Pol. J. Environ. Stud. Vol. XX, No. X (XXXX), 1-10

DOI: *10.15244/pjoes/210697* ONLINE PUBLICATION DATE: 2025-11-06

Original Research

Comparative Analysis of Plant Response to Artificial Electromagnetic Fields

Kalsoom Asghar Ali[1], Hanen Karamti[2], Tahreem Fatima[1], Muhammad Amjad Yousaf[3], Zia-Ul-Haq[1]*

[1]Department of Physics, University of Agriculture, Faisalabad, Pakistan
[2]Department of Computer Sciences, College of Computer and Information Sciences, Princess Nourah bint Abdulrahman, Saudi Arabia
[3]Hebei Collaborative Innovation Center for Eco-Environment; Hebei Key Laboratory of Animal Physiology, Biochemistry and Molecular Biology; College of Life Sciences, Hebei Normal University, 050024 Shijiazhuang, Hebei Province, P.R. China

Received: 28 February 2025
Accepted: 13 September 2025

Abstract

Achieving high germination rates and healthy seedling growth is one of the ongoing challenges in maize production, especially in view of the growing need for food worldwide and the requirement for sustainable agricultural methods. Pre-sowing magnetic field treatment has emerged as a viable, safe method for enhancing seed performance. Research on maize seed response to magnetic field treatment, especially in Pakistan, remains limited. This gap highlights the importance of investigating pre-sowing magnetic field treatment as a regional approach to improve maize productivity. To address this gap, this study evaluated the effects of pre-sowing MF treatment on maize seeds with four treatments: T_1 (100 mT for 30 sec), T_2 (100 mT for 1 min), T_3 (150 mT for 30 sec), and T_4 (150 mT for 1 min), along with the control T_0. Results showed that T_2 significantly enhanced germination percentage (75% vs. 49% in control), reduced mean germination time by 40%, and increased vigor index I and II by 37.5% and 66.2%, respectively. Chlorophyll a and b increased by 30.5% and 42%, and enzyme activities such as SOD and CAT improved by 179.1% and 97.7%, respectively, along with mineral ion concentrations. Higher doses (T_3, T_4) were less effective, indicating reduced results with excessive exposure. Principal Component Analysis (PCA) further confirmed these findings, highlighting T_2 (100 mT for 1 min) as the most effective treatment. This study addresses the limited research on maize seeds and demonstrates that pre-sowing magnetic field treatment, particularly T_2, is a cost-effective, eco-friendly technique for enhancing crop productivity. These results offer a strong basis for integrating pre-sowing magnetic field treatment technology into modern farming practices and contribute to the development of sustainable solutions for improving food security in the region.

Keywords: magnetic field, physiological and biochemical traits, enzyme activity, mineral ions

*e-mail: zh_uaf@yahoo.ca

Introduction

Maize (*Zea mays* L.) is a globally significant staple crop, providing food and industrial raw materials to millions worldwide. Enhancing maize productivity is important for addressing food security challenges, particularly in the face of climate change, soil degradation, and increasing global demand [1]. Germination and early seedling growth play a pivotal role in determining overall crop yield and resilience. Traditionally, seed enhancement techniques such as chemical priming and genetic modifications have been widely used to improve seed vigor. However, these methods often pose environmental and economic concerns, necessitating the exploration of eco-friendly, cost-effective, and sustainable alternatives [2].

The literature indicates that over the last twenty years, the majority of work has focused on the use of various biophysical methods across multiple fields, including agriculture, to enhance production. These include the use of ionizing radiation such as ultraviolet (UV), gamma, ultrasound, and different types of lasers for seed bio-stimulation, electromagnetic stimulation of seeds, and the use of electro-frequency for weed control [3]. Although these methods have proven fruitful for increasing production, many questions remain unanswered regarding their mechanism of action. To improve seed germination potential, several seed treatments have been used [4]. These treatments include pelleting, seed coating, heat treatments, and seed priming by inducing various biochemical reactions in the seed, including starch hydrolysis, enzyme activation, and dormancy breaking. Seed priming enhances germination. However, maize farming faces several challenges, like climate change, soil depletion, and pests that threaten maize quality [5]. Water scarcity is another significant issue; many regions around the world have limited water supplies for irrigation. To tackle these issues, researchers are exploring different strategies to enhance seed performance and crop yields.

One such promising approach is pre-sowing magnetic field treatment, which has gained attention for its ability to stimulate plant growth through non-invasive and energy-efficient mechanisms [6]. Magnetic field exposure has been reported to influence various physiological and biochemical processes in plants, including enhanced water absorption, accelerated enzymatic activities, improved ion transport, and modulation of oxidative stress responses [7]. These effects contribute to improved germination rates, seedling vigor, and overall plant health. While previous studies have investigated the impact of magnetic fields on crops such as wheat [8], there remains a significant gap in understanding the biophysical and biochemical responses of maize seeds to magnetic field treatments. Moreover, the lack of standardized protocols for optimal magnetic field intensity and exposure duration has limited the widespread adoption of this technique in agricultural practices [9]. In Pakistan, maize production during late winter and early spring faces challenges due to delayed and reduced seedling emergence. As a result, there is a need to apply various strategies to improve maize germination in Pakistan. In this regard, the effects of the pre-sowing magnetic field seed treatment on the germination of various grains, horticultural crops, and vegetables have been shown [10]. To the best of our knowledge, no prior research has examined the impact of pre-sowing MF on the germination, biophysical, and biochemical parameters of maize in Pakistan. This knowledge gap encouraged us to investigate the effects of pre-sowing magnetic field treatment on early growth stages of maize seeds, chlorophyll content, and enzyme activity during germination.

