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Seed pre-treatment with electromagnetic field (EMF) differentially enhances germination kinetics and seedling growth of maize (*Zea mays* L.)

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A R T I C L E I N F O

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A B S T R A C T

Pre-sowing treatment of seeds with different intensities and exposure times to electromagnetic fields (EMF) has proved to be beneficial in increasing the productivity of crops. The purpose of the recent study was to evaluate the effects of electromagnetic fields applied prior to cultivation to seeds of two maize genotypes namely FH-1046 and YH-5427. Sterilized seeds were exposed to three doses of EMF and sown in six treatments levels i.e. T_0 (as control), T_1 (60mT for 3 min.), T_2 (120mT for 3 min.), T_3 (180mT for 3 min.), T_4 (60mT for 6 min.), T_5 (120mT for 6 min.), and T_6 (180mT for 6 min.). There were three replicates in each treatment. Results showed EMF exposure as an augmenting factor as it caused up to 50 % improvement in seed germination performance. The EMF exposure increased germination kinetics and triggered enhancement in morphological characteristics i.e., higher leaf area, plant height, more fresh and dry weight; higher concentration of physiological pigments like chlorophyll *a*, *b*, and carotenoids; upregulated antioxidative enzymatic activities; and, higher mineral ions concentration such as Na^+, K^+, and Ca^{2+}. A growth promotory effect of all doses of electromagnetic field was observed on crop performance, however, T_3 (180mT for 3 min.) and T_5 (120mT for 6 min.) resulted in the highest germination indices, vegetative proliferations and biochemical assays. Of the two genotypes of maize, FH-1046 proved to be more sensitive the EMF as compared to YH-5427. It was concluded that maize growth and grain yield might be directly enhanced through the useful aspects of EMF by its analytical and sustainable utilization at the large scale of agricultural farming.

1. Introduction

The variable environments differentially influence growth attributes and yield performance of agricultural crops under field conditions. Interaction of physical factors such as gravity, radiations, heat, and electric and magnetic fields, exhibit significant roles in the biochemical reactions and physiological responses of plants (Aladjadjiyan, 2012). To overcome nutritional requirements and supply of food, different biotechnological and agronomical practices have been observed over the last several years such as pre-sowing chemical and physical treatments of seeds, and, development of pest and drought-resistant genetically modified varieties (Azadi et al., 2016).

Geodynamics of earth develops a core of electromagnetic field that protects the biosphere from harmful solar radiations. In the last few decades, the magnitude of the earth's EMF has been altered due to anthropogenic activities. The range of the geomagnetic field is 25–65 mili tesla. EMF stands vital for sustaining the Earth's vulnerability to cosmological radiation. In a few centuries, Earth's magnetic field has been reduced by 10 % (Roach, 2004). Changes in the Earth's EMF may have differential effects on the crops' productivity and overall

Abbreviations: GP, Germination percent; SG, Speed of germination; FEI, Filed emergence index; RGC, Relative germination coefficient; VI1, Germination vigour index 1; VI2, Germination vigour index 2; GC, Germination coefficient; NLP, Number of leaves per plant; PH, Plant height; RL, Root length; SL, Shoot length; PFW, Plant fresh weight; RFW, Root fresh weight; SFW, Shoot fresh weight; PDW, Plant dry weight; RDW, Root dry weight; SDW, Shoot dry weight; PTW, Plant turgid weight; RWC, Relative water content; Cha, Chlorophyll *a*; Chb, Chlorophyll *b*; Tch, Total Chlorophyll; Car, Carotenoids; SOD, Superoxide dismutase; POD, Peroxidase; CAT, Catalase; RCa, Root calcium; SCa, Shoot calcium; RK, Root potassium; SK, Shoot potassium; RNa, Root sodium; SNa, Shoot sodium.

