

## Concentration-Dependent Responses of Linseed to Moringa-Mediated Iron Oxide Nanopriming under Early-Season Drought

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### ABSTRACT

Green-synthesised iron oxide nanoparticles (IONPs) may provide a low-input seed treatment for improving crop establishment under water limitation, but their effects are frequently dose-dependent. This pot experiment evaluated Moringa oleifera-mediated IONP seed priming in linseed (*Linum usitatissimum* L.) under well-watered and early-season drought conditions. The IONPs were examined by Fourier-transform infrared spectroscopy and vibrating-sample magnetometry. Seeds were untreated, hydroprimed, or primed for 12 h with 50, 100, or 150 ppm IONPs. Treatments were arranged as a 5 x 2 factorial completely randomised design with three replicates. Water regimes were maintained at 75% or 35% field capacity through 50 days after sowing. Drought delayed emergence and reduced chlorophyll index, plant height, tiller number, grain yield, and biological yield. Under drought, 100 and 150 ppm shortened time to 50% emergence by about 18% relative to untreated seed, while 100 ppm produced the highest emergence index (1.02) and final emergence (80%). However, these early benefits did not improve productivity. Hydropriming produced the highest grain yield under both water regimes (0.41 and 0.32 g pot<sup>-1</sup>), whereas 150 ppm produced the lowest grain and biological yield under drought (0.23 and 1.36 g pot<sup>-1</sup>). Green IONP nanopriming therefore improved early establishment at an

intermediate dose but did not recover yield. Dose optimisation, complete particle characterisation, and field validation are required before agronomic recommendation.

**Keywords:** Drought Stress; Flax; Green Synthesis; Iron Oxide Nanoparticles; Nanopriming; Seed Emergence; Water Relations

## Introduction

Linseed (*Linum usitatissimum* L.), also known as oilseed flax, is a multipurpose crop valued for edible and industrial oil, alpha-linolenic acid, lignans, protein, and dietary fibre. Its comparatively short growth cycle and diverse end uses make it relevant to temperate and semi-arid farming systems, where crop choice must balance nutritional value, economic return, and adaptation to variable rainfall. Despite this potential, linseed establishment and productivity are sensitive to water limitation, particularly when drought coincides with germination, early vegetative development, flowering, or seed filling. Water deficit restricts cell expansion, stomatal conductance, carbon assimilation, nutrient transport, and reproductive development, ultimately reducing biomass and seed yield (Basu *et al.*, 2016; Ozturk *et al.*, 2021; Zuk *et al.*, 2015).

Early-season drought is especially important because poor or uneven emergence limits the number of productive plants before the crop canopy is established. Restricted imbibition delays metabolic reactivation, while reduced soil-water availability can impair reserve mobilisation, radicle elongation, and seedling growth. As drought continues, stomatal closure lowers carbon dioxide uptake, chlorophyll function may decline, and oxidative pressure can increase through the excessive formation of reactive oxygen species. Plants may conserve water through osmotic adjustment and reduced leaf expansion, but these protective responses can also restrict tillering and biomass accumulation. Consequently, an intervention that improves emergence must be evaluated beyond the seedling stage to determine whether its early advantage persists through maturity and yield formation (Basu *et al.*, 2016; Ozturk *et al.*, 2021).

Seed priming is a practical pre-sowing strategy in which seeds are partially hydrated sufficiently to initiate pre-germinative metabolism without allowing radicle protrusion. Priming can accelerate and synchronise emergence because membrane repair, enzyme activation, reserve mobilisation, and antioxidant defence begin before sowing (Paparella *et al.*, 2015). Hydropriming is the simplest form and requires only water, whereas nutrient priming and nanopriming can additionally place small quantities of active materials close to the seed surface. However, treatment performance depends on crop species, seed lot, hydration period, solution concentration, drying procedure, and the severity of the subsequent stress. A valid assessment of an advanced priming treatment should therefore include hydropriming as a low-cost benchmark rather than comparing it only with untreated seed (Johnson and Puthur, 2021).