This study adopts a comprehensive, multi-dimensional approach to evaluating the effects of pre-sowing magnetic field treatment on maize seeds, extending beyond germination rates to explore molecular, biochemical, and structural responses. It investigates antioxidant enzyme activities, metabolic changes, membrane integrity, and microstructural alterations to gain deeper mechanistic insight into seed performance. A range of MF intensities and durations (100 mT for 30 sec, 100 mT for 1 minute, and 150 mT for 30 sec) was tested to identify the most effective combination. Advanced statistical analysis, including Principal Component Analysis (PCA), confirmed T_2: 100 mT for 1 min as the optimal treatment. This study represents a significant advancement in the field of agricultural biophysics. The insights gained from this research could contribute to the development of standardized, scalable protocols for implementing magnetic field technology in maize cultivation, ultimately supporting global efforts toward sustainable and climate-resistant agriculture.

Materials and Methods

Uniform, healthy, and well-ripened maize seeds of the same size were selected from the Plant Breeding and Genetics Department, University of Agriculture, Faisalabad, Pakistan (Fig. 1).

Seeds Sterilized

To prepare for germination, seeds were cleaned with distilled water, sterilized in 3% formaldehyde for 10 minutes, and rinsed thoroughly. The seeds were oven-dried at 85ºC until a constant weight was achieved and packed in air bags for further use.

Pre-sowing Magnetic Field Exposure

Seeds were exposed to a rectified sinusoidal, non-uniform electromagnetic field at 50 Hz using a copper coil electromagnetic field stimulator at varying intensities. Magnetic field doses and exposure times are shown in Table 1.

Fig. 1. Seeds were separated and divided into three parts.

Seed Plantation Design

There were fifteen plastic pots arranged in a completely randomized design (CRD) [11]. Maize seeds were placed in plastic pots. Maize seeds were sown in a washed sand culture for 45 days. To eliminate the heavy metals and finer particles, the sand was thoroughly cleaned with tap water and distilled water, air-dried, and sieved to ensure uniform particle size. The number of germinated seeds was measured after 72, 96, 146, and 194 hours of sowing.

Irrigation and Crop Management

Pots were pre-irrigated and then watered every two days with 250 mL of water. In crop management, thinning, hoeing, and pest control were used for healthy seedlings during germination.

Collection of Data

After sowing the seeds, germination was recorded at 72, 96, 146, and 194 hours. After 15 days, the growth rate was measured by selecting two small-sized and two large-sized plants from each replicate. After 28 days of planting, six healthy plants (two from each replicate) were removed from each pot and taken to the lab (carried in ice bags and protected from the sun) to maintain the consistency of the tissues.

Biophysical Parameters

Germination and Growth Measures

Germination percentage, seed germination index, mean germination time, seedling vigor, and relative water content were calculated using formulas [12]. Plant height was measured from the base to the tip, as shown in Fig. 2. Leaf area was measured using a planimeter. The root and shoot lengths (cm) were observed in 28-day-old seedlings, as shown in Fig. 2. The fresh weight of roots and shoots was calculated using an electric balance. Samples were shade-dried, followed by oven-drying at 80±2ºC until constant weight. All data were statistically analyzed.

Biochemical Parameters

Chlorophyll Content Analysis

Chlorophyll content was determined using the acetone method [13]. Fresh leaves (0.1 g) from each

Table 1. Magnetic field doses and exposure time.

Treatments	Replications			Magnetic field strength (mT)	Time of exposure
	R_1	R_2	R_3		--------
T_o	T_0R_1	T_0R_2	T_0R_3	Control	
T_1	T_1R_1	T_1R_2	T_1R_3	100	30 sec
T_2	T_2R_1	T_2R_2	T_2R_3	100	1 minute
T_3	T_3R_1	T_3R_2	T_3R_3	150	30 sec
T_4	T_4R_1	T_4R_2	T_4R_3	150	1 minute