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performance. An electromagnetic field is an invisible force produced by electric charges. The bio-molecules involved in the germination process retain electrical as well as magnetic properties. Finding out the optimum intensities of EMF for each plant species may facilitate obtaining excellent outcomes of germination, growth and net yield of crops (Ordas, 2002). Pre-sowing seeds treatment with electromagnetic fields (EMF) and irrigation with electromagnetically exposed water are one of the worthwhile techniques used in recent agricultural technology (Zuniga et al., 2016).

Seed germination is a critical phase of plant development where a strong boost in seed germination helps in establishment of healthy crop stands. These changes in seed germination capacity is measured using a number of seed germination attributes like germination percent, seed emergence index, speed of germination and field emergence index (Vashisth and Nagarajan, 2008; Tanveer et al., 2013). In this regard, vigour index 1 and 2 are more often used as indicators to access capability of seeds to germinate under stressful environments. Seed germination vigour index 1 specifies the capacity of germinating seeds to attain certain height, while, vigour index 2 measures the percentage of germinating seeds against the change in dry weight of seedlings within a given time span (Baki and Anderson, 1973, Kandasamy et al., 2020). Thus both these vigour indices have very useful implementations in plant research to predict capability of seed germination under variable environments.

Electromagnetic field treatments in plants are a biophysical technique to enhance plants' vitality and vigour (Boix et al., 2023; Hafeez et al., 2023). This method is beneficial in the rapid and vigorous growth of plants (Bhardwaj et al., 2012). Biophysical treatments like EMF makes the potential energy of chemicals attached to the biological membranes available as workable kinetic energy, hence, it increases the electrical potential of membranes, intensifies the interaction among metabolites, and activates the growth processes (Iqbal et al., 2012; Hafeez et al., 2023). As a result, it upregulates various biochemical and physiological processes promoting early germination and floral developments (Putti et al., 2023). Moreover, this technique mediates resistance against pests and diseases. In this way, there will be less demand for chemical fertilizer and pesticides reducing the adverse influences of chemicals on the ecosystem. That's why, researchers may adopt this technology for farming and avail numerous advantages as it costs less and saves time (Vashisth and Nagarajan, 2010). The maintenance of cell membrane integrity and reduction in iron absorption in treated seedlings indicates that Fenton's chemistry has been reduced, lowering the risk of oxidative burst (Payez et al., 2013). Other findings evidence suggests the effects of magnetic field on growth processes and other functions of cells like genetic expressions, translation process and metabolism of meristems (Chow and Tung, 2000).

The exposure of seeds to electromagnetic field (EMF) treatments has the potential in enhancing seed germination. This is influenced by specific parameters of the electromagnetic field itself (frequency, intensity, and duration), the type of seeds being treated, and environmental conditions (Maffei, 2018). While the exact mechanisms are not fully understood yet, there are several proposed ways in which EMF treatments may positively influence germination. The first visually observed attribute is increased plumule and radicle growth. In particular, the EMF treatments have been associated with enhanced radicle (embryonic root) growth. This can facilitate the rapid emergence of the seedling from the seed coat and its subsequent establishment in the soil. Once the seeds emerge out of soil, the EMF treated seeds show more uniform seed germination. This can be beneficial for achieving a consistent stand of plants in agricultural crops (Payez et al., 2013). Such enhancements in seed germination by the EMF treatments may be due to stimulation in the activity of enzymes involved in the germination process. This includes enzymes like amylase (which breaks down starches into sugars), protease (which breaks down proteins into amino acids), and lipase (which breaks down fats into fatty acids and glycerol). Enhanced enzyme activity can accelerate the mobilization of stored nutrients, providing energy for germination (Rajendra et al., 2005).

