

Impact of Magnetic Nanoparticle-based Priming on Potato Seed Germination in Bangladesh

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ABSTRACT

Nanopriming, the pre-sowing treatment of seeds with engineered nanoparticles, has demonstrated promising superiority over conventional priming methods in enhancing germination, vigor, and stress resilience, with Fe₃O₄ magnetic nanoparticles (MNPs) emerging as particularly promising candidates owing to their remarkable advantages. Despite this potential, the effect of Fe₃O₄ MNPs on True Potato Seed (TPS) germination remains underexplored, even though poor TPS germination under conventional methods poses a direct threat to food security and farmer livelihoods in Bangladesh, where potato (*Solanum tuberosum* L.) is a strategically important crop. In this study, Fe₃O₄ MNPs were synthesized via chemical co-precipitation and characterized by X-ray Diffraction (XRD), Field Emission Scanning Electron Microscopy (FE-SEM), Energy Dispersive X-ray Spectroscopy (EDX), and Dynamic Light Scattering (DLS) with Zeta potential analysis to confirm phase purity, morphology, elemental composition, and colloidal stability. TPS of the Bari-1 variety were primed at 10, 40, and 70 mg/L for 8 h, and germination was monitored over 14 days under controlled laboratory conditions. Seeds treated at 40 mg/L achieved a peak germination rate of 85.15%, representing over 25% improvement compared to the hydroprimed control (64.99%), whereas the 70 mg/L treatment suppressed germination below control levels. These findings establish 40 mg/L as the optimal priming concentration and demonstrate the practical potential of Fe₃O₄ MNP nanopriming for enhancing TPS germination in Bangladesh.

Keywords: Nanopriming, Fe₃O₄ nanoparticles, True Potato Seeds (TPS), Seed germination, Sustainable agriculture, *Solanum tuberosum* L.

1. INTRODUCTION

Potato (*Solanum tuberosum* L.) ranks as the third most consumed crop globally, following rice and wheat. It constitutes a strategically important food source in Bangladesh. The nation stands among the world's leading potato producers, generating 9.87 million metric tons across 468.7 thousand hectares [1]. Seed germination represents the foundational stage of crop development. However, conventional priming methods, such as hydropriming and osmopriming, exhibit limited efficacy in improving germination performance. This limitation is particularly evident for inherently low-vigor seeds [2], [3]. These constraints have catalyzed a growing interest in advanced seed enhancement technologies. Consequently, nanotechnology has emerged as a promising frontier for achieving the rapid, vigorous, and uniform germination essential to modern agricultural productivity.

Seed nanopriming involves the pre-sowing treatment of seeds with engineered nanoparticles. It represents a scientifically credible and agriculturally practical advancement over conventional techniques. Nanoparticles possess exceptional physicochemical properties. These

properties enable deeper tissue interaction and more intense metabolic activation than standard aqueous priming solutions can achieve [3], [5]. Furthermore, nanopriming offers practical scalability through ultralow dosage requirements. It also reduces ecological risks because residuals can be removed via simple aqueous rinsing [3], [5]. Nanoparticles enter seed tissues through direct diffusion, active transport, or transmembrane protein channels. This entry initiates physiological cascades that enhance water uptake, activate antioxidant mechanisms, and accelerate starch hydrolysis. These combined processes accelerate the generation of energy required for seedling growth [5], [6].

The controlled elevation of reactive oxygen species (ROS) serves as a critical molecular signal during germination. Nanoprimed seeds exhibit enhanced antioxidant enzyme activity that aligns with the established "oxidative window" concept. This alignment leads to higher germination rates and hastened seedling development [6], [8]. Beyond the immediate germination phase, nanopriming promotes uniform seedling establishment and improves tolerance to abiotic stresses.