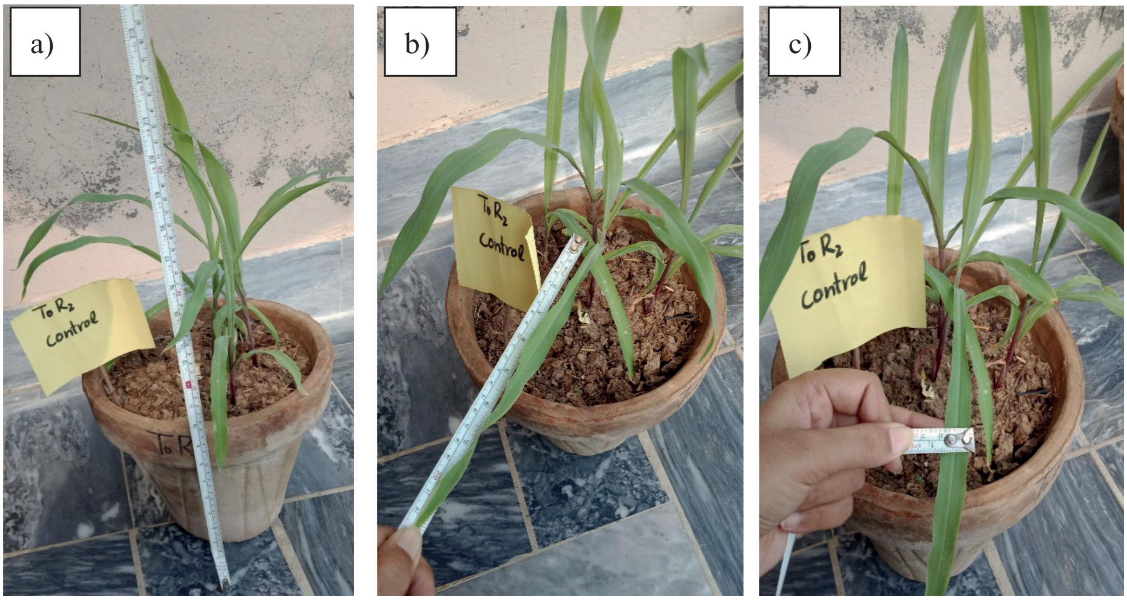

Fig. 2. Measured plant height, leaf length, and width using a measuring tape.

sample were ground with 1mL of acetone, and the homogenate was filtered into a volumetric flask. The supernatant's absorbance was measured at 663 nm and 645 nm using a spectrophotometer. Chlorophyll a, chlorophyll b, and total chlorophyll were calculated using formula [14].

Analysis of Enzymatic Activities

The solution was prepared on a magnetic hot stirrer, and it was ready for further chemical analysis.

Estimation of Superoxide Dismutase (SOD) Activity

Superoxide Dismutase activity was measured using the method [15], founded on the photochemical suppression of Nitroblue Tetrazolium reduction at 560 nm. The 1mL reaction mixture contained 100 mL of enzyme extract, 13.2 mg of riboflavin, 222 mg of methionine, 0.0375 mL of Triton X, 15 mg of nitroblue tetrazolium, and distilled water. The sample was exposed to fluorescent bulbs for 15 minutes to start the reaction. Absorbance was recorded at 560 nm; one unit of SOD was defined as the enzyme quantity causing 50% inhibition of NBT reduction.

Determination of Peroxidase (POD) Activity

POD activity was calculated following the method [16]. The 1 mL reaction mixture included 50 mM phosphate buffer (pH 7), 20 mM guaiacol, 40 mM H_2O_2, and 100 mM enzyme extract. The reaction was initiated by adding guaiacol, and absorbance was recorded at 470 nm after 20 seconds. One unit of peroxidase activity was defined as 0.01 absorbance change per minute per mg of protein.

Determination of Catalase Activity

The reaction solution contained 100 mL enzyme extract, 5.9 mM H_2O_2, and 50 mM phosphate buffer (pH 7). Absorbance was recorded at 240 nm using a UV-visible spectrophotometer. Activity was expressed as units per mg of protein [17].

Determination of Mineral Ions

Oven-dried root and shoot samples (0.01 g) were ground into powder and kept in clean plastic bags. 2 mL of concentrated H_2SO_4 (96-99 percent pure) was added to the powder in digestion flasks, which were left overnight. To complete digestion, 1mL of H_2O_2 was added while heating the mixture (50 to 250°C) until it became colorless. The material was filtered and diluted to a 50mL volume [18]. Ion concentrations were determined using a flame photometer with a standard solution.

Statistical Analysis

Mean values with standard deviations were calculated and visualized using the latest R Studio version 4.2.2 (Table 2).

Results and Discussion

Pre-sowing magnetic field treatment significantly enhanced germination kinetics. Treated seeds showed improved germination performance as compared to untreated seeds (Fig. 3). T_2 and T_3 showed the highest germination (75% and 60%, respectively), while T_4 (26%) was lower than the control (49%).

Table 2. The impact of MF on biophysical and biochemical parameters of maize.

Parameters	MeanSD	Parameters	MeanSD
Germination Percentage	53.8±18.1	Root Length (cm)	13.7±3.67
Seed Germination Index	5.18±2.07	Shoot Length (cm)	38.8±6.26
Mean Emergence Time	6±0.71	Chlorophyll a	8.78±1.77
Vigor Index I	2964.1±1394.21	Chlorophyll b	5.64±1.43
Vigor Index II	82.54±54.18	Total Chl (ab)	14.43±3.19
Relative Water Content	81.42±5.44	POD	38.8±8.58
Area of Leaf (cm^2)	28.2±13.8	SOD	14±3.16
Length of Leaf (cm)	18.6±5.19	CAT	5.8±2.13
Number of Leaves	5.2±1.92	Calcium (Ca)	1963.0±310.0
Width of Leaf (cm)	1.44±0.372	Magnesium (Mg)	1502.0±79.3
Root Fresh Weight (g)	0.187±0.0776	Copper (Cu)	9.83±3.03
Root Dry Weight (g)	1.41±0.649	Iron (Fe)	194.0±12.1
Shoot Fresh Weight (g)	1.17±0.599	Manganese (Mn)	82.6±23.3
Shoot Dry Weight (g)	5.61±1.51	Zinc (Zn)	32.8±2.88
Plant Height (cm)	52.8±9.91		