Other hormonal changes under the EMF treatment include activation of gibberellin biosynthesis. Studies have suggested that EMF treatments may also stimulate the synthesis of gibberellins, which in turn promote the expression of genes involved in germination. The EMF treatment also enhances water absorption by seeds. Adequate water uptake is crucial for initiating the germination process, as it activates various enzymes and metabolic pathways. Some researchers show that EMF treatments may increase the permeability of cell membranes. This can facilitate the movement of water and nutrients into the seed, which is essential for germination to occur (Johal et al., 2022). Other physiological process regulated by EMF treatments may influence the signaling pathways and cellular responses involved in germination. This can lead to changes in gene expression, protein synthesis, and metabolic activity that favor germination. Finally, EMF exposure help ameliorate the damaging effects caused by reactive oxygen species (ROS). Excessive levels of ROS can be detrimental to germination, and EMF treatments may contribute to maintaining a more favorable oxidative balance (Wang and Zhang, 2017).

Keeping in view the stimulatory effects of EMF on plants as illustrated in previous research investigations, our research mainly anticipated unveiling the potential effects of EMF on the metabolic machinery of the maize plants and perceiving changes occurring in germination processes and growth patterns. The hypothesis tested in this study was whether the seed pre-treatment with different doses of electromagnetic field (EMF) can differentially influence germinating seeds and seedling growth of maize (*Zea mays* L.) under normal conditions.

2. Materials and methods

This research was carried out in the year 2021 at the research field of Old Botanical Garden, University of Agriculture Faisalabad, Pakistan (31°25′7.3740″ N and 73°4′44.7924 E; 184 m altitude) under natural environmental conditions. Seeds of two heat-resilient maize cultivars, namely FH-1046 and YH-5427 were obtained from the Ayyub Agricultural Research Institute Faisalabad, Pakistan.

2.1. Seeds sterilization

Seeds were sterilized with 0.05 % mercuric chloride solution for 10 min. followed by washing with distilled water thrice. Sterilized seeds were air-dried and stored in paper bags for further use.

2.2. Application of EMF treatments

Sterilized seeds were subjected to 50 Hz rectified sinusoidal non-uniform electromagnetic field with various strengths as T_0 (as control), T_1 (60mT for 3 min.), T_2 (120mT for 3 min.), T_3 (180mT for 3 min.), T_4 (60mT for 6 min.), T_5 (120mT for 6 min.), and T_6 (180mT for 6 min.). Seeds for different treatments were held between the two poles of the apparatus in north and south orientations carried in plastic bags. A special type of magnetic stimulator was designed to stimulate the seeds. This device was constructed in Bio-electromagnetism Lab at the Department of Physics, University of Agriculture Faisalabad, Pakistan. It consisted of copper wires of 1.016 mm thickness, 3000 turns per coil with 75 O coils resistance. Electromagnet frame wall thickness was one centimeter, height 22 cm, width 17 cm and length 28 cm. The core of iron having diameter and length were determined as 90 nm, and 160 nm, respectively.

2.3. Plantation layout and seed sowing

The experimental trial was laid down in seven treatments in triplicates for each cultivar of maize with one control. Total thirty-six plastic pots (32 cm diameter × 28 cm height) filled with 8 kg thoroughly mixed and sieved coarse-silty loam textured soil were arranged in Complete

