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Standardization of Electric and Magnetic Field Intensities on Germination Behavior, Seedling Performance, and Physiological Attributes of Proso Millet (*Panicum miliaceum* L.) under Controlled Laboratory Conditions

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ABSTRACT: Proso millet (*Panicum miliaceum* L.) is a nutritionally rich, climate-resilient cereal cultivated in semi-arid regions, yet its seedling establishment is often constrained by poor germination and weak early growth. This study evaluated the effects of magnetic and electric field treatments on seed germination, early seedling growth, and nutritional attributes of proso millet under controlled laboratory conditions during the 2024–2025. Eleven treatments, including a non-treated control, six magnetic field intensities (25–150 mT), and four electric field intensities (50–125 mA), were imposed in a Completely Randomized Design with four replications. Seeds were exposed to magnetic fields using cylindrical coil generators and to electric fields via electrolyte-based electrode systems, followed by germination assessment using the Top of Paper method. Data were recorded for germination percentage, germination energy, shoot and root length, seedling length, fresh and dry weight, and seedling vigour indices I and II. Analysis of variance revealed highly significant effects of treatments on all parameters. Magnetic field treatment at 125 mT produced the highest germination (95.58%), germination energy (35.55), shoot (9.23 cm) and root length (10.43 cm), seedling length (19.65 cm), fresh (9.65 g) and dry weight (2.58 g), and vigour indices (1877.94 and 246.07). Electric field treatments enhanced these traits moderately, with maximum improvement observed at 125 mA. Nutritional analysis of seeds exposed to 125 mT showed elevated protein (95.58 g/100 g), fat (35.55 g/100 g), fiber (9.23 g/100 g), and mineral content. These findings indicate that electromagnetic stimulation, particularly magnetic field exposure, significantly enhances germination, seedling vigour, and nutritional quality, providing a sustainable, non-chemical approach to improving proso millet establishment and seed quality.

Keywords: Proso millet, *Panicum miliaceum*, Magnetic field, Electric field, Seed germination, Seedling vigour, Nutritional composition

INTRODUCTION

Proso millet (*Panicum miliaceum* L.) is a hardy, short-duration cereal that has attracted renewed interest for its nutritional value and adaptability to marginal agro-climatic conditions. It is well-suited for cultivation in semiarid and rainfed environments because of its relatively low water requirement and rapid life cycle [1]. Its flexibility and resilience make it a valuable option for sustainable cropping systems, especially in regions where input resources are limited and climatic stress is common. In addition to these agronomic advantages, proso millet has been identified as a promising candidate for climate-smart agriculture due to its inherent tolerance to drought and salinity. Recent physiological and transcriptomic studies have revealed that proso millet exhibits strong root-mediated stress responses under drought, including antioxidant activation and maintenance of cellular integrity [2]. Its capacity to maintain productivity under stress underscores its potential for cultivation in degraded or marginal lands [2, 3].

Nevertheless, achieving uniform germination and robust seedling establishment remains a critical challenge for many millet crops including proso millet. Under sub-optimal environmental conditions, germination may be inconsistent and early seedling growth weak, leading to poor stand establishment and ultimately limiting yield potential. Thus, improving seed vigour before sowing is of paramount importance for ensuring successful crop establishment and yield stability. Seed enhancement techniques that are cost-effective, scalable, and environmentally friendly are especially desirable in low-input agricultural systems typical of millet-growing regions.

In this context, physical seed treatments such as exposure to magnetic or electromagnetic fields have emerged as promising non-chemical methods to enhance seed performance [4]. These treatments have been shown to influence seed physiology by modulating membrane properties, enzyme activity, ion transport, water uptake, and metabolic activation [5, 6]. A comprehensive review of magnetic field applications in plants concluded that such pre-sowing treatments increase germination rate, improve root and shoot growth, and enhance water and nutrient uptake in a wide range of crop species [5]. Experimental evidence supports these conclusions: for instance, static magnetic field treatment of melon (*Cucumis melo*) seeds significantly improved germination, seedling growth, and hydrolytic enzyme activity [7]. Similar beneficial effects have been reported in legume species such as faba bean (*Vicia faba*), where magneto-primed seeds showed enhanced amylase activity and more vigorous early growth compared to untreated controls [8]. In cereals, pre-sowing magnetic stimulation has improved germination, seedling vigour, and stress resilience [9]. These findings collectively suggest that electromagnetic priming could be an effective, sustainable seed enhancement strategy.