T_2 increased germination by 70% over the control. These findings align with earlier research that demonstrated faster germination in MF-treated cucumber seeds [19]. The Seed Emergence Index, which shows both speed and uniformity of germination, improved under MF treatment. T_1, T_2, and T_3 showed higher SEI values than the control, but T_2 showed the highest (53.3%). MGT was lower in T_1 and T_2, indicating faster germination. T_2 reduced MGT by 40% compared to untreated seeds (Fig. 3); MF-treated turmeric seeds showed lower MGT and improved germination and growth compared to the control [20]. Magnetic field treatments enhanced both vigor index I and II in maize seedlings. T_2 showed the highest increase in vigor index I (37.5%) and vigor index II (66.2%) compared to the control, indicating the highest improvement. Whereas, T_4 significantly reduced both indices and showed a negative impact at high doses. These results align with previous research on sunflowers, where MF treatments also improved vigor indices [21]. After 28 days of sowing, plant growth was significantly enhanced at lateral developmental stages. All magnetic field doses, except T_4, significantly increased growth compared to the control. T_2 showed the highest growth rate. These results align with earlier research on faba beans, where exposure to 125mT and 250mT magnetic fields also enhanced early growth and development more than the control [22]. Plant height increased by 14.5% (T_1), 26.6% (T_2), and 20.3% (T_3), while T_4 decreased by 20.5% compared to T_0. Root lengths of T_0, T_1, T_2, T_3, and T_4 were 11(T_0), 14.5(T_1), 18(T_2), 16(T_3), and 09(T_4) cm, while T_2 showed the highest increase of 38.9% compared to the control (Fig. 3). The same trend has been reported in flax seeds and other crops in response to MF [23]. Shoot length also improved, with T_2 showing a 17.8% increase. The same trend was seen in lentil seeds treated with a magnetic field [24]. Leaf area increased by 28.4% (T_1), 56% (T_2), and 45.8% (T_3), while it decreased 91% in T_4 compared to the control (Fig. 3). This pattern aligns with other research using MF on onion [25]. Pre-sowing magnetic field treatments positively impacted root and shoot weight. Treatments T_2 and T_3 significantly increased root fresh weight by 46.2% and 37.2%, respectively, compared to T_0. While T_4 showed a 156.8% decrease (Fig. 3). Shoot fresh weight also improved in T_1 (14%), T_2 (34.2%), and T_3 (26.6%), but decreased by 40% in T_4 compared to the control (Fig. 3). Similar improvements were found in lemon balm, where 100mT for 15 minutes or 150mT for 5 minutes increased fresh and dry root and shoot weights [26]. All treatments, except T_4, enhanced root and shoot dry weights. The highest improvement was observed in T_2, with 52% and 48%, respectively. Brinjal seedlings grown from magnetically treated seeds also showed higher dry weight, root length, and surface area after one month of growth [27].

Pre-sowing magnetic field treatment significantly affected chlorophyll content. T_2 (100 mT for 1 min) and T_3 (150 mT for 30 sec) showed the greatest amount of chlorophyll a levels, 30.5% and 22.4% higher than the control (Fig. 3). Chlorophyll b was enhanced by 42% in T_2 and 26.6% in T_3, respectively. Total chlorophyll was also enhanced at the same magnetic field levels, while T_4 indicated a negative response compared to the control. These results supported earlier research showing that magnetic fields increase chlorophyll

