAR)

Net Assimilation Rate measures the efficiency of converting intercepted light into dry matter per unit leaf area. Nanochelates enhance NAR by increasing chlorophyll density, improving Rubisco activity and maintaining higher stomatal conductance (Fatollahpour *et al*., 2020; Poudel *et al*., 2023). By preventing nutrient precipitation in the soil, nanochelated formulations ensure the continuous availability of essential micronutrients such as Fe and Zn (Cui *et al*., 2020). In chickpea and mung bean, application of nano-Zn increased photosynthetic efficiency and CO, fixation rates, thereby boosting NAR values during pod development (Ashrafuzzaman *et al*., 2000).

Table 1: Effect of nanochelates on growth parameters.

Growth parameter	Crop examples	Nanochelate used	Effect observed	Reference
Days to germination	Mung bean, mustard	Nano-Zn, Nano-Fe	Reduced germination time by 2-3 days; improved seed vigor	Abdelmonem (2020); Mallikarjuna (2021)
Plant height	Chickpea, soybean, mustard	Nano-Zn, Nano-Fe	Increased height by 20-25%; sturdier stems	Liu *et al*. (2022); Jashni, Fateh and Aynehband (2017)
Root length	Lentil, groundnut	Nano-Fe, Multi-nutrient	28% increase in root length; denser root network	Meng *et al*. (2018); Kalantar Ahmadi and Shoushi Dezfouli (2025)
Leaf number and leaf area	Soybean, chickpea, black gram	Nano-Zn, Nano-Fe	25-30% more leaves; larger leaf area; higher chlorophyll content	Mallikarjuna (2021); Abdelmonem (2020)
Number of branches	Chickpea, pigeon pea, mustard	Nano-B, Nano-Zn	15-20% increase in branching; more pod sites	Liu *et al*. (2022); Jadhav *et al*. (2023)

Relative growth rate (RGR)

Relative Growth Rate represents the rate of biomass increase relative to the existing biomass. Nano chelates contribute to higher RGR by improving nutrient uptake kinetics and enabling faster metabolic responses to environmental conditions (Phan *et al*., 2019). The nanoscale delivery system allows for rapid translocation of micronutrients, ensuring that both newly formed and mature tissues receive adequate nutrition (Teng *et al*., 2018). In pulses and small millets, foliar application of nano-Fe, nano-Zn and nano-P sustained higher RGR values by promoting vigorous leaf expansion, greater root proliferation and efficient photosynthate distribution (Pandey and Gupta, 2012; Rajput *et al*., 2022).

Dry matter accumulation (DMA)

Effective conversion of absorbed nutrients and intercepted light into plant biomass is a central determinant of crop productivity. Nano chelates, particularly those containing nano-Zn and nano-Fe, significantly enhance this process by improving nutrient uptake efficiency (Ashrafuzzaman *et al*., 2000), accelerating chlorophyll biosynthesis and activating key enzymes involved in the Calvin cycle (Teng *et al*., 2018). Their nanoscale size facilitates faster nutrient transport from roots to metabolically active tissues (Phan *et al*., 2019), while the chelated form maintains nutrient stability in the rhizosphere, preventing losses through precipitation or fixation (Cui *et al*., 2020). Sustained micronutrient supply has been shown to maintain optimal stomatal conductance and enhance carbohydrate synthesis (Teng *et al*., 2018), which in turn promotes sturdy stem formation, denser foliage and deeper root systems. Pandey and Gupta (2012) observed significant yield improvements in black gram with foliar Zn during reproductive stages, linking it to enhanced biomass accumulation and impact of nanochelates on physiological parameters are mentioned in Table 2.

Table 2: Impact of nano chelates on physiological parameters.