Nanopriming has attracted attention because nanoparticles possess a high surface-area-to-volume ratio and may interact with seed-coat pores and young tissues at relatively low application rates. Proposed mechanisms include improved water uptake, modification of aquaporin activity, stimulation of antioxidant systems, enhanced reserve mobilisation, and controlled micronutrient delivery near the embryo

(Khan *et al.*, 2019; Nile *et al.*, 2022). These responses are not uniformly beneficial. Particle composition, size, aggregation, surface coating, dissolution, concentration, and exposure route can shift a response from stimulation to membrane injury, redox imbalance, root inhibition, or nutrient disturbance (Aqeel *et al.*, 2022; Lv *et al.*, 2019; Wang *et al.*, 2023). Dose-response testing is therefore essential, because a concentration that accelerates emergence may not necessarily support later vegetative growth or reproductive productivity.

Iron is a suitable candidate for nutrient-based nanoprimering because it contributes to chlorophyll biosynthesis, photosynthetic electron transport, respiration, enzyme activity, and cellular redox regulation. Although many agricultural soils contain substantial total iron, plant-available forms can remain limited under alkaline conditions because ferric compounds are poorly soluble (Liang, 2022). Iron oxide nanoparticles may provide a concentrated local source during germination and early seedling development, when respiratory activity and enzyme systems are rapidly reactivated. Studies in wheat, sorghum, and flax have reported improvements in germination, physiological performance, or stress tolerance following iron-based nanoparticle treatments, but the magnitude and direction of response vary across crops, particle preparations, doses, and environmental conditions (Adrees *et al.*, 2020; Maswada *et al.*, 2018; Noor *et al.*, 2022; Waqas Mazhar *et al.*, 2022).

The present study therefore examined whether *M. oleifera*-mediated iron oxide nanoparticle (IONP) seed priming could improve linseed establishment, plant water status, growth, and yield under well-watered and early-season drought conditions. The objectives were to characterise the synthesised material, compare untreated seed and hydropriming with 50, 100, and 150 ppm IONP treatments, and determine whether changes in emergence were translated into improved performance at maturity. It was hypothesised that an intermediate IONP concentration would improve stand establishment and reduce drought-related yield loss, whereas the highest concentration would provide no additional benefit because nanoparticle responses are commonly concentration dependent.

Plant-mediated synthesis has been proposed as a way to reduce dependence on hazardous reducing and stabilising reagents. *Moringa oleifera* leaves contain phenolic compounds and other bioactive constituents that can support metal-ion reduction and surface capping during nanoparticle formation. This approach may improve the environmental compatibility of synthesis, but the term green describes the preparation route rather than guaranteeing biological safety or agronomic effectiveness at every dose. Green-synthesised nanoparticles still require physicochemical characterisation, comparison with simpler treatments, and assessment across the full crop cycle (Ijaz *et al.*, 2020; Mittal *et al.*, 2020; Sarraf *et al.*, 2022; Usman *et al.*, 2020).

## Materials and methods

### Experimental conditions and soil

The pot experiment was conducted during 2023-2024 in a wire-house at the Department of Agronomy, The Islamia University of Bahawalpur in Pakistan reported day and night temperatures of roughly  $25 \pm 3^{\circ}\text{C}$  and  $15 \pm 3^{\circ}\text{C}$ . Plastic pots contained 3.5 kg of air-dried, sieved soil. Twelve seeds were sown per pot and thinned to six plants after emergence. The soil was sandy loam, moderately alkaline, non-saline, and

low in organic matter and major nutrients (Table 1). The source analysis contained no numerical soil-iron value.

**Table 1. Physicochemical properties of the experimental soil.**

| Property                                | Value                   | Interpretation      |
|-----------------------------------------|-------------------------|---------------------|
| Texture                                 | Sandy loam              | -                   |
| Sand                                    | 54%                     | -                   |
| Silt                                    | 32%                     | -                   |
| Clay                                    | 14%                     | -                   |
| pH                                      | 8.42                    | Moderately alkaline |
| Electrical conductivity                 | 0.68 dS m <sup>-1</sup> | Non-saline          |
| Total nitrogen                          | 0.044%                  | Low                 |
| Available P <sub>2</sub> O <sub>5</sub> | 6 ppm                   | Low                 |
| Available K <sub>2</sub> O              | 149 ppm                 | Medium              |
| Organic matter                          | 0.46%                   | Low                 |

## IONP synthesis and characterisation

Fresh *M. oleifera* leaves were washed and extracted in water at 60 g L<sup>-1</sup> by heating at approximately 80 degrees C for 1 h. After filtration, 0.1 M iron(III) nitrate was added to the extract at a 1:2 volume ratio under continuous stirring. The green-to-black colour change indicated iron oxide formation. The mixture was dried at room temperature and then at approximately 50 degrees C. Functional groups and Fe-O bonding were examined by ATR-FTIR (500-4000 cm<sup>-1</sup>), and magnetic behaviour was measured by vibrating-sample magnetometry. Because X-ray diffraction, electron microscopy, hydrodynamic size, and zeta-potential data were unavailable, the product is conservatively described as IONPs without assigning a single crystalline phase.