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It also modulates hormonal balance to effectively reset the metabolic clock of the seed. This positions nanoprimering as a transformative technology for agricultural systems where reliable crop establishment is a critical priority [3],[7]. A schematic illustration is presented in [Fig. 1] to visualize the expected germination outcomes as a function of priming treatment. This illustration was conceptualized based on findings reported in peer-reviewed literature. These studies collectively indicate that nanoprimering enhances seed germination kinetics, accelerates metabolic activation, and promotes robust seedling establishment relative to conventional hydropriming [5], [8]. The upper pathway depicts the hydroprimed condition, which is characterized by delayed germination and limited root development. Conversely, the lower pathway represents the nanoprimered condition, which exhibits enhanced germination rates and more vigorous seedling morphology. The scientific investigation of nanoprimering has yielded consistently encouraging results across diverse nanoparticle types and crop species. Metallic nanoparticles demonstrate clear advantages over conventional priming agents in enhancing germination performance and seedling vigor [3], [6]. Among these, silver and zinc oxide nanoparticles have been extensively studied. In fact, ZnO nanoparticles have become the most investigated priming agents globally across cereals and legumes [5]. In the Bangladeshi context, pioneering studies have established the efficacy of ZnO nanoprimering for local vegetable crops, reporting germination improvements of up to 61.7% under optimized conditions [3]. Recently, iron oxide magnetic nanoparticles (Fe_3O_4) have emerged as particularly promising agents. They offer unique magnetic properties, exceptional biocompatibility, and a superior capacity to regulate hormonal balance, antioxidant enzyme activity, and metabolic pathways [6], [8]. Studies on wheat, barley, and bean have demonstrated that

Fe_3O_4 nanoparticles enhance germination rates, increase amino acid and soluble sugar content, and reduce solute leakage. They also improve stress defense mechanisms while maintaining seed viability. These effects compare favorably to other metallic nanoparticles [7], [8]. However, the nature of these physiological responses is highly concentration-dependent. Low doses typically promote growth, whereas high doses induce inhibition. This variability necessitates precise dosage optimization for each specific crop system [6]. Despite the established promise of Fe_3O_4 magnetic nanoparticles in enhancing germination across various crops, their application to True Potato Seed (TPS) remains entirely unexplored. This gap in research is particularly consequential for Bangladesh, where potato production underpins national food security and rural livelihoods, yet conventional hydropriming offers only modest and inconsistent improvements in TPS germination performance. Research Significance and Novelty: This study addresses this fundamental deficiency by generating the first systematic experimental dataset on Fe_3O_4 magnetic nanoparticle priming of TPS. The research establishes precise, concentration-dependent response boundaries and identifies an evidence-based optimal dosage. By evaluating these nanomaterial interactions specifically within TPS for the first time, this work bridges a critical gap between advanced nanomaterial synthesis and practical agricultural applications. Ultimately, these insights advance both agricultural nanotechnology and sustainable crop establishment strategies for resource-constrained farming systems.

2. MATERIALS AND METHODS

2.1 Synthesis of Fe_3O_4 Magnetic Nanoparticles

2.1.1 Reagents and Materials

Magnetite nanoparticles were synthesized via a modified chemical co-precipitation method using analytical-grade reagents without further purification. Ferric chloride hexahydrate ($\text{FeCl}_3 \cdot 6\text{H}_2\text{O}$), ferrous sulfate heptahydrate ($\text{FeSO}_4 \cdot 7\text{H}_2\text{O}$), and ammonium hydroxide solution (NH_4OH , 25% w/v) were procured from Labtex Bangladesh. Deionized water (DI water, resistivity $\geq 18.2 \text{ M}\Omega \cdot \text{cm}$) and absolute ethanol ($\text{C}_2\text{H}_5\text{OH}$) served as solvents throughout the synthesis and washing steps. Photographic representation of the analytical-grade chemical precursors employed in the synthesis of Fe_3O_4 magnetic nanoparticles are shown in Fig. 2 (a)-(c).



Fig.1: Experimental workflow comparing traditional hydropriming and Fe_3O_4 nanoparticle-mediated priming protocols for TPS.