Physiological parameter	Nanochelate type	Effect on crop	Reference
Dry matter accumulation (DMA)	Nano-Zn, Nano-Fe	Up to 32% increase in biomass; improved stem and root growth	Teng *et al*., 2018; Phan *et al*., 2019; Cui *et al*., 2020; Panhamza and Gupta, 2012
Leaf area (LA)	Nano-Zn, Nano-Fe	>20% increase in leaf area; enhanced canopy coverage and drought tolerance	Pandey *et al*., 2006; Fatollahpour Grangah *et al*., 2020; Phan *et al*., 2019; Teng *et al*., 2018
Leaf area index (LAI)	Nano-Fe, Nano-Zn	Maintained higher LAI into reproductive phase; delayed senescence	Phan *et al*., 2019; Poudel *et al*., 2023; Dimkpa and Bindraban, 2018; Pandey *et al*., 2006;
Crop growth rate (CGR)	Nano-Zn	Increased CGR during vegetative and reproductive phases	Rajput *et al*., 2022; Phan *et al*., 2019;
Net assimilation rate (NAR)	Nano-Zn, Nano-Fe	Improved photosynthetic efficiency and CO_2 fixation	Fatollahpour Grangah *et al*., 2020; Poudel *et al*., 2023; Cui *et al*., 2020;
Relative growth rate (RGR)	Nano-Fe, Nano-Zn, Nano-P	Sustained higher RGR; better stress recovery; improved photosynthate distribution	Phan *et al*., 2019; Teng *et al*., 2018; Pandey and Gupta, 2012; Rajput *et al*., 2022

Biochemical changes influenced by nano chelates

Beyond promoting structural growth, nano chelates induce important biochemical modifications that directly support plant health and productivity. These enhancements include improved pigment synthesis for photosynthesis (Ancua and Sonia, 2020), increased protein content for metabolic and structural functions (Arrutia *et al*., 2020), heightened antioxidant enzyme activity for stress mitigation (Avelar *et al*., 2021) and the accumulation of osmolytes like proline for osmotic adjustment (Assatory *et al*., 2019). Such biochemical adjustments maintain metabolic homeostasis under varying environmental conditions and contribute to higher crop resilience and yield potential (Gerliani *et al*., 2020).

Chlorophyll content (Chl a, Chl b, Total)

Chlorophyll biosynthesis depends heavily on micronutrients such as Fe, Zn and Mn, which act as cofactors in pigment-forming pathways. Nano chelates

efficiently deliver these essential elements to chloroplasts, ensuring their incorporation into chlorophyll molecules and electron transport proteins.

Chlorophyll a

Nanochelate applications have been shown to significantly enhance chlorophyll a content, which is critical for the primary light-absorbing reactions of photosynthesis. For instance, Aradhana *et al*. (2022) demonstrated that foliar application of nano-Fe in soybean increased chlorophyll a content by approximately 35%, improving the plant's capacity for photochemical energy conversion. Similarly, Gharibzahedi and Smith (2020) reported that nano-Mn treatments in maize raised chlorophyll a level by 28%, correlating with improved photosynthetic efficiency and biomass accumulation.

Chlorophyll b

Chlorophyll b acts as an accessory pigment, broadening the spectrum of light absorption and transferring energy to chlorophyll a. Jiang *et al*. (2022) observed that nano-Zn application in mustard plants increased chlorophyll b content by around 22%, contributing to delayed leaf senescence and prolonged photosynthetic activity. Additionally, Kahraman *et al*. (2018) found that nano-Fe chelates enhanced chlorophyll b levels in groundnut by 30%, supporting stronger light harvesting during the later growth stages. The combined increase in chlorophyll a and b content results in deeper green foliage, stronger canopy photosynthesis and greater carbohydrate production, which ultimately supports higher crop yields.