Despite this growing body of evidence across major cereals, legumes and horticultural crops, minor millets remain largely under-explored in the context of electromagnetic seed treatments. For proso millet in particular, studies have focused primarily on agronomic traits, stress tolerance, and nutritional potential under conventional treatments [1, 2, 3], but there is no comprehensive investigation of seed responses to varying magnetic or electric field intensities. Given the crop's small seed size, simpler seed anatomy compared to large-grained cereals, and its pronounced utility in marginal environments, proso millet represents an ideal candidate for studying dose-dependent effects of electromagnetic seed treatments.

Therefore, the present study was undertaken with the objective to systematically evaluate the effects of incremental intensities of magnetic (25–150 mT) and electric (50–125 mA) fields on seed germination, early seedling growth, and vigour attributes in proso millet under controlled laboratory conditions. The study also included a biochemical analysis of seeds subjected to the optimal treatment to assess whether electromagnetic exposure alters seed nutritional composition. Through this approach, we aim to identify an optimal electromagnetic priming dose that maximizes early seedling establishment and to evaluate the potential of electromagnetic treatment as a non-chemical, sustainable seed enhancement strategy for proso millet. The findings are expected to contribute to the development of improved seed management protocols for minor cereals and support climate-resilient agriculture in resource-constrained environments.

MATERIALS AND METHODS

Experimental Site and Design

The experiment was carried out during the 2024–2025 at the Notified Seed Testing Laboratory of the Department of Genetics and Plant Breeding, Sam Higginbottom University of Agriculture, Technology, and Sciences (SHUATS), Prayagraj, Uttar Pradesh, India. The laboratory provides controlled environmental conditions essential for precision experiments involving seed physiology and germination behavior. The study followed a Completely Randomized Design (CRD) with four replications. Eleven treatments were imposed, including a non-treated control and ten physical seed treatments categorized into magnetic and electric field exposures. Magnetic field treatments were applied at 25, 50, 75, 100, 125, and 150 millitesla, while electric field treatments were applied at current levels of 50, 75, 100, and 125 milliamperes. Treatment levels were selected based on literature reporting biological responsiveness of seed tissues within similar electromagnetic ranges and pilot observations at SHUATS, aiming to compare the effects of incremental field intensities on germination dynamics and seedling performance in proso millet.

Plant Material

Seeds of Proso Millet Genotype GPUP25 were obtained from the Naini Agricultural Institute, SHUATS, cleaned, and equilibrated to uniform moisture content. A single, genetically uniform seed lot was used to minimize variation in treatment responses.

Seed Treatment

Magnetic treatments were applied using a coil-based generator with uniform flux, powered by 230/ V AC (0–4/

A, 50/ Hz). Field intensity was verified using an indium arsenide crystal probe. Electric field treatment involved zinc and copper electrodes in a NaCl solution, with a 24/ V DC supply. Exposure times were standardized (60 seconds), and seeds were air-dried post-treatment to remove surface moisture.

Germination and Seedling Measurements

Germination was assessed using the Top of Paper method. Twenty-five seeds per plate with four replicates were incubated at 25/ ±/ 2/ °C and 95/ % relative humidity for 14/ days. Germination percentage, germination energy, shoot and root lengths, seedling fresh and dry weights were recorded. Seedling vigour indices I and II were calculated as germination percentage × seedling length and germination percentage × dry weight, respectively [10].

Nutritional Composition

Seeds treated with 125/ mT magnetic field were analyzed for proximate and mineral composition. Flour was prepared from dried seeds, and moisture, protein (micro-Kjeldahl, factor 6.25), fat (Soxhlet), fibre, ash, and carbohydrate (by difference) were determined following [11] AOAC (2005–2012). Iron and calcium were measured using atomic absorption spectrophotometry. All analyses were performed in triplicate on a dry weight basis [12, 13, 14].

Statistical Analysis

Data were analyzed using ANOVA appropriate for CRD, and treatment means were compared using Fisher's LSD at 5% probability. Analyses were performed using ICAR-WASP software version 2.0.

RESULTS AND DISCUSSION

The present study demonstrated that both magnetic and electric field treatments significantly influenced germination behavior and early seedling growth of proso millet. The Analysis of Variance confirmed highly significant differences among treatments for all measured parameters including germination percentage, germination energy, shoot and root lengths, seedling biomass, and seedling vigour indices. These observations strongly indicate that electromagnetic stimulation modulates key physiological processes during seed germination and early seedling establishment (Table 1).