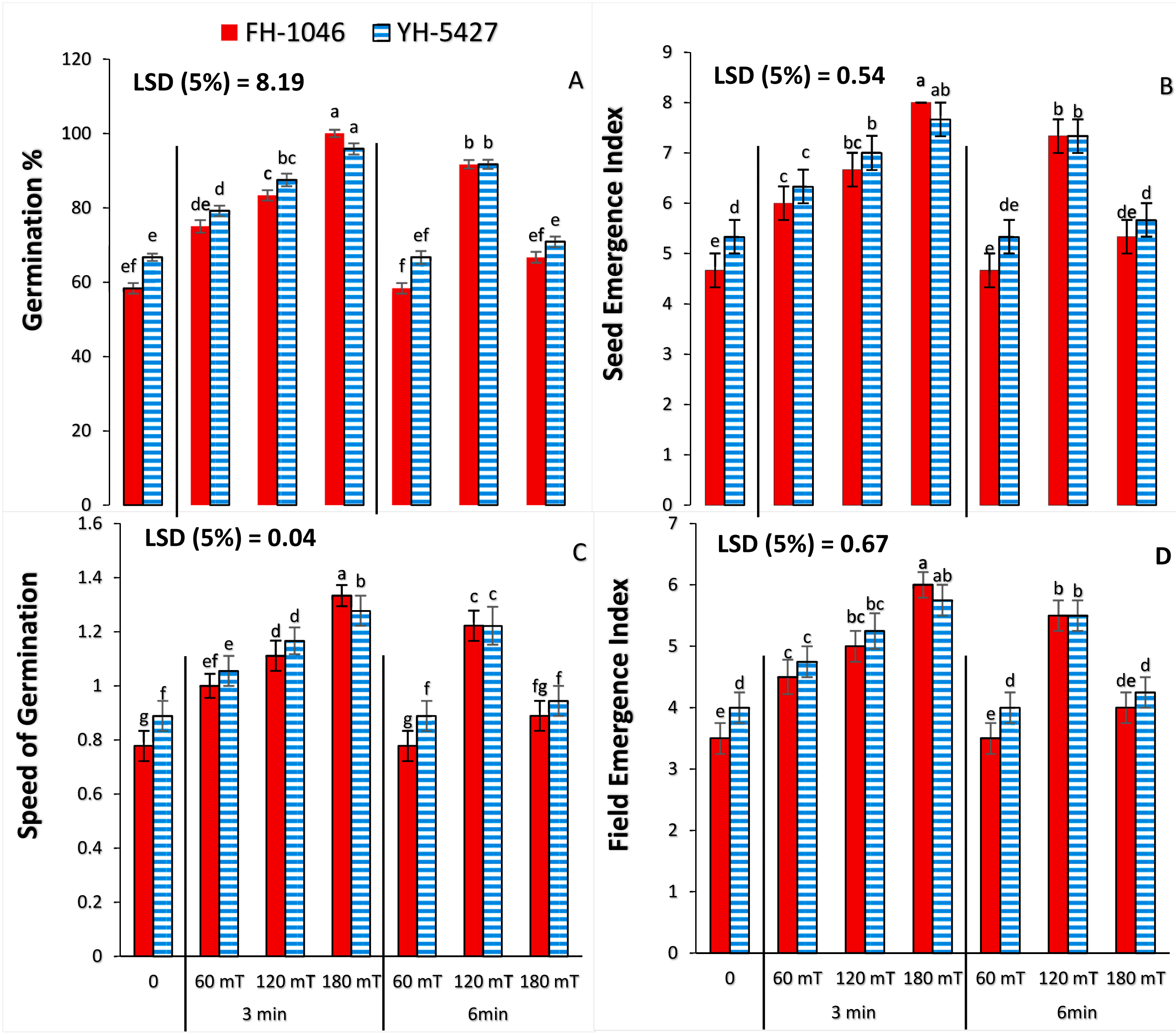

Fig. 1. Seed germination percentage (A), emergence index (B), speed of germination (C) and field emergence index (D) of magnetically primed maize seeds for different exposure times.

Randomized Design (CRD) in three replicates. After proper moisturizing and onset of suitable climatic conditions, eight electromagnetically treated seeds were sown in each pot.

2.4. Crop management and harvesting

After germination, only four healthy seedlings were maintained in each pot by thinning and crop management practices were applied such as herbs were removed by hoeing and pests were controlled by spraying suitable pesticides, if needed. Samples were taken from 45 days old plants for the investigation of morphological, physiological and biochemical properties.

2.5. Data collection

Fresh samples were taken from the second full grown leaves and carefully carried to the laboratory (transported in ice bags & avoiding sunlight) so that the water content of the tissues and chemical ingredients remained stable.