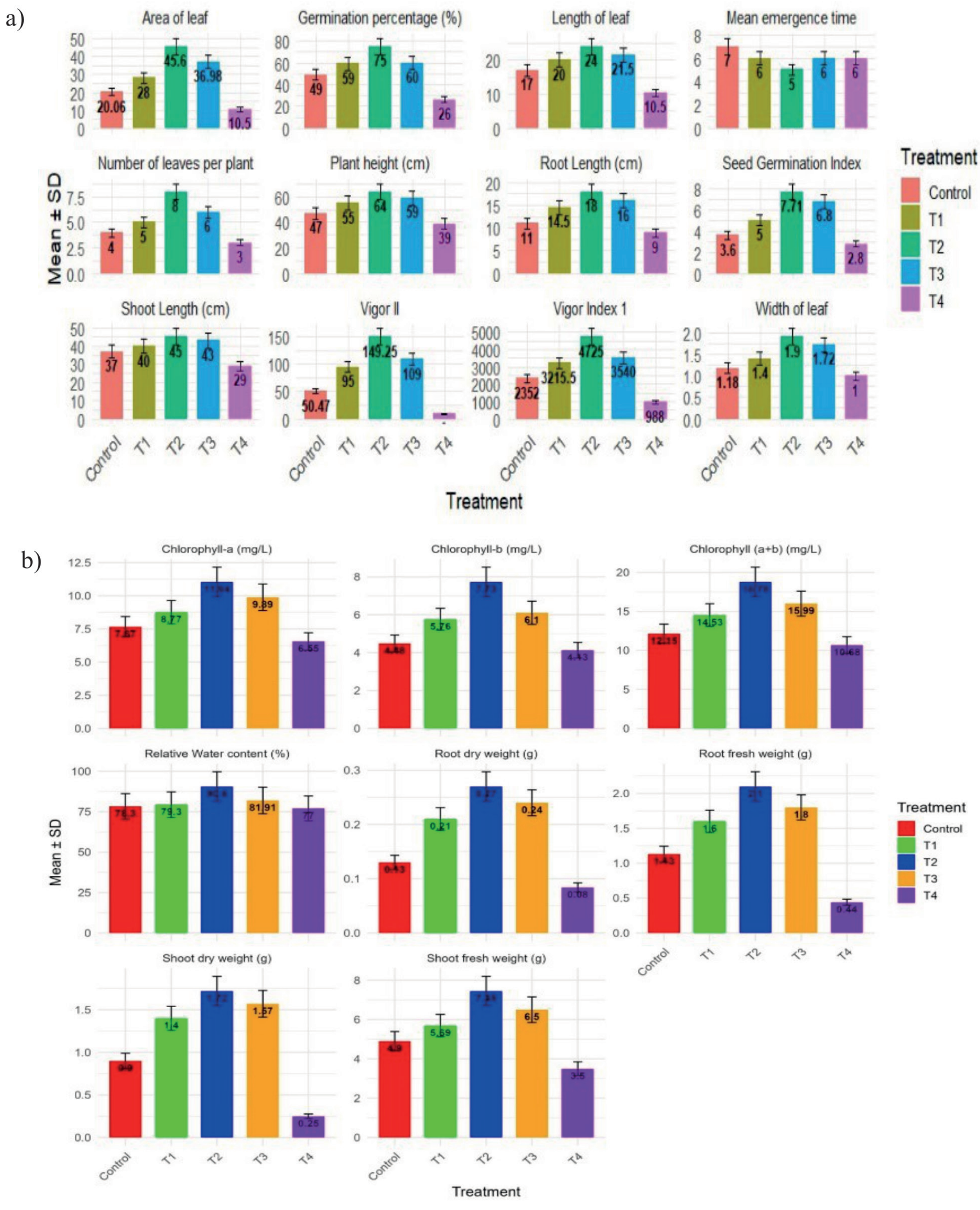

Fig. 3. Effect of pre-sowing magnetic field on biophysical parameters and chlorophyll content of maize.

in green chili [28]. Antioxidant enzyme activity increased under MF exposure (Fig. 4). The highest catalase and peroxidase activities were found at the same levels as chlorophyll a. Catalase activity rose by 97.73% at T_2 and 54.55% at $T_{3.}$ Superoxide dismutase activity peaked at 179.1% (100 mT for 30 sec) and 158.2% (150 mT for 30 sec). Peroxidase activity was highest at T_2 (166.67%) and T_3 (146.67%). Magnetic fields significantly affected the ionic composition of maize plants. The 100 mT for 30 seconds showed the highest increases in calcium (2261.5 mg/kg) and magnesium (1620.51 mg/kg), showing a strong enhancement of macronutrient uptake. Similarly, the pre-sowing magnetic field showed significant improvements

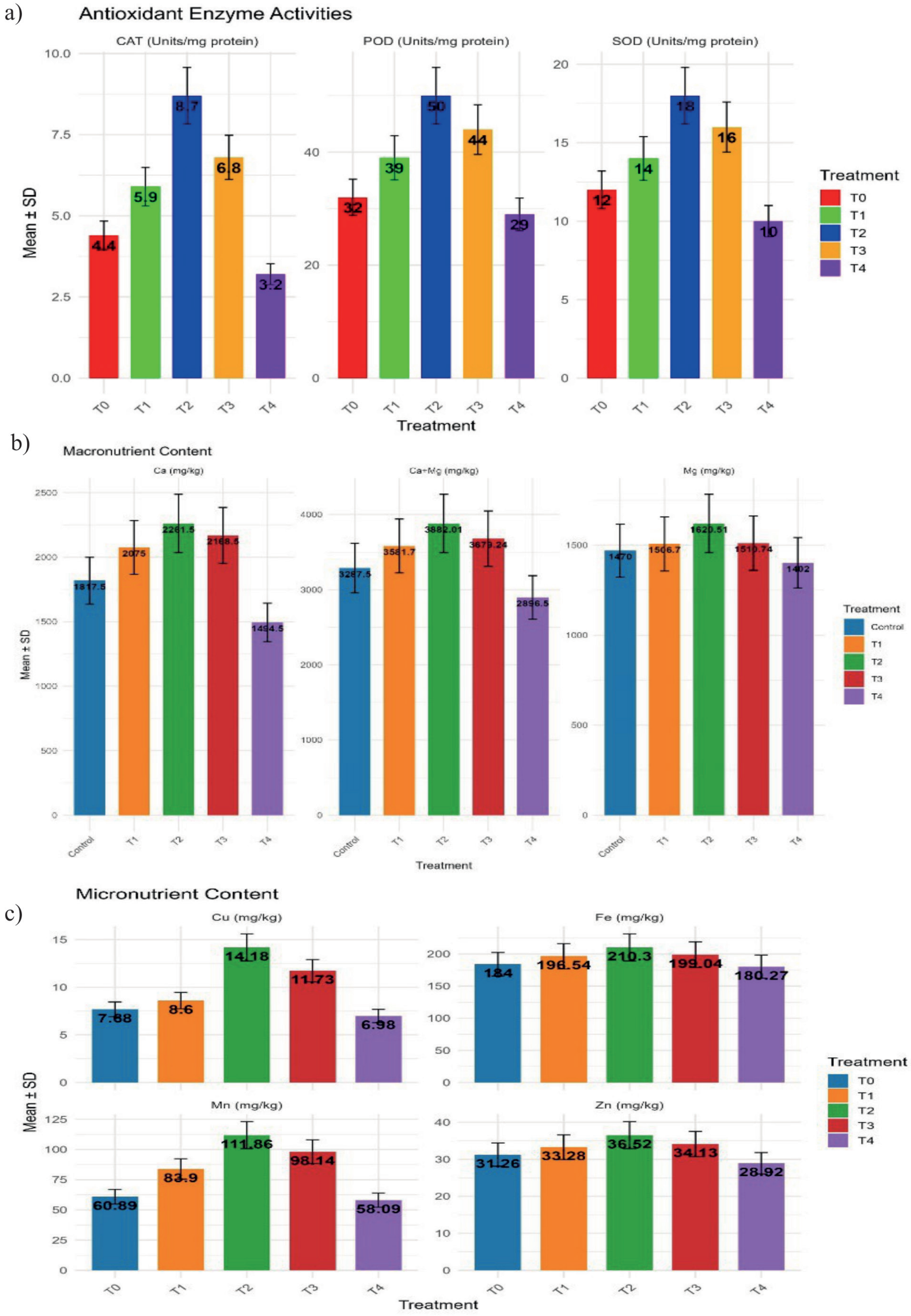

Fig. 4. Effect of pre-sowing magnetic field on biochemical parameters of maize.