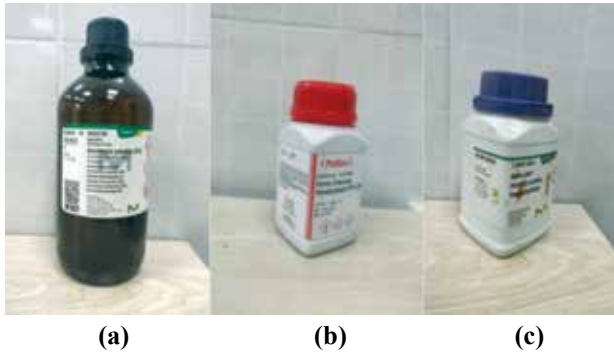


Fig. 2: Photographic representation of the chemical precursors used in the co-precipitation synthesis of Fe_3O_4 magnetic nanoparticles (a) 25% ammonium hydroxide (NH_4OH), (b) Ferric chloride hexahydrate ($\text{FeCl}_3 \cdot 6\text{H}_2\text{O}$), (c) Ferrous sulfate heptahydrate ($\text{FeSO}_4 \cdot 7\text{H}_2\text{O}$).

2.1.2 Synthesis Procedure

Magnetite (Fe_3O_4) nanoparticles were synthesized utilizing a modified chemical co-precipitation technique. A stoichiometric precursor solution was prepared by dissolving 6.1 g of ferric chloride hexahydrate ($\text{FeCl}_3 \cdot 6\text{H}_2\text{O}$) and 4.2 g of ferrous sulfate heptahydrate ($\text{FeSO}_4 \cdot 7\text{H}_2\text{O}$) in 100 mL of deionized water. This solution was heated to 90°C under continuous mechanical stirring. Upon reaching the target temperature, 10 mL of 25% ammonium hydroxide (NH_4OH) was rapidly introduced to the reaction vessel to induce precipitation.

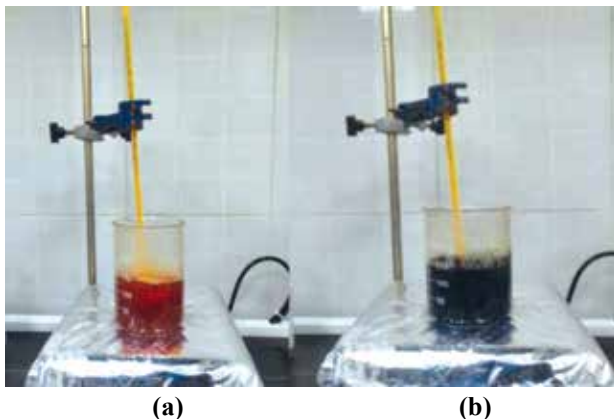


Fig. 3: Visual representation of the co-precipitation reaction (a) before and (b) after alkaline induction.

The mixture was maintained at 90°C for 30 minutes to facilitate crystal growth and phase maturation. Following this duration, the suspension was allowed to cool to ambient temperature. The resulting black precipitate was isolated via vacuum filtration and washed repeatedly with deionized water to eliminate residual ionic impurities, yielding purified Fe_3O_4 nanostructures.



Fig. 4: Dried powder form of the synthesized Fe_3O_4 magnetic nanoparticles obtained after vacuum filtration and oven drying.

The nanoparticles were subsequently washed three times with deionized water and then dried in an oven for 72 hours. After complete drying, the nanoparticle powder was collected.

2.1.3 Seed Selection

True potato seeds (TPS) of *Solanum tuberosum* cultivar BARI-1 were obtained from the Tuber Crops Research Centre (TCRC), Gazipur, Bangladesh. Prior to use, seeds were visually inspected and only morphologically uniform, intact seeds were retained for the experiment. TPS was selected as the experimental material owing to its agronomic relevance as a cost-effective and disease-free propagation pathway for smallholder potato production in Bangladesh.



Fig. 5: True potato seeds (TPS) of *Solanum tuberosum* L. cultivar BARI-1 used as the experimental seed material.

2.2 Preparing of Priming Solution and Seed Priming

The synthesized MNPs, were utilized for seed priming at varying concentrations (10, 40 and 70 mg/L). Fresh priming solutions were prepared by dispersing the respective nanoparticles in deionized water using ultrasonic vibration (100 W, 40 kHz) for 30 minutes. Healthy, uniform-sized *Solanum tuberosum* (TPS) seeds were selected and thoroughly washed under running

tap water to ensure cleanliness. Prior to priming, seeds were surface-cleaned under running tap water and gently blotted dry with sterile tissue paper to remove surface moisture. Cleaned seeds were subsequently immersed in the respective MNP suspensions for 8 hours at room temperature. A hydroprimed control group, consisting of seeds soaked in deionized water under identical conditions, was included in all experimental runs. Following priming, seeds were removed from solution, blotted dry, and immediately transferred to germination assay conditions.