2.6. Germination kinetics and morphological parameters

Shoot and root lengths were measured with the help of measuring tape after 45 days of seed germination. Fresh weights of shoot and root were measured immediately after harvesting with the help of a digital weighing balance (Shimadzu AUX 220, Japan). The samples were oven-dried at 65 °C (Sheldon Manufacturing Inc., Portland, Oregon) for 24 h until constant weight to measure the dry weights of the samples.

ISTA (2004) recommendations were used to determine the following germination parameters.

$$Germination\% = nk/nc \times 100$$

where, nk denotes the number of seeds that have sprouted, while nc denotes the total number of seeds sown.

$$Fieldemergenceindex(FI) = \frac{Plantsemergedonday \times daysafterplanting}{Totalplantsemerged}$$

$$Speedofgermination = \sum (n/t)$$

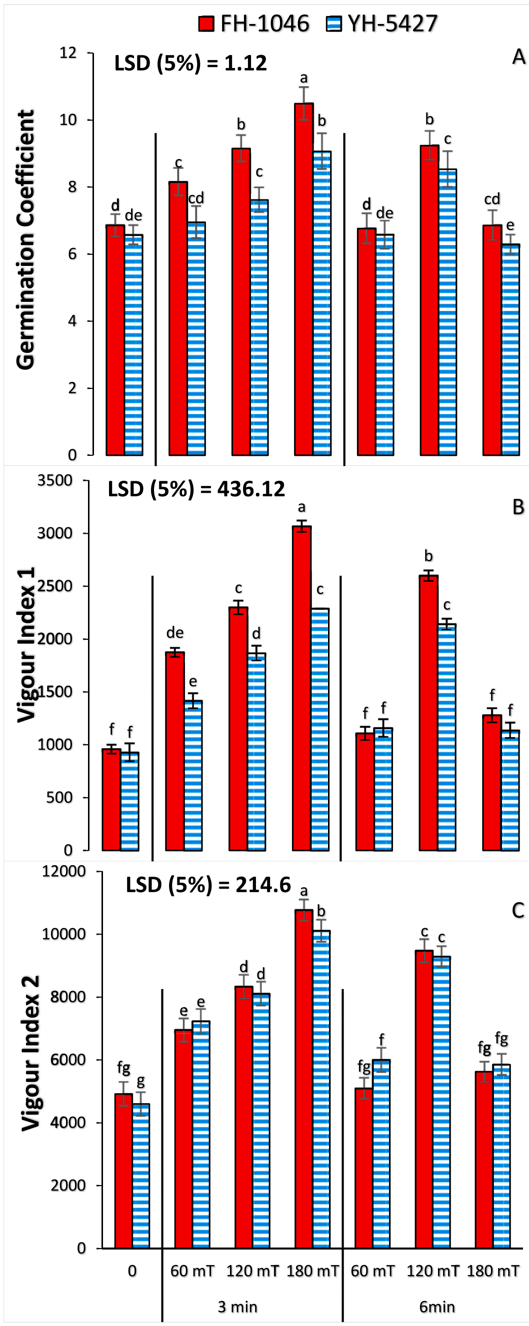

Fig. 2. Seed germination coefficient (A), and, vigour indices 1 (B) and 2 (C) of magnetically primed maize seeds for different exposure times.

$$Relativegerminationratecoefficient = \frac{n \times t}{nc}$$

where n is the number of germinated seeds at time t and nc represents the number of control group seeds germinated at time t.