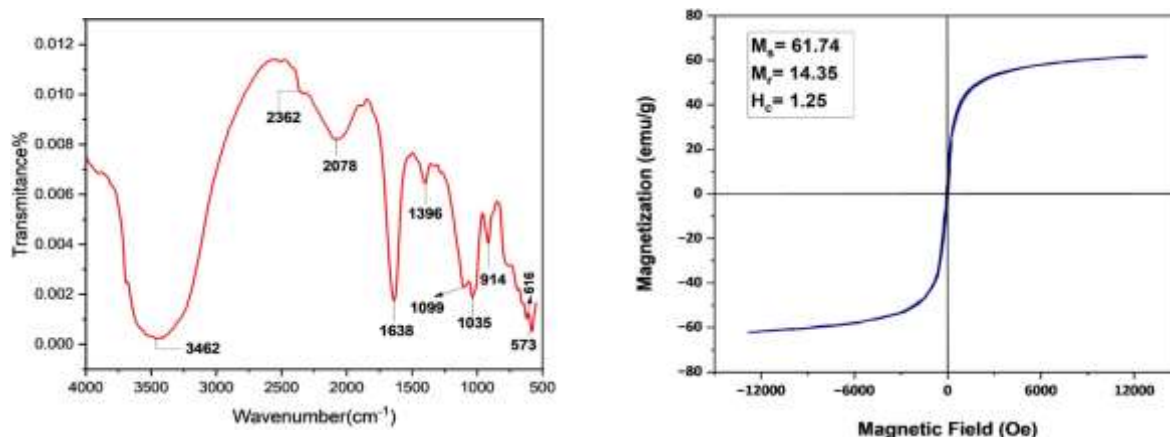


Figure 1. Characterisation of *M. oleifera*-mediated IONPs: (a) ATR-FTIR spectrum, including the Fe-O band near 573 cm<sup>-1</sup>; and (b) room-temperature magnetisation curve with saturation magnetisation of 61.74 emu g<sup>-1</sup>.

## Experimental design and water regimes

Five seed treatments were evaluated under two water regimes in a 5 x 2 factorial completely randomised design with three replicates (30 pots). Treatments were untreated dry seed, hydropriming, and 50, 100, or 150 ppm IONP priming. Seeds were immersed for 12 h at a 1:5 seed-to-solution ratio with aeration, rinsed, and shade-dried towards their original mass before sowing. Pots were maintained at 75% field capacity (well-watered) or 35% field capacity (drought) by alternate-day weighing and irrigation through 50 days after sowing. Plants were harvested at 120 days after sowing when about 75% of capsules were mature. All pots received 152 mg diammonium phosphate and 63 mg sulphate of potash.

## Measurements and statistical analysis

Emergence was counted daily. Final emergence was expressed as a percentage of seed sown; time to 50% emergence (T50) was estimated by linear interpolation; and emergence index was calculated as the sum of newly emerged seedlings divided by the corresponding day. At maturity, plant height, tiller number, grain yield, and above-ground biological yield were recorded. Relative water content (RWC) was calculated as  $[(\text{fresh mass} - \text{dry mass})/(\text{turgid mass} - \text{dry mass})] \times 100$ , chlorophyll index was measured with a CL-01 meter, and harvest index was calculated as  $\text{grain yield}/\text{biological yield} \times 100$ . Data were analysed by two-way ANOVA in Statistix 10.1, followed by Tukey HSD at  $p < 0.05$ . The source report retained categorical ANOVA probabilities and Tukey grouping letters but not exact F statistics, standard errors, or confidence intervals; therefore, the tables reproduce the original significance categories and mean-separation letters without recalculating unsupported precision.