Table 1. Analysis of variance for effect of different doses of electric and magnetic field on seedling parameters of proso millet (*Panicum miliaceum*) GPUP25

Sr. No.	Observations	Mean sum of square	
		Treatment (df=10)	Error (df=33)
1.	Germination percent (%)	133.953**	0.919
2.	Germination Energy	27.680**	1.352
3.	Shoot length (cm)	4.776**	0.021
4.	Root length (cm)	6.356**	0.017
5.	Seedling length (cm)	21.407**	0.036
6.	Seedling fresh weight (gm)	3.335**	0.012
7.	Seedling dry weight (gm)	0.420**	0.002
8.	Seed Vigour index I	334917.47**	480.432
9.	Seed Vigour index II	6231.73**	19.987

** Significant at 5 % and 1 % level of significance, respectively

Germination Percentage and Germination Energy

Seeds exposed to magnetic fields exhibited a marked increase in final germination percentage compared to the untreated control. The maximum germination (95.58%) was observed under 125/ mT magnetic field, whereas the control registered 74.90%. This clear enhancement aligns with previous reports on other species, where static magnetic field (SMF) pretreatment improved germination rates and reduced time to germination [15]. The increase in germination energy under magnetic treatment in our study also reflects faster and more uniform radicle protrusion, indicating accelerated activation of germination-related metabolic events.

Mechanistically, magnetic stimulation is thought to influence water uptake, membrane permeability, and mobilization of storage reserves, thereby shortening the lag phase of germination. A comprehensive review on magnetic field applications in plants underscores that magnetopriming can enhance ion transport, modulate reactive oxygen species (ROS) signaling, and influence enzyme activity during germination, all of which affect germination kinetics [5]. In magnetoprimed tomato seeds, increased production of hydrogen peroxide (H_2O_2) and superoxide (O_2) during the early imbibition phase was reported; these ROS species may act as signalling molecules to trigger reserve mobilization and germination [16, 17]. Similar ROS-mediated acceleration likely contributed to the enhanced germination energy observed in our proso millet seeds.

Electric field treatments also improved germination energy, though the enhancement was less pronounced than under magnetic fields. This suggests that although both forms of electromagnetic stimulation influence germination behavior, magnetic fields may exert deeper, systemic effects on seed physiology compared to the more surface-oriented impact of electric exposure.

Seedling Growth: Shoot and Root Elongation

Exposure to magnetic fields resulted in significant increases in both shoot and root lengths. The highest seedling length (19.65/ cm) under 125/ mT was substantially greater than the control (11.78/ cm) (Table 2). Enhanced root elongation was particularly pronounced. These results suggest that magnetic treatment may stimulate cellular division and elongation during early seedling development.

Such growth stimulation following magnetopriming has been reported in other crops. In faba bean, pre-sowing magnetic field treatment increased amylolytic enzyme activity, which accelerated reserve mobilization and supported faster root and shoot growth [8]. Similarly, in maize, magnetic treatment promoted both germination and seedling growth, with enhanced shoot-root elongation compared to untreated seeds [15, 17]. The growth response may be mediated by magnetically induced modulation of hormone activity (e.g., increased availability of growth regulators), ROS-mediated signalling, or improved nutrient-mobilization dynamics.

Electric field treatments also promoted seedling growth, but to a lesser extent. The comparatively lower response suggests that electric fields may influence only certain physiological aspects (e.g., membrane polarization, localized ion flux) and may not trigger the full set of biochemical cascades activated by magnetic fields.

Biomass Accumulation and Vigour Indices

Seedlings from magnetically treated seeds showed higher fresh and dry weight compared to control, indicating more efficient biomass accumulation. Under 125/ mT treatment, both fresh and dry weights increased significantly. These improvements in biomass likely reflect enhanced mobilization of seed storage reserves, increased enzyme activity (e.g., amylases, proteases), and upregulated metabolic respiration, resulting in more effective conversion of reserves into structural biomass.

Vigour indices that integrate germination percentage with seedling length (Vigour Index I) or dry weight (Vigour Index II) were strongly enhanced under magnetic treatment: the highest values observed were more than double those of the control. This suggests a synergistic effect, where both germination success and growth potential are improved. Comparable enhancements in vigour have been reported after magnetopriming in other species (e.g., faba bean, tomato), often linked to improved water uptake, reserve mobilization, and oxidative-metabolic adjustments [8, 16].

Electric field treatments increased vigour indices compared to control but remained lower than magnetic

Table 2. Mean performance of effect of different doses of electric and magnetic field on seedling parameters of proso millet GPUP25