in micronutrients, with copper increasing by 11%, 45.8%, and 35% in T_1, T_2, and T_3 respectively, but decreasing by 10% in T_4 compared to T_0. However, iron demonstrated the highest impact in T_2 (12.5%), T_1 (6.4%), and T_3 (7.6%), but T_4 showed a 2.1% decrease compared to the control. Manganese and zinc also indicated the same trend; the maximum enhancement was 45.6% and 14.4% in T_2 in comparison with the control T_0. It was found that pre-sowing magnetic field treatment of maize showed potential in enhancing germination, growth, mineral contents, chlorophyll contents, and enzymatic activities under field environments. Pre-sowing magnetic field treatment has been proposed to change the permeability of cell membranes, allowing energy and water molecules to pass through the cell, which would improve metabolism. During seed germination, it was found that magnetically treated seeds increased concentrations of the enzymes required for seed germination at various stages. Another theory suggests that magnetic fields affect biological processes using mobile electron charges, liquid crystals, non-conventional spins, or free radicals. These free radicals are highly energetic chemically and also speed up the metabolism during sprouting [29]. According to the study, there have also been observations indicating higher water absorption, which may be the cause of improved germination. MF exposure is reported to alter cell membrane permeability and activate ion transport channels, particularly those involved in calcium signaling, which plays a critical role in regulating germination and early growth processes [30]. Enhanced calcium ion flux may facilitate signal transaction pathways essential for

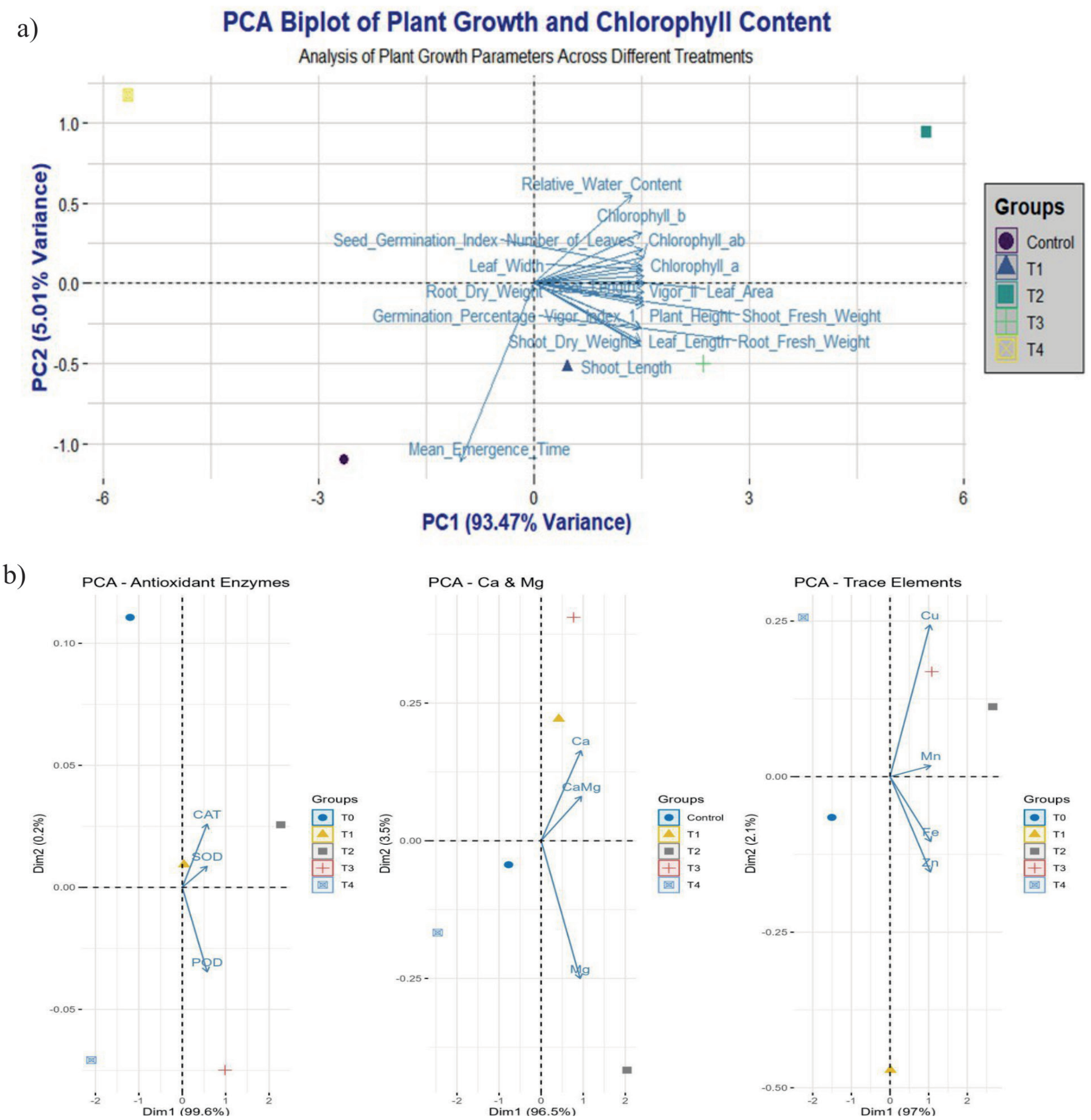

Fig. 5. PCA biplot of biophysical and biochemical parameters.