## Results

### Nanoparticle characterisation and factorial effects

ATR-FTIR bands occurred near 3462, 2362, 2078, 1638, 1396, 1099, 1035, 914, 616, and 573  $\text{cm}^{-1}$  (Figure 1a). The broad 3462  $\text{cm}^{-1}$  band indicated surface hydroxyl groups, while the low-wavenumber band supported Fe-O bonding. The remaining bands were consistent with plant-derived surface functional groups. VSM confirmed a strong magnetic response and a saturation magnetisation of 61.74 emu  $\text{g}^{-1}$  (Figure 1b), supporting formation of a magnetically responsive iron oxide material.

Water regime significantly affected every trait except final emergence. Seed treatment affected all variables, and water regime x seed treatment interactions were significant for all traits except T50 and harvest index (Table 2). Thus, most priming responses depended on water availability.

**Table 2. Significance of water regime, seed treatment, and their interaction in the factorial ANOVA.**

| Variable        | Water regime | Seed treatment | Interaction |
|-----------------|--------------|----------------|-------------|
| T50             | ***          | ***            | ns          |
| Emergence index | ***          | ***            | ***         |
| Final emergence | ns           | ***            | ***         |

| Variable               | Water regime | Seed treatment | Interaction |
|------------------------|--------------|----------------|-------------|
| Relative water content | ***          | ***            | ***         |
| Chlorophyll index      | ***          | ***            | ***         |
| Plant height           | ***          | ***            | ***         |
| Tiller number          | ***          | ***            | ***         |
| Grain yield            | ***          | ***            | **          |
| Biological yield       | ***          | **             | **          |
| Harvest index          | ***          | **             | ns          |

\*\*\*  $p < 0.001$ ; \*\*  $p < 0.01$ ; \*  $p < 0.05$ ; ns, not significant. Probability categories are reproduced from the original factorial ANOVA.

## Stand establishment

Drought increased mean T50 from 9.26 to 10.36 days and reduced the emergence index from 0.86 to 0.73. The 100 and 150 ppm treatments produced the shortest T50 values in both regimes. Under drought, T50 was 9.05 and 9.00 days, respectively, compared with 11.00 days for untreated seed. The 100 ppm treatment also gave the highest emergence index under well-watered (1.01) and drought (1.02) conditions. Final emergence showed a treatment-by-water interaction: 100 ppm produced 80.00% under drought, whereas 50 ppm produced 55.33%. Hydropriming maintained 77.66% and 76.00% emergence under well-watered and drought conditions, respectively (Table 3).

**Table 3. Effects of seed priming and water regime on linseed stand establishment.**

| Treatment     | T50 WW                          | T50 D                          | EI WW              | EI D               | Emergence WW (%)    | Emergence D (%)     |
|---------------|---------------------------------|--------------------------------|--------------------|--------------------|---------------------|---------------------|
| Untreated     | 10.13 <sub>AB</sub>             | 11.00 <sub>A</sub>             | 0.62 <sub>C</sub>  | 0.66 <sub>C</sub>  | 61.33 <sup>D</sup>  | 77.00 <sup>AB</sup> |
| Hydropriming  | 9.83 <sup>A</sup> <sub>BC</sub> | 11.33 <sub>A</sub>             | 0.96 <sub>AB</sub> | 0.62 <sub>C</sub>  | 77.66 <sup>AB</sup> | 76.00 <sup>AB</sup> |
| 50 ppm IONPs  | 9.91 <sup>A</sup> <sub>BC</sub> | 11.46 <sub>A</sub>             | 0.86 <sub>B</sub>  | 0.46 <sub>D</sub>  | 81.00 <sup>A</sup>  | 55.33 <sup>D</sup>  |
| 100 ppm IONPs | 8.03 <sup>C</sup>               | 9.05 <sup>B</sup> <sub>C</sub> | 1.01 <sub>A</sub>  | 1.02 <sub>A</sub>  | 72.33 <sup>BC</sup> | 80.00 <sup>A</sup>  |
| 150 ppm IONPs | 8.40 <sup>B</sup> <sub>C</sub>  | 9.00 <sup>B</sup> <sub>C</sub> | 0.85 <sub>B</sub>  | 0.88 <sub>AB</sub> | 68.33 <sup>C</sup>  | 77.66 <sup>AB</sup> |
| Regime mean   | 9.26 <sup>B</sup>               | 10.36 <sub>A</sub>             | 0.86 <sub>A</sub>  | 0.73 <sub>B</sub>  | 72.13               | 73.33               |

WW, well-watered; D, drought; EI, emergence index; T50, time to 50% of final emergence; IONPs, iron oxide nanoparticles. Within each trait, means sharing at least

one lowercase letter are not significantly different at  $p < 0.05$  by Tukey HSD. Uppercase letters compare water-regime means; no letters are shown where the main effect was not significant. Values are means of three pots.