2.3 Germination Assay

Germination tests were carried out on primed and hydroprimed seeds in triplicate. Briefly, sterile filter paper (Whatman No. 1) was placed in sterile glass Petri dishes and moistened with 5 mL of deionized water. Thirty seeds were evenly placed in each dish, then covered with lids and sealed with Parafilm to prevent moisture loss. The dishes were incubated in the dark with a recorded mean temperature of 19.06°C and a relative humidity of 76.28%. Germination was evaluated by observing the appearance of the radicle, with observations recorded every 24 hours over a 14-day period. To maintain moisture, 5 mL of distilled water was added to each dish every other day.



Fig. 6: Germination of Fe_3O_4 MNP-primed and hydroprimed true potato seeds observed in sealed Petri dishes during the 14-day incubation period.

2.4 Physicochemical Characterization of Fe_3O_4 MNPs

The structural and physicochemical properties of the synthesized nanoparticles were assessed using a suite of complementary analytical techniques. Crystal phase identification and mean crystallite size estimation were performed by X-ray diffraction (XRD) using $\text{Cu K}\alpha$ radiation ($\lambda = 1.5406 \text{ \AA}$), with the mean crystallite size calculated according to the Scherrer equation. Surface functional group analysis was carried out by Fourier-transform infrared spectroscopy (FTIR) over the range $400\text{--}4000 \text{ cm}^{-1}$. Particle morphology and size distribution were examined by field-emission scanning electron microscopy (FE-SEM) coupled with energy-dispersive X-ray spectroscopy (EDX) for elemental composition

verification. Hydrodynamic diameter and colloidal stability of nanoparticle suspensions were determined by dynamic light scattering (DLS) and zeta potential measurements, respectively. All experiments were performed in triplicate, with data expressed as mean SEM and data visualization was performed using Origin 2021.

4. RESULTS AND DISCUSSION

4.1 Characterization of MNP

4.1.1 Crystalline Structures

The crystallographic structure, phase, and purity of the synthesized samples have been investigated using the XRD patterns. The crystalline nature of nanoparticles was confirmed by X-ray crystallography. The XRD pattern of the synthesized MNPs is shown in Fig. 8.

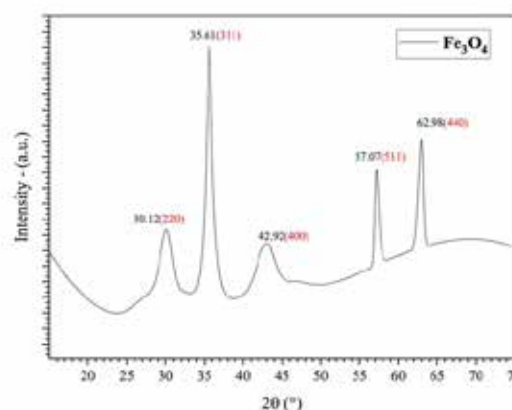


Fig. 7: X-ray diffraction pattern of the synthesized Fe_3O_4 magnetic nanoparticles confirming phase purity and cubic spinel crystal structure.

The diffracted intensities were recorded from 20 to 70 degrees. For the synthesized MNP, five strong Bragg reflections at 30.12, 35.62, 42.92, 57.07, and 62.98 degrees correspond to the planes of (220), (311), (400), (511), and (440), respectively, which can be indexed according to the facets of the face-centered cubic crystal structure of magnetite.[5],[10]. The average crystal size of the particles was calculated to be around 8.30nm using the Scherrer formula by averaging the full width at half maximum (FWHM) of the six aforementioned peaks, in accordance with established methodology [11].

4.1.2 Elemental Composition

The EDX spectroscopic analysis reveals a chemical profile characterized primarily by iron and oxygen, which serve as the fundamental constituents of the synthesized specimen. The spectrum identifies prominent peaks for Iron (Fe) and Oxygen (O) with mass concentrations of 59.81%

and 23.49%, respectively, while a minor carbon signal is observed, likely originating from the sample mounting media. The distribution of these elements, particularly the high atomic percentage of oxygen, strongly supports the successful formation of an iron oxide phase. The absence of extraneous signals suggests a high degree of elemental purity, indicating that the major detected components effectively define the chemical identity of the sample within the sensitivity limits of the measurement.