metabolic activation. Moreover, MF treatment has been shown to stimulate the activity of antioxidant enzymes, which help mitigate oxidative stress and support redox homeostasis during seedling development [31]. Recent transcriptomic and proteomic studies further revealed that MF treatment at high doses unregulated genes associated with photosynthesis, stress response, and energy metabolism. Additionally, MF has been linked to increased expression of aquaporins, facilitating enhanced water transport across cell membranes and improving hydration status during germination. These synergistic effects collectively contribute to improved seed vigor, chlorophyll biosynthesis, enzymatic activity, and nutrient uptake in magnetically treated maize seeds.

Principal Component Analysis (PCA)

The principal component analysis (PCA) biplot (Fig. 5) illustrates variations in plant growth and chlorophyll content under different treatments (control, T_1, T_2, T_3, and T_4). PCA reduced the dataset into two principal components: PC1 (93.47%) and PC2 (6.01%), together explaining all the variance in the dataset. The biplot represents the relationship between treatments and parameters, with arrow direction and length indicating the contribution and correlation of each parameter. The positioning of treatment reflects its impact on growth and other traits, while distinct symbols and colors distinguish treatment impacts.

Conclusion

This study demonstrated that pre-sowing magnetic field treatments significantly improved germination, growth, biophysical, and biochemical characteristics of maize. Among all treatments, 100mT for 1 minute (T_2) showed the most positive effects, enhancing germination rate, seedling vigor, root and shoot lengths, chlorophyll content, antioxidant enzyme activity (SOD, POD, and CAT), and the concentrations of micro and macronutrients. These findings highlight the potential of optimal doses of magnetic field treatment as an innovative and eco-friendly method to improve the growth and performance of maize seeds in Pakistan and all over the world.

Acknowledgments

Princess Nourah bint Abdulrahman University Researchers Supporting Project Number (PNURSP2025R192), Princess Nourah bint Abdulrahman University, Riyadh, Saudi Arabia.

Conflict of Interest

The authors declare no conflict of interest.

References

1. MUSITIA V., AYUA E., KINYUA M., KAMAU H. Effects of gamma irradiation on physico-chemical and functional properties of Irish potato tubers and flours: Dose and varietal dependent. African Journal of Education Science and Technology, **8** (1), **2024**.
2. FALLAH S.F., ESLAMI Z., DANCHENKO M., BARÁTH P., BUJDOSÓ G., GOLALIPOUR M., SADEGHIPOUR H.R. Failure in lipid gluconeogenesis, perturbed amino acid metabolism and chaperon activation characterize declined germination potential of aging walnut kernels. Scientia Horticulturae, **329**, 113020, **2024**.
3. HAFEEZ M.B., ZAHRA N., AHMAD N., SHI Z., RAZA A., WANG X., LI J. Growth, physiological, biochemical and molecular changes in plants induced by magnetic fields: A review. Plant Biology, **25** (1), 8, **2023**.
4. STEFI A.L., MARGARITIS L.H., CHRISTODOULAKIS N.S. The effect of the non-ionizing radiation on exposed, laboratory cultivated maize (*Zea mays* L.) plants. Flora, **233**, 22, **2017**.
5. LI Y., TIAN F. Impact of climate change on maize yield and response strategies: A review study. Advances in Resources Research, **4** (3), 497, **2024**.
6. BEZERRA E.A., CARVALHO C.P., COSTA FILHO R.N., SILVA A.F., ALAM M., SALES M.V., RAMOS M.V. Static magnetic field promotes faster germination and increases germination rate of Calotropis procera seeds stimulating cellular metabolism. Biocatalysis and Agricultural Biotechnology, **49**, 102650, **2023**.
7. ALI M.F., AHMAD M.S.A., GAAFAR A.R.Z., SHAKOOR A. Seed pre-treatment with electromagnetic field (EMF) differentially enhances germination kinetics and seedling growth of maize (*Zea mays* L.). Journal of King Saud University - Science, **36** (5), 103184, **2024**.
8. ZHANG Y., DOU H., YANG L., ZHANG Y., SUN W., RUAN Y., WANG H. Innovative approach to utilizing magnetic fields to enhance wheat yield: Evidence from field studies in China. Plant, Soil and Environment, **70** (10), **2024**.
9. BHAVANI L.L., DAYAL A. Effect of magnetic and electric treatments on growth, yield and seedling parameters of chickpea (*Cicer arietinum* L.). Environment Conservation Journal, **25** (3), 726, **2024**.
10. FATIMA A., KATARIA S., PRAJAPATI R., JAIN M., AGRAWAL A.K., SINGH B., GADRE R. Magnetopriming effects on arsenic stress-induced morphological and physiological variations in soybean involving synchrotron imaging. Physiologia Plantarum, **173** (1), 88, **2021**.
11. IQBAL M., UL HAQ Z., MALIK A., AYOUB C.M., JAMIL Y., NISAR J. Pre-sowing seed magnetic field stimulation: A good option to enhance bitter gourd germination, seedling growth and yield characteristics. Biocatalysis and Agricultural Biotechnology, **5**, 30, **2016**.
12. FERRONI L. M., DOLZ M. I., GUERRA M. F., MAKINISTIAN L. Static magnetic field stimulates growth of maize seeds. arXiv Preprint, arXiv:2303.00512, **2023**.
13. RITCHIE R.J., SMA-AIR S. A rapid method for developing chlorophyll equations using alternative solvents: DMF (N, N-dimethylformamide). Journal of Applied Phycology, **1**, 9, **2024**.
14. ERCAN I., TOMBULUGLU H., ALQAHTANI N., ALOTAIBI B., BAMHREZ M., ALSHUMRANI R., KAYED T.S. Magnetic field effects on the magnetic