## Water status, chlorophyll, and growth

RWC and chlorophyll index showed significant interactions. Under drought, 50 and 100 ppm produced the highest recorded RWC (58.67% and 59.46%), compared with 46.35% for untreated seed. However, mean RWC was unexpectedly higher under drought than under well-watered conditions (53.93% versus 43.68%). Chlorophyll index declined from 0.33 to 0.10 with drought. The 150 ppm treatment produced the highest well-watered value (0.73), but hydropriming was numerically highest under drought (0.19).

Drought reduced mean plant height from 39.92 to 28.00 cm and tillers from 4.80 to 3.28 plant<sup>-1</sup>. Heights were similar among treatments when well-watered, but under drought the 100 ppm treatment produced the shortest plants (20.59 cm). Untreated plants retained 5.00 tillers under drought, whereas 100 and 150 ppm produced 2.39 and 2.11 tillers, respectively (Table 4).

**Table 4. Physiological and growth responses to seed priming under well-watered and drought conditions.**

| Treatment    | RWC<br>WW           | RWC<br>D            | Chl<br>W<br>W      | Chl<br>D           | Height<br>WW       | Height<br>D        | Tillers<br>WW     | Tillers<br>D       |
|--------------|---------------------|---------------------|--------------------|--------------------|--------------------|--------------------|-------------------|--------------------|
| Untreated    | 36.93 <sub>e</sub>  | 46.35 <sub>d</sub>  | 0.26 <sub>bc</sub> | 0.04 <sub>c</sub>  | 40.21 <sup>a</sup> | 32.05 <sup>b</sup> | 4.70 <sup>a</sup> | 5.00 <sup>a</sup>  |
| Hydropriming | 49.02 <sub>cd</sub> | 52.27 <sub>bc</sub> | 0.10 <sub>bc</sub> | 0.19 <sub>bc</sub> | 40.20 <sup>a</sup> | 30.20 <sup>b</sup> | 5.00 <sup>a</sup> | 3.89 <sup>ab</sup> |
| 50 ppm       | 37.44 <sub>e</sub>  | 58.67 <sub>a</sub>  | 0.24 <sub>bc</sub> | 0.06 <sub>c</sub>  | 40.83 <sup>a</sup> | 31.12 <sup>b</sup> | 4.78 <sup>a</sup> | 3.00 <sup>bc</sup> |
| 100 ppm      | 37.95 <sub>e</sub>  | 59.46 <sub>a</sub>  | 0.33 <sub>b</sub>  | 0.12 <sub>bc</sub> | 39.20 <sup>a</sup> | 20.59 <sup>b</sup> | 5.00 <sup>a</sup> | 2.39 <sup>c</sup>  |
| 150 ppm      | 57.04 <sub>ab</sub> | 52.89 <sub>bc</sub> | 0.73 <sub>a</sub>  | 0.11 <sub>bc</sub> | 39.20 <sup>a</sup> | 26.02 <sup>c</sup> | 4.55 <sup>a</sup> | 2.11 <sup>c</sup>  |
| Regime mean  | 43.68 <sub>B</sub>  | 53.93 <sub>A</sub>  | 0.33 <sub>A</sub>  | 0.10 <sub>B</sub>  | 39.92 <sup>A</sup> | 28.00 <sup>B</sup> | 4.80 <sup>A</sup> | 3.28 <sup>B</sup>  |

RWC, relative water content (%); Chl, relative chlorophyll index; height in cm; tillers per plant. Within each trait, means sharing at least one lowercase letter are not significantly different at  $p < 0.05$  by Tukey HSD; uppercase letters compare water-regime means. Lettering is reproduced from the original mean-comparison output. The counterintuitive RWC regime mean is retained from the source dataset.