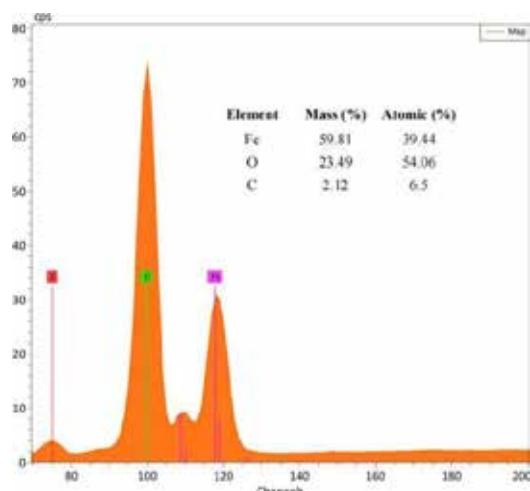


Fig. 8: Energy-dispersive X-ray spectrum and quantitative elemental composition of the synthesized Fe_3O_4 magnetic nanoparticles.

4.1.3 Particle Morphology and Size Distribution

The morphology and particle size distribution of the synthesized magnetic nanoparticles were evaluated by field emission scanning electron microscopy, as depicted in Fig. 9. The micrographs revealed a predominantly spherical morphology with a distribution comprising both smaller and larger particles. Quantitative analysis of 111 individual particles yielded a mean diameter of 10.38 ± 2.51 nm. Notable agglomeration was observed, with particles forming clusters incorporating both size fractions, a behavior characteristic of iron oxide nanoparticles at this scale.

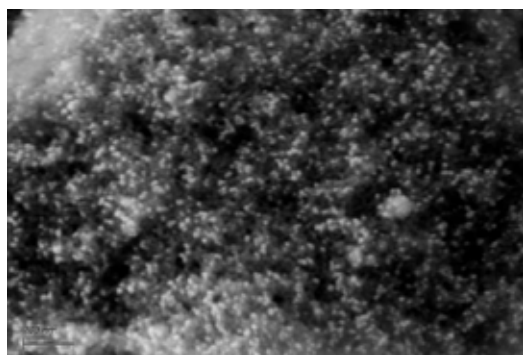


Fig. 9: Field-emission scanning electron microscopy micrograph of synthesized Fe_3O_4 magnetic nanoparticles.

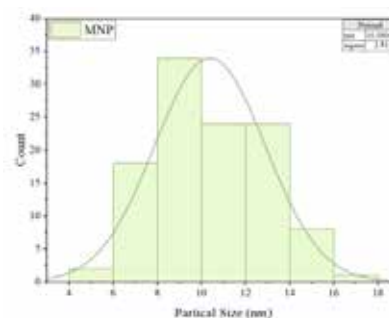


Fig. 10: FE-SEM micrograph and particle size distribution analysis of Fe_3O_4 magnetic nanoparticles.

The histogram reveals a right-skewed size distribution, with the predominant particle population concentrated in the 8–10 nm size range, consistent with the mean diameter of 10.38 ± 2.51 nm determined from image analysis. The normal distribution overlay confirms reasonable agreement with a Gaussian profile across the measured population, though a tail extending toward 16–18 nm reflects the presence of a minor fraction of larger particles, likely attributable to localized agglomeration during synthesis or drying. The relatively narrow distribution width corroborates the controlled nucleation conditions achieved under the co-precipitation protocol employed in this study.

4.1.4 Hydrodynamic Diameter and Colloidal Stability

The hydrodynamic size of the synthesized MNPs in aqueous solution was evaluated using dynamic light scattering (DLS), revealing a mean diameter of 259.1 ± 61.8 nm (Fig. 11). This hydrodynamic size is notably larger than the diameters typically observed via SEM or TEM, a discrepancy attributed to the solvation shell and surface stabilizers surrounding the particles in a liquid medium. [14],[9] The measured distribution reflects the effective size of the particles as they move through the solvent, providing a realistic representation of their behavior in a dispersed state.