Soluble protein content

Proteins form the structural matrix of plant cells and act as catalysts for nearly all metabolic reactions. The application of nano chelated micronutrients, especially nano-Zn, enhances amino acid synthesis and protein assembly by stimulating key enzymes such as RNA polymerase and carbonic anhydrase. Lian *et al*. (2020) reported that nano-Zn treatments increased soluble protein content in leaves by over 25%, indicating improved nitrogen assimilation efficiency. Likewise, Malik *et al*. (2024) found that nano-Fe supplementation in lentil enhanced seed protein levels without compromising oil content, suggesting more effective nutrient partitioning. Additional studies also support these findings, such as Ochoa-Meza *et al*. (2019) and Rani and Badwaik (2021), who documented increases in soluble protein content across various pulse and oilseed crops with nano chelate treatments. These biochemical gains improve plant vigor, optimize metabolic performance and contribute to the enhanced nutritional quality of harvested grains and oilseeds.

Proline accumulation

Proline plays a central role in osmotic regulation, protecting macromolecules and membranes under dehydration stress. Application of nano chelates, particularly nano-Zn and nano-B, has been shown to stimulate proline biosynthesis pathways, enabling plants to retain more cellular water during drought episodes. Malik *et al*. (2024) reported that nano-Zn application in mung bean increased leaf proline content by 27%, which improved membrane stability and enzymatic activity under low moisture conditions. Similarly, Rani and Badwaik (2021) observed that lentil plants treated with nano-B maintained higher proline accumulation during flowering and pod filling, aiding faster recovery after stress alleviation. Additional recent studies by Ochoa-Meza *et al*. (2019); Gerliani *et al*. (2020) and Ancua and Sonia (2020) also confirmed elevated proline levels following nanochelate treatment, supporting improved drought tolerance in pulses and oilseeds.

Antioxidant enzymes (SOD, CAT, POD)

Abiotic stresses such as drought, salinity and heat elevate reactive oxygen species (ROS) production, which can impair membrane integrity, enzyme function and DNA stability. Nano chelates strengthen the plant's antioxidative defense by increasing the activity of key enzymes like superoxide dismutase (SOD), catalase (CAT) and peroxidase (POD). Lian *et al*. (2020) demonstrated that nano-Zn and nano-Fe applications in groundnut under mild drought stress boosted SOD and CAT activities by 18-30%, reducing lipid peroxidation damage. Malik *et al*. (2024) further confirmed that such treatments in mung bean maintained high POD activity throughout the reproductive phase, enabling plants to cope with oxidative stress more effectively. Supporting these findings, Ochoa-Meza *et al*. (2019), Rani and Badwaik (2021) and Gharibzahedi and Smith (2020) reported enhanced antioxidant enzyme activity following nanochelate application across diverse crops and stress conditions.Impact of Nanochelates on biochemical Parameters of Oil Seeds and Pulses are given in Table 3. This biochemical resilience helps safeguard photosynthetic machinery and metabolic pathways during critical yield-determining periods. And the

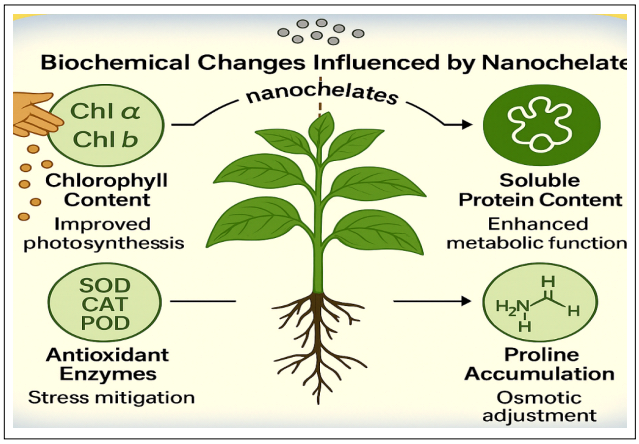


Fig 3: Biochemical changes influenced by nanochelates.

biochemical changes influenced by nano chelates are mentioned in Fig 3.