## Yield and harvest index

Drought reduced grain yield from 0.33 to 0.27 g pot<sup>-1</sup> and biological yield from 2.76 to 1.56 g pot<sup>-1</sup>. Hydropriming produced the highest grain yield in both regimes (0.41

and 0.32 g pot<sup>-1</sup>). None of the IONP treatments exceeded the untreated control under drought; yields were 0.27, 0.24, and 0.23 g pot<sup>-1</sup> at 50, 100, and 150 ppm, respectively. The 100 ppm treatment produced the highest biological yield when well-watered (3.10 g pot<sup>-1</sup>), but this advantage disappeared under drought. The lowest drought biological yield occurred at 150 ppm (1.36 g pot<sup>-1</sup>). Harvest index was higher under drought because biological yield declined proportionally more than grain yield; hydropriming produced the highest values in both regimes (14.21% and 20.82%) (Table 5).

**Table 5. Grain yield, biological yield, and harvest index under the two water regimes.**

| Treatment     | Grain WW           | Grain D            | Biomass WW         | Biomass D         | HI WW (%)                        | HI D (%)                        |
|---------------|--------------------|--------------------|--------------------|-------------------|----------------------------------|---------------------------------|
| Untreated     | 0.30 <sup>b</sup>  | 0.27 <sup>cd</sup> | 2.63 <sup>b</sup>  | 1.73 <sup>c</sup> | 11.70 <sup>de</sup>              | 15.96 <sup>bc<sub>d</sub></sup> |
| Hydropriming  | 0.41 <sup>a</sup>  | 0.32 <sup>b</sup>  | 2.90 <sup>ab</sup> | 1.56 <sup>c</sup> | 14.21 <sup>bc<sub>de</sub></sup> | 20.82 <sup>a</sup>              |
| 50 ppm IONPs  | 0.32 <sup>b</sup>  | 0.27 <sup>cd</sup> | 2.60 <sup>b</sup>  | 1.63 <sup>c</sup> | 12.38 <sup>cd<sub>e</sub></sup>  | 16.95 <sup>ab</sup>             |
| 100 ppm IONPs | 0.32 <sup>b</sup>  | 0.24 <sup>de</sup> | 3.10 <sup>a</sup>  | 1.53 <sup>c</sup> | 10.47 <sup>e</sup>               | 16.13 <sup>bc</sup>             |
| 150 ppm IONPs | 0.30 <sup>bc</sup> | 0.23 <sup>e</sup>  | 2.56 <sup>b</sup>  | 1.36 <sup>c</sup> | 11.85 <sup>cd<sub>e</sub></sup>  | 17.36 <sup>ab</sup>             |
| Regime mean   | 0.33 <sup>A</sup>  | 0.27 <sup>B</sup>  | 2.76 <sup>A</sup>  | 1.56 <sup>B</sup> | 12.12 <sup>B</sup>               | 17.44 <sup>A</sup>              |

Grain and biomass values are g pot<sup>-1</sup>; HI, harvest index; WW, well-watered; D, drought. Within each trait, means sharing at least one lowercase letter are not significantly different at  $p < 0.05$  by Tukey HSD; uppercase letters compare water-regime means. Values are means of three pots.

## Discussion

### Emergence improved at an intermediate dose

The clearest IONP benefit occurred during establishment. The 100 ppm treatment shortened T50, increased emergence index in both regimes, and maintained 80% final emergence under drought. Controlled hydration can initiate membrane repair, enzyme activation, and reserve mobilisation before sowing (Paparella *et al.*, 2015), while nanoparticles may modify seed-coat transport and deliver iron near the embryo. Because iron supports respiratory and electron-transfer enzymes, a moderate local supply may accelerate early metabolism.

The poor drought response at 50 ppm and strong response at 100 ppm demonstrate a non-linear dose effect. Suspension stability, aggregation, seed-surface coverage, and the balance between hydration and metal exposure may have differed among concentrations. Comparable concentration dependence has been reported for metal-oxide seed treatments, with stimulation at selected doses and inconsistent or inhibitory

effects outside the optimum range (Aqeel *et al.*, 2022; Maswada *et al.*, 2018). The absence of particle-size and dispersion data prevents a firm mechanistic explanation. The 150 ppm treatment also shortened T50 but did not improve final emergence beyond the 100 ppm treatment, indicating diminishing returns at the upper concentration. This distinction is agronomically important because a treatment can accelerate the timing of emergence without increasing the number of established plants. For field use, both speed and stand density must be considered, particularly in drought-prone soils where rapid drying can expose late-emerging seedlings to greater mortality.