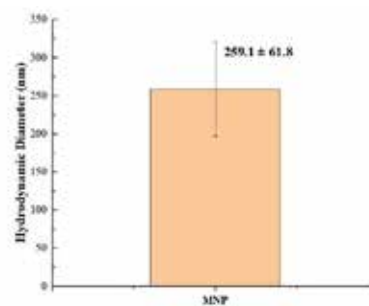


Fig. 11: Dynamic light scattering (DLS) analysis showing the hydrodynamic diameter distribution of Fe_3O_4 magnetic nanoparticles in aqueous suspension.

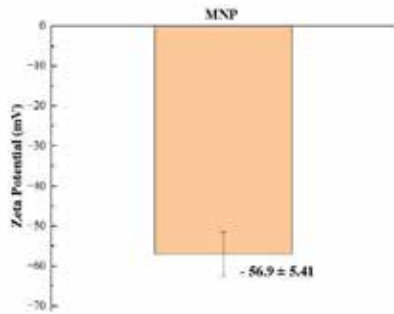


Fig.12: Zeta potential distribution of Fe_3O_4 magnetic nanoparticles in aqueous suspension.

The analysis reveals a zeta potential value of -56.9 ± 5.41 mV for the synthesized MNPs. Previous studies suggest that nanoparticles with high zeta potential values (with an absolute value greater than 30 mV) generally exhibit high colloidal stability [12],[13]. Accordingly, the observed negative zeta potential value for the MNPs indicates superior stability of these nanoparticles. This enhanced stability aligns with the expectation that particles with highly negative zeta potential values are less susceptible to aggregation due to stronger interparticle electrostatic repulsion.

4.2 Germination Response of TPS to Fe_3O_4 -based Nanopriming

The germination performance of *Solanum tuberosum* L. cv. BARI-1 TPS subjected to Fe_3O_4 MNP nanopriming at 10, 40, and 70 mg L^{-1} , alongside the hydroprimed control, was monitored over a 14-day incubation period under controlled environmental conditions (mean temperature: 19.06 ± 0.5 °C; relative humidity: $76.28 \pm 2.1\%$). All germination data represent the mean of three independent replicates, and the temporal germination profiles are presented in Fig. 13. To ensure statistical rigor, each concentration was evaluated in triplicate (3 sets), with all reported values representing the calculated mean of these replicates. The vertical lines on the bar chart represent the [Standard Deviation (SD)], visually mapping the variance within the replication sets. To mathematically validate the performance gaps, a Two-Way ANOVA (with Treatment Concentration and Time Interval as the main factors) has been conducted on the raw replication data-set. Standard compact letter displays (a, b, c) have been added above the bars in the updated figure to clearly illustrate which treatment groups are significantly different from the hydroprimed control and from each other at each time point. This standardized microclimate ensured that the observed variations in germination kinetics were primarily attributable to the MNP concentration gradients

rather than external fluctuations. Temporal analysis of germination dynamics reveals a significant acceleration in metabolic transition for seeds treated with mid-range nanoparticle concentrations. By Day 10, the 40 mg/L MNP treatment emerged as the primary catalyst, yielding a germination rate of 73.10% a 12.5% improvement over the HydroPrimed control (64.99%). This initial momentum intensified by Day 12, where the 40 mg/L cohort achieved 79.25%, effectively widening the performance gap to 17% above the control. In contrast, the 70 mg/L concentration exhibited a definitive inhibitory threshold,

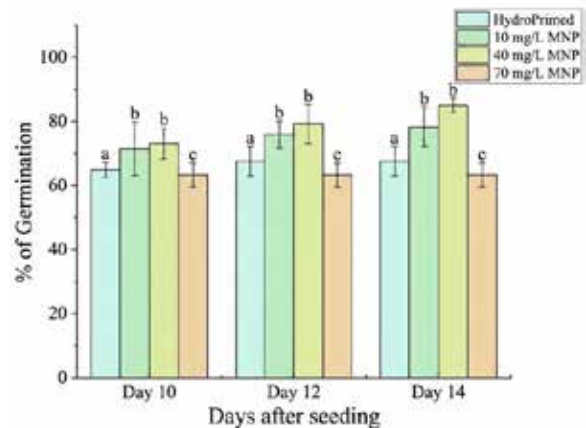


Fig. 13: Temporal germination rate (%) of *Solanum tuberosum* L. cv. BARI-1 true potato seeds primed with Fe_3O_4 magnetic nanoparticles at varying concentrations (10, 40, and 70 mg L^{-1}) and hydroprimed control over a 14-day observation period.