The seed germination vigour indices 1 and 2 were determined following Baki and Anderson (1973) as follows:

$$Vigourindex1 = Germination(\%) \times seedlinglength(root + shoot)$$

$$Vigourindex2 = Germination(\%) \times seedlingdryweight(root + shoot)$$

$$Relativewatercontent(RWC) = \frac{Freshweight - dryweight}{Weightofturgidseedlings - dryweight} \times 100$$

2.7. Analysis of enzymatic activities

The quantities of catalase (CAT) and peroxidase (POD) were determined using Chance and Maehly (1995) method. The 1 mL reaction mixture (50 mM phosphate buffer at pH 7, 20 mM guaiacol, 40 mM H_2O_2, and 100 mL enzyme extract) were combined for 3 min. The concentration of POD was measured as absorption at 470 nm using a spectrophotometer (Hitachi-U2001, Kyoto, Japan) and activity was expressed in units per mg of protein. In the CAT reaction solution, 50 mM phosphate buffer at pH 7, 5.9 mM H_2O_2, and 100 mL enzyme extract was used. The amount of catalase was taken as absorption at 240 nm on a UV/visible spectrophotometer (Hitachi-U2001, Kyoto, Japan). The activity was expressed in units per mg of protein.

The SOD activity was measured using the Giannopolitis and Ries (1977) method, which involves monitoring the photochemical reduction of nitroblue tetrazolium. In a 1 mL reaction mixture, 100 mL enzyme extract, 13.2 mg riboflavin, 222 mg methionine, 0.0375 mL TritonX in 17.5 mL distilled water, and 15 mg nitroblue tetrazolium were combined. For 15 min., the reaction mixture was illuminated with a light intensity of 350 nm. One unit of SOD was defined as the amount of enzyme required to reduce substrate (nitroblue tetrazolium) by 50 % at a wavelength of 560 nm measured with UV/visible spectrophotometer (Hitachi-U2001, Kyoto, Japan).

2.8. Estimation of photosynthetic pigments

The amount of chlorophyll in the sample was calculated using Arnon (1949) method while carotenoids were measured by the method of Davies (1965). A 0.1 g of fresh plant material (leaf) was extracted in 5 mL of 80 % acetone overnight under dark conditions in the refrigerator to estimate photosynthetic pigments. After centrifuging the extract at 10,000 $\times$ *g* for 5 min., the absorbance of the supernatants was measured with a UV/Visible Spectrophotometer (Hitachi-U2001, Kyoto, Japan) at 663 nm, 645 nm, and 480 nm. The concentration of chlorophyll *a*, *b* and carotenoids was calculated using appropriate formulae and expressed as mg g^{-1} fresh weight.

2.9. Determination of mineral ions

The protocol of Wolf (1982) for acid digestion was followed. After being oven-dried, the roots and shoots of plants were measured as 0.01 g each. For ions analysis, these materials were ground to powder and stored in clean, dry plastic bags. In digestion flasks, the powder was taken, and 2 mL of concentrated H_2SO_4 (95–98 percent pure) was added and placed overnight in a warm place. To speed up the process, each digestion mixture was added with a 1 mL H_2O_2 solution and placed on a hot plate (50–250 °C) until fumes appeared. In increments of 1mLH_2O_2 was added until the reaction mixture became colourless. The substance was filtered through filter paper and volumetric flasks were used to make the volume to 50 mL using distilled water. The concentrations of metabolically important ions (Na^+, K^+ and Ca^{2+}) were measured using a flame photometer (PFP-7, Jenway, Japan) after adjusting readings against known standards.

2.10. Statistical analysis

The statistical analysis (ANOVA) was done using the CoStat computer package (v 6.303) and used to calculate LSD values (5 %) at a confidence level of 95 %. The LSD values so generated were used to place letters of significance among treatment in figures where EMF $\times$ Time $\times$ Cultivars interaction terms were significant (Steel and Torrie, 1980). A customized R code was used to visualize clustered heatmaps where various germination, growth and physiological attributes of maize cultivars were clustered based on their response similarity to EMF exposure. The PCA biplots were also constructed using a customized R code to visualize the response of different growth, physiological and