### **Physiological responses did not predict productivity**

Under drought, 50 and 100 ppm produced the highest recorded RWC, whereas hydropriming produced the highest chlorophyll index. Iron-containing nanoparticles have been associated with improved water relations, pigment maintenance, and antioxidant activity in stressed plants (Adrees *et al.*, 2020; Noor *et al.*, 2022). Nevertheless, the RWC pattern must be interpreted cautiously because its overall mean was higher under drought despite clear reductions in chlorophyll, height, biomass, and yield. This may reflect sampling time, leaf age, short-term rehydration, transcription error, or water conservation through restricted leaf expansion and transpiration rather than improved carbon gain.

The high chlorophyll index at 150 ppm under well-watered conditions disappeared under drought. Iron is essential for chlorophyll synthesis and photosynthetic electron transport, but excessive or poorly regulated iron may intensify reactive oxygen formation. The result is consistent with a narrow effective range in which improved iron availability is beneficial under favourable conditions but becomes neutral or harmful when drought restricts metabolism (Liang, 2022; Wang *et al.*, 2023).

The physiological measurements also highlight the need for complementary indicators. RWC is influenced by leaf age, sampling time, and the interval between detachment and weighing, while chlorophyll meter values describe relative greenness rather than carbon assimilation. Future experiments should therefore measure leaf water potential, stomatal conductance, photosynthetic rate, and transpiration at standardised times. Combining these measurements with tissue iron concentration would clarify whether the recorded responses arose from improved iron nutrition, osmotic adjustment, reduced leaf area, or measurement variability.

### **Faster emergence did not recover yield**

The main agronomic finding was the separation between early vigour and final performance. Hydropriming produced the greatest grain yield under both water regimes, whereas IONP treatments equalled or underperformed untreated seed under drought. At 100 and 150 ppm, faster emergence was accompanied by shorter plants and fewer tillers, indicating that seedling-stage gains were not sustained through reproductive development.

Several factors may explain this decoupling. The 35% field-capacity treatment imposed a strong early limitation, the alkaline and low-organic-matter soil may have altered particle dissolution and aggregation, and prolonged exposure to higher concentrations may have disturbed root growth or redox balance. Plant responses to

nanomaterials depend on particle chemistry, soil conditions, and exposure duration, and growth inhibition can occur above a species-specific optimum (Alidoust and Isoda, 2014; Lv *et al.*, 2019). The present yield response also contrasts with Waqas Mazhar *et al.* (2022), who reported improved flax performance after IONP priming. Differences in phase, size distribution, surface coating, genotype, priming protocol, drought timing, and soil medium could account for the discrepancy.

Hydropriming is therefore an essential benchmark. It activates pre-germinative metabolism without introducing a reactive material, is inexpensive, and is readily adoptable (Johnson and Puthur, 2021). In this experiment, the additional complexity of IONPs did not provide a yield advantage over water alone. Sustainability or cost-effectiveness claims for nanopriming should consequently be tested against hydropriming rather than only untreated seed.

The contrasting response reported by Waqas Mazhar *et al.* (2022) further shows that nominal concentration alone is not a transferable treatment descriptor. Two suspensions labelled 100 ppm may differ substantially in primary particle size, agglomeration, surface coating, dissolved iron fraction, and seed-contact area. Reporting these characteristics, together with soil pH, organic matter, and irrigation history, is necessary before results can be compared across laboratories or translated into a field recommendation.

## Conclusion

*Moringa oleifera*-mediated IONP priming altered linseed responses to early-season drought in a concentration-dependent manner. The 100 ppm treatment improved emergence speed and index, and 50-100 ppm increased recorded RWC under drought, but these benefits did not improve final productivity. Hydropriming produced the highest grain yield under both water regimes, while 150 ppm reduced grain and biological yield under drought. The results support further mechanistic study of 100 ppm for early establishment but do not justify a general yield recommendation. Until dose optimisation, complete particle characterisation, and field validation are achieved, hydropriming remains the more defensible low-cost treatment for yield-oriented use.

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