stagnating at 63.44% from Day 10 through the end of the observation period. By the Day 14 terminal assessment, the superiority of the 40 mg/L treatment was solidified, reaching a peak efficacy of 85.15% (a 25.7% increase over control), whereas the 70 mg/L treatment resulted in a 6.4% deficit relative to standard hydro-priming. The biphasic response observed here indicates that while low iron oxide nanopriming concentrations enhance seed coat porosity and imbibition, the 70 mg/L dosage triggers distinct phytotoxicity [16]. This high-dose inhibition stems from a combination of mechanical and physiological constraints: dense surface aggregation physically blocks aquaporin channels to restrict hydraulic conductivity, while excessive internal accumulation accelerates reactive oxygen species (ROS) production, causing severe membrane damage and lipid peroxidation [17]. Consequently, 70 mg/L represents a critical toxicological threshold where physical restriction and oxidative stress entirely override the developmental benefits of iron mobilization. These results suggest that

while optimized MNP concentrations significantly lower the energetic barriers to germination, supra-optimal dosing triggers physiological stagnation, underscoring the necessity of precision concentration for maximizing seed vigor.

5. CONCLUSION

This research identifies a nonlinear physiological response in True Potato Seed (TPS), pinpointing 40 mg/L of Fe₃O₄ magnetic nanoparticles as the optimal concentration for accelerating germination kinetics and lowering metabolic activation barriers. The subsequent stagnation observed at 70mg/L highlights a critical biostimulatory limit, beyond which nanotoxicity begins to impede physiological gains.

The significance of this study lies in its successful translation of agricultural nanotechnology from a theoretical laboratory concept to a scalable, eco-conscious cultivation strategy. By defining the precise therapeutic window for Fe₃O₄ nanoparticles in TPS, this work provides a reproducible framework to enhance crop vigor in vital agro-ecological zones like Bangladesh. Crucially, the next phase of this research will evaluate the performance of these MNP primed seeds under abiotic stress. This will determine whether the initial physiological boost discovered in this study successfully translates into sustained climate resilience against environmental volatilities.

6. ACKNOWLEDGEMENT

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REFERENCES

- [1] A. R. Sallam, A. A. Mahdi, and K. Y. Farroh, "Improving drought stress tolerance in potato (*Solanum tuberosum* L.) using magnetite and zinc oxide nanoparticles," *Pakistan Journal of Biochemistry and Molecular Biology*, vol. 23, no.37,2022,doi:https://doi.org/10.56557/PCBMB/2022/v23i37-387886.
- [2] M. T. MacDonald and V. R. Mohan, "Chemical Seed Priming: Molecules and Mechanisms for Enhancing Plant Germination, Growth, and Stress Tolerance," *Current Issues in Molecular Biology*, vol. 47, no. 3, p. 177, Mar. 2025, doi: https://doi.org/10.3390/cimb47030177.
- [3] S. H. Nile et al., "Nano-priming as emerging seed priming technology for sustainable agriculture—recent developments and future perspectives," *Journal of Nanobiotechnology*, vol. 20, no. 1, Jun. 2022, doi: https://doi.org/10.1186/s12951-022-01423-8.
- [4] R. Javed, M. A. Ahmad, A. Gul, T. Ahsan, and M. Cheema, "Comparison of chemically and biologically synthesized nanoparticles for the production of secondary metabolites, and growth and development of plants," *Comprehensive Analytical Chemistry*, pp. 303–329, 2021, doi: https://doi.org/10.1016/bs.coac.2021.02.002.
- [5] G. Vaidyanathan, S. Sendhilnathan, and R. Arulmurugan, "Structural and magnetic properties of Co_{1-x}Zn_xFe₂O₄ nanoparticles by coprecipitation method," *Journal of Magnetism and Magnetic Materials*, vol. 313, no. 2, pp. 293299, Jun.2007,doi:http://dx.doi.org/10.1016/j.jmmm.2007.01.010.
- [6] K. Kornarzyński, A. Sujak, G. Czernel, and D. Wiącek, "Effect of Fe₃O₄ nanoparticles on germination of seeds and concentration of elements in *Helianthus annuus* L. under constant magnetic field," *Scientific Reports*, vol. 10, article no. 8068, 2020, doi: https://doi.org/10.1038/s41598-020-64849-w.
- [7] N. Gupta, P. M. Singh, V. Sagar, A. Pandya, M. Chinnappa, R. Kumar, and A. Bahadur, "Seed priming with ZnO and Fe₃O₄ nanoparticles alleviate the lead toxicity in *Basella alba* L. through reduced lead uptake and regulation of ROS," *Plants*, vol. 11, no. 17, article 2227, 2022, doi: https://doi.org/10.3390/plants11172227.