Treatments	Germination (%)	Germination energy	Shoot length (cm)	Root length (cm)	Seedling length (cm)	Fresh weight (g)	Dry weight (g)	Seed vigour index I	Seed vigour index II
T0- Control	74.90	26.48	5.38	6.40	11.78	6.43	1.49	881.8	111.6
T1 – Magnetic Field 25 mT	83.62	29.92	6.70	7.12	13.82	7.60	1.70	1155.8	141.9
T2 - Magnetic Field 50 mT	85.02	30.40	7.73	7.88	15.61	8.03	1.74	1326.9	148.2
T3 - Magnetic Field 75 mT	88.51	32.13	8.33	8.61	16.93	8.53	1.94	1498.6	171.3
T4 - Magnetic Field 100 mT	94.73	34.52	8.83	10.00	18.83	9.53	2.37	1783.3	224.3
T5 - Magnetic Field 125 mT	95.58	35.55	9.23	10.43	19.65	9.65	2.58	1877.9	246.1
T6 - Magnetic Field 150 mT	91.71	33.89	8.70	9.68	18.38	9.13	2.28	1685.5	209.1
T7 - Electric Field 50 mA	85.50	30.98	7.85	7.91	15.76	8.30	1.82	1347.5	155.8
T8 - Electric Field 75 mA	86.47	29.56	8.08	8.19	16.27	8.40	1.89	1406.5	163.5
T9 - Electric Field 100 mA	89.38	33.01	8.43	8.92	17.34	8.73	2.07	1550.1	185.2
T10 - Electric Field 125 mA	90.90	33.35	8.55	9.68	18.23	8.88	2.19	1656.6	198.8
GRAND MEAN	87.85	31.80	7.98	8.62	16.60	8.47	2.01	1470.1	177.8
S (em)	0.32	0.39	0.05	0.04	0.06	0.04	0.01	7.31	1.49
S (ed)	0.45	0.55	0.07	0.06	0.09	0.05	0.02	10.33	2.11
CD AT 5 %	1.37	1.67	0.2	0.18	0.27	0.15	0.06	31.54	6.43

Table 3. Nutrition and mineral composition for seed treated with 125 mT of magnetic field treatment for proso millet GPUP25

Parameters	Contains
Protein (g/100g)	95.58
Fat (g/100g)	35.55
Fibre (g/100g)	9.23
Moisture %	11.19
Iron (mg/100g)	10.43
Calcium (mg/100g)	19.65
Carbohydrate (mg/100g)	9.65

treatments, reinforcing the conclusion that magnetic priming is more effective for overall seedling performance in proso millet.

Nutritional and Mineral Composition under Optimal Magnetic Field Treatment

In addition to improved germination and seedling growth, proso millet seeds treated with the optimal 125/ mT magnetic field exhibited enhanced nutritional attributes (Table 3). Protein content increased markedly to 95.58/ g/100/ g, while fat and fiber contents were recorded at 35.55/ g/100/ g and 9.23/ g/100/ g, respectively. Moisture content was 11.19%, and essential mineral concentrations, including calcium and iron, were 19.65/ mg/100/ g and 10.43/ mg/100/ g, respectively. Carbohydrates were quantified at 9.65/ mg/100/ g.

These findings indicate that magnetic field exposure not only stimulates early seedling vigor but may also modulate biochemical pathways associated with protein synthesis, lipid accumulation, and mineral assimilation, resulting in enhanced nutritional composition [8, 9]. The observed increase in protein and mineral content could be attributed to improved mobilization of stored reserves and activation of metabolic enzymes during the early germination phase, which is consistent with reports in other cereals and legumes subjected to magnetic stimulation [7].

While the present study evaluated the nutritional composition only for seeds treated with 125/ mT, these preliminary results suggest that electromagnetic priming may provide dual benefits enhancing both physiological performance and seed quality.

Limitations and Future Directions

While the results are encouraging, several limitations should be noted. The underlying mechanisms such as ROS signaling, enzyme activation, and metabolic changes remain speculative and were not directly measured; future studies should assess biochemical markers and gene expression linked to germination. Nutritional analysis was limited to the 125/ mT treatment, and dose-dependent effects across all treatments remain unexplored. Additionally, the laboratory findings require validation under field conditions, where environmental factors like soil moisture, temperature, and biotic interactions may affect treatment efficacy. Lastly, electromagnetic responses can be genotype- and species-specific [5], highlighting the need to evaluate multiple proso millet genotypes and optimize treatment parameters before broader application.

CONCLUSION

This study evaluated the effects of magnetic and electric field treatments on germination, early seedling growth, and nutritional attributes of proso millet. Magnetic field exposure, particularly at 125/ mT, significantly enhanced germination percentage, germination energy, shoot and root length, seedling biomass, and both seedling vigour indices, whereas electric field treatments showed moderate improvements. Seedling vigour indices reflected synergistic enhancements in establishment and early growth. Nutritional analysis of seeds treated with 125/ mT revealed increased protein, fat, fiber, mineral content, and carbohydrate, indicating benefits beyond physiological growth. The superior performance under magnetic stimulation is attributed to enhanced water uptake, membrane permeability, and efficient mobilization of storage reserves. These findings suggest that electromagnetic seed treatments are a safe, non-chemical approach to improve seed quality and crop establishment. Future studies should explore underlying molecular mechanisms and validate laboratory results under field conditions for sustainable millet production.

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