Effect of nano chelates on yield and yield attributes

Nano chelates are nano-sized formulations of essential micronutrients such as Fe, Zn, Mn, B and Cu, bound with chelating agents to enhance solubility and plant availability. Their very small particle size and chemical stability allow faster absorption, reduced nutrient losses and sustained delivery during key growth stages. These advantages translate into notable yield benefits, driven by several interconnected physiological and biochemical mechanisms.

Improving flowering and seed development

Micronutrients of boron and zinc play critical roles in pollen development, fertilization efficiency and seed formation. Nano chelated forms ensure these nutrients are supplied at the correct growth stage, increasing the number of pods or seeds per plant. In mustard, combined applications of nano-B and nano-Zn improved pollen viability, raised siliqua count and increased 1000-seed weight, giving yield improvements of around 25% (Rai *et al*., 2012). Comparable yield gains have been reported in legumes and oilseeds, with better pod set and heavier seeds under nano chelate treatment (Tarafdar *et al*., 2014).

Enhancing nutrient uptake and movement in plants

Due to size of nanoscale dimensions, these chelated particles can pass through leaf stomata or cuticle layers, enabling direct nutrient entry into plant tissues. This minimizes nutrient immobilization in soil and reduces leaching losses, keeping nutrients available when plants need them most. In chickpea, nano-Zn foliar treatments raised seed zinc concentration and yield by about 20% over conventional $ZnSO_4$ (Mahmoud *et al*., 2020). Early nano fertilizer research demonstrated that these formulations overcome many inefficiencies of standard fertilizers by delivering nutrients in a controlled, targeted manner (Prasad *et al*., 2012).

Boosting photosynthetic performance

Applications of nano-chelated micronutrients often result in higher concentrations of chlorophyll pigments and greater activity of photosynthesis-related enzymes. This improves light harvesting and carbon fixation capacity. In Pigeonpea, foliar sprays of nano-Fe and nano-Zn increased photosynthetic rates by roughly 18-25%, which led to more panicles per plant and better grain filling (Rameshaiah *et al*., 2015). Similar trends have been documented in wheat, where nano-Zn raised chlorophyll index values, total biomass and final yield (Zulfiqar *et al*., 2019). The resulting increase in assimilate production supports more robust reproductive growth.

Strengthening stress resilience for consistent yields

Nano chelates can improve tolerance to environmental stresses by increasing the activity of antioxidant enzymes such as superoxide dismutase (SOD), catalase (CAT) and peroxidase (POD), as well as boosting osmolyte levels like proline. These effects help plants maintain photosynthesis

Table 3: Impact of nanochelates on biochemical parameters of oil seeds and pulses.

Biochemical parameter	Nanochelate type	Effect observed	Crop examples	Reference
Chlorophyll a content	Nano-Fe, Nano-Mn	↑ by 28-35%	Soybean, maize	Aradhana *et al*., 2022; Gharibzahedi and Smith, 2020
Chlorophyll b content	Nano-Zn, Nano-Fe	↑ by 22-30%; delayed senescence	Mustard	Jiang *et al*., 2022; Kahraman *et al*., 2018
Soluble protein content	Nano-Zn, Nano-Fe	↑ by 25% or more	Chickpea, lentil, mustard	Lian *et al*., 2020; Malik *et al*., 2024; singh *et al*., 2019; Rani and Badwaik, 2021
Antioxidant enzymes (SOD, CAT, POD)	Nano-Zn, Nano-Fe	↑ enzyme activity by 18-30%; improved stress tolerance	Groundnut, mung bean	Lian *et al*., 2020; Malik *et al*., 2024; Ochoa *et al*., 2019; Rani and Badwaik, 2021; Gharibzahedi and Smith, 2020
Proline accumulation	Nano-Zn, Nano-B	↑ by 27%; better drought resilience	Mung bean, lentil	Ochoa *et al*., 2019; Rani and Badwaik, 2021; Gerliani *et al*., 2020; Ancua and Sonia, 2020

and growth under adverse conditions like drought, salinity, or extreme temperatures. For example, nano-B in lentils under water-limited conditions enhanced antioxidant protection and increased yield by roughly 15% (Hasanuzzaman *et al*., 2018). Likewise, nano-Zn applications in wheat preserved chlorophyll, relative water content and photosynthetic activity under saline stress (Dimkpa *et al*., 2019).