- [8] M. Smiri, "Environmental effect of magnetite nanoparticles (Fe_3O_4 NPs) on germination rate and seedling growth from bean," *Polish Journal of Environmental Studies*, vol. 33, no. 5, 2024, doi: <https://doi.org/10.15244/pjoes/183080>.
- [9] S. Yeasmin, A. R. Dipto, A. B. Zakir, S. D. Shovan, M. A. H. Suvo, M. A. Bhuiyan, M. N. Amin, T. U. Rashid, S. Islam and A. Habib, Nanopriming and AI for Sustainable Agriculture: Boosting Seed Germination and Seedling Growth with Engineered Nanomaterials, and Smart Monitoring through Deep Learning, *ACS Appl. Nano Mater.*, 2024, 7, 8703–8715.
- [10] K. J. Esha et al., "Synthesis and Characterization of Polyethylenimine-Coated Magnetic Nanoparticles for DNA Binding toward Pollen-Directed Gene Delivery Applications," *IEEE Transactions on NanoBioscience*, pp. 1–1, 2026, doi: <https://doi.org/10.1109/tnb.2026.3666861>.
- [11] M. Mascolo, Y. Pei, and T. Ring, "Room temperature co-precipitation synthesis of magnetite nanoparticles in a large pH window with different bases," *Materials*, vol. 6, no. 12, p. 5549–5567, Nov. 2013. [Online]. Available: <http://dx.doi.org/10.3390/ma6125549>.
- [12] M. S. Mostafa, S. Yeasmin, M. M. H. Pranto, S. M. Reza, T. U. Rashid, H. Das, M. Rahman and A. Habib, Annealing-induced optimization of green-synthesized ZnO nanoparticles for improved nanopriming in sustainable agriculture, *Nanoscale Adv.*, 2025, 7, 5589–5600.
- [13] A. Brunelli, A. Foscari, G. Basei, G. Lusvardi, C. Bettiol, E. Semenzin, A. Marcomini and E. Badetti, Colloidal stability classification of TiO_2 nanoparticles in artificial and in natural waters by cluster analysis and a global stability index: Influence of standard and natural colloidal particles, *Sci. Total Environ.*, 2022, 829, 154658.
- [14] S. M. Savassa, N. M. Duran, E. S. Rodrigues, E. De Almeida, C. A. Van Gestel, T. F. Bompadre and H. W. P. de Carvalho, Effects of ZnO nanoparticles on *Phaseolus vulgaris* germination and seedling development determined by X-ray spectroscopy, *ACS Appl. Nano Mater.*, 2018, 1, 6414–6426.
- [15] A. Konate, X. He, Z. Zhang, Y. Ma, P. Zhang, G. Alugongo and Y. Rui, Magnetic (Fe_3O_4) nanoparticles reduce heavy metals uptake and mitigate their toxicity in wheat seedling, *Sustainability*, 2017, 9, 790. <https://doi.org/10.3390/su9050790>
- [16] M. Smiri, Environmental effect of magnetite nanoparticles (Fe_3O_4 NPs) on germination rate and seedling growth from bean, *Pol. J. Environ. Stud.*, 2024, 33, 5284–5293. <https://doi.org/10.15244/pjoes/183080>.