properties, germination, chlorophyll fluorescence, and nutrient content of barley (*Hordeum vulgare* L.). Plant Physiology and Biochemistry, **170**, 36, **2022**.
15. GIANNOPOLITIS C.N., RIES S.K. Superoxide dismutases: I. Occurrence in higher plants. Plant Physiology, **59** (2), 309, **1977**.
16. CHANCE B., MAEHLY A.C. Assay of Catalases and Peroxidases. Academic Press, **1955**.
17. SHAHZADI A., NOREEN Z., ALAMERY S., ZAFAR F., HAROON A., RASHID M., FIAZ S. Effects of biochar on growth and yield of wheat (*Triticum aestivum* L.) under salt stress. Scientific Reports, **14** (1), 20024, **2024**.
18. WOLF B. A comprehensive system of leaf analyses and its use for diagnosing crop nutrient status. Communications in Soil Science and Plant Analysis, **13**(12), 1035, **1982**.
19. GHANBARPOURI M., GHAHSAREH A.M., ATTAABADI M., HODAJI M. Effect of magnetic treatment on strong cucumber (*Cucumis sativus* L.) transplant production. Pakistan Journal of Agricultural Sciences, **58** (2), **2021**.
20. KAMBLE S.N., SATDIVE R.K., MANWATKAR S.N., SALUNKHE C., ITTEERA J., SINGH K., SINGH S. Influence of magnetic field on the growth, development, and rhizome yield of turmeric (*Curcuma longa* L.). Plant Cell, Tissue and Organ Culture, **150** (3), 555, **2022**.
21. PIZETTA S.C., DE DEUS F.P., DE OLIVEIRA PAIVA P.D., DIOTTO A.V., THEBALDI M.S., COLODETTI T.V., PECHARA DA COSTA JAEGGI M.E. Post-harvest growth and longevity of ornamental sunflowers irrigated using magnetized water with different irrigation depths. New Zealand Journal of Crop and Horticultural Science, **51** (4), 509, **2023**.
22. PODLEŚNA A., BOJARSZCZUK J., PODLEŚNY J. Effect of pre-sowing magnetic field treatment on some biochemical and physiological processes in faba bean (*Vicia faba* L. spp. minor). Journal of Plant Growth Regulation, **38**, 1153, **2019**.
23. ĆALIĆ D., RISTIĆ-DJUROVIĆ J.L., ĆIRKOVIĆ S., MILOJEVIĆ J., BELIĆ M., STANIŠIĆ M., ZDRAVKOVIĆ-KORAĆ S. Overcoming low germination and low quality of flax seeds (*Linum usitatissimum* L.) in unfavorable storage using static magnetic fields. Agriculture, **13** (11), 2120, **2023**.
24. OREKHOVA S.M. Effect of magnetic fields of different configurations on lentil seed germination. **2023**.
25. AFIFA R.I., ISLAM N., CHOUDHURY S. Effects of priming on onion seed germination and field performance during summer sowing. Journal of Scientific Research and Reports, **30** (4), 252, **2024**.
26. ULGEN C., TURKER A. Impacts of three different magnetic field applications on seed germination and seedling development of *Melissa officinalis* L. Biological Diversity and Conservation, **17** (1), 18, **2024**.
27. JYOTHI G.B.N., RAI P.K., KHNADKA S., SRIKANTH D. Effect of magnetic and electric field seed treatment on the seedling attributes of brinjal (Solanum melongena) seeds. International Journal of Chemical Studies, **6**, 2780, **2018**.
28. WEI L., YANG N., XU X., HUANG H., JIN Y. Application of magnetic field to delay quality changes by regulating the homeostasis of energy metabolism in green chili during storage. Postharvest Biology and Technology, **213**, 112948, **2024**.
29. WANG S., ZHANG L., WANG H., FAN W., HU Y., TU Z. Magnetic field: A non-thermal technology in food processing. Food Control, **110692**, **2024**.
30. GRINBERG M., ILIN N., NEMTSOVA Y., SARAFANOV F., IVANOVA A., DOLININ A., MAREEV E. Response of photosynthesis and electrical reactions of wheat plants upon the action of magnetic fields in the Schumann resonance frequency band. Plant Signaling and Behavior, **19** (1), 2294425, **2024.**
31. EREZ M.E., ÖZBEK M. Magnetic field effects on the physiologic and molecular pathway of wheat (*Triticum turgidum* L.) germination and seedling growth. Acta Physiologiae Plantarum, **46** (1), 5, **2024**.