Nano chelates represent a significant advancement in micronutrient delivery technology for pulses and oilseeds, leveraging their ultra-small particle size and chelated structure to enhance nutrient solubility, mobility and controlled release. This improved efficiency is reflected in multiple growth parameters, including faster germination, increased plant height, enhanced root development and greater leaf expansion, all of which collectively contribute to a stronger vegetative foundation for improved crop performance.

Physiologically, nano chelates enhance vital processes such as dry matter accumulation, leaf area development and overall growth rates by facilitating more efficient nutrient uptake and translocation within the plant system. This promotes robust photosynthetic activity and metabolic efficiency, supporting greater biomass production and canopy expansion. The nanoscale delivery also supports sustained nutrient availability during critical growth phases, which is essential for maintaining high physiological efficiency even under environmental stresses.

On the biochemical level, nano chelates stimulate key metabolic pathways, leading to increased chlorophyll content, higher soluble protein levels and elevated activity of antioxidant enzymes. These changes improve photosynthetic capacity and enhance the plant's defense against oxidative stress, thus strengthening resilience to abiotic challenges such as drought and salinity. Additionally, the accumulation of osmolytes of proline contributes to osmotic adjustment, further supporting stress tolerance.

The combined effects of enhanced growth, improved physiological function and biochemical resilience translate directly into measurable yield benefits. Nano chelates boost photosynthetic efficiency and nutrient use, strengthen stress tolerance mechanisms and optimize reproductive development by improving flowering and seed set. This integrated approach results in higher seed quality, greater pod numbers and improved overall productivity compared to conventional fertilizer treatments.

CONCLUSION

Nano chelates provide a promising strategy for optimizing micronutrient delivery in pulses and oilseeds, addressing critical limitations of traditional fertilization methods. Their unique properties enable more effective nutrient uptake, sustained availability and targeted action within plants, which collectively enhance growth, physiological performance and biochemical stability. By improving stress resilience and reproductive success, nano chelates contribute to consistent and increased crop yields. Adoption of nano chelate-based fertilization can therefore play a vital role in sustainable agricultural intensification, helping to meet the rising food demands while minimizing nutrient losses and environmental impacts.

By addressing significant drawbacks of conventional fertilization techniques, nano-chelates provide a promising strategy for enhancing micronutrient delivery in pulses and oilseeds. Their unique physicochemical properties, such as small particle size, high surface area and controlled release capabilities, allow for more efficient nutrient uptake, prolonged availability and targeted action within plant tissues. This precision in nutrient delivery not only boosts vegetative growth but also optimizes physiological processes, including photosynthesis, enzyme activity and hormonal balance, thereby improving overall plant vigor.

Nano-chelates also positively influence biochemical pathways by enhancing antioxidant enzyme activity, stabilizing cellular membranes and reducing oxidative stress under adverse environmental conditions. Moreover, they play a pivotal role in reproductive development by improving flowering, pod setting and seed filling, which collectively lead to higher and more consistent yields. Their ability to mitigate abiotic stresses such as drought, salinity and heavy metal toxicity further strengthens plant resilience, ensuring stable productivity under challenging growth conditions.

Additionally, the use of nano-chelates can minimize nutrient losses through leaching or volatilization, thereby reducing fertilizer input requirements and associated environmental contamination. They support soil health by maintaining a balanced micronutrient status and promoting beneficial microbial activity. Integrating nano-chelates into crop management systems aligns with the principles of precision agriculture and sustainable intensification, helping to meet the rising global food demand while conserving natural resources and reducing the ecological footprint of farming practices.

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Disclaimer

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Conflict of interest

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