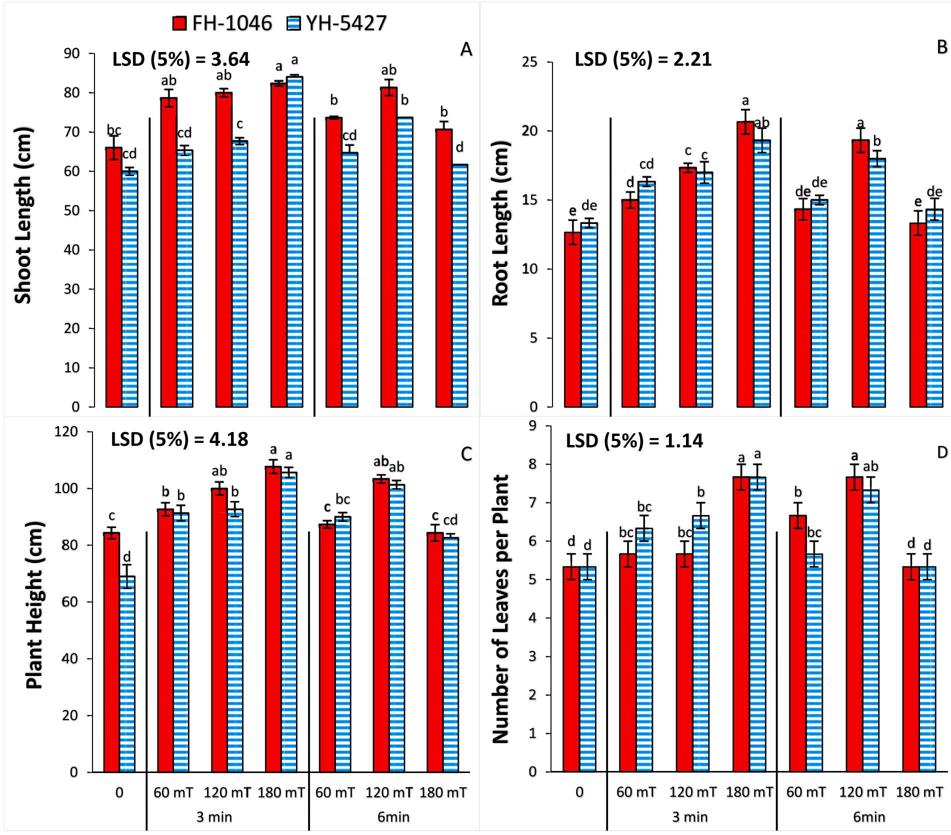

Fig. 3. Shoot (A) and root (B) lengths, plant height (C) and number of leaves per plant (D) of maize plants grown from magnetically primed seeds magnetized for different exposure times.

biochemical attributes against applied EMF at different time intervals. The strength of different variables was then expressed from steel blue (the least contributory as 1) to red (the most contributory as 3.25). All visualization was done in R Studios (v 1.1.463) backended by R console (R i386 4.0.5).

3. Results

Maize seeds treated with electromagnetic field (EMF) had significantly greater germination performance than untreated seeds ($P \leq 0.05$. Magnetic treatments increased the germination kinetics of maize. Germination attributes were in almost similar patterns when subjected to different doses of EMF and time of exposure (Figs. 1 and 2). Highest germination % age (171.41 % and 157.15 %), speed of germination (174.29 % and 151.34 %), field emergence index (177.34 % and 150.34 %), and germination coefficient (152.91 % and 134.69 %) were observed at the T_3 (treatment with 180mT magnetic field for 3 min.) and T_5 (120mT for 6 min.), respectively.

Magnetically treated seeds exhibited vigorous growth as compared to untreated seeds ($P \leq 0.05$. As evident from Figs. 3 and 4, magnetic induction resulted in the production of greater fresh and dry biomass of the maize plants. Broader leaf area, taller heights, and more fresh and dry weights of the seedlings indicated the useful impacts of EMF on the growth and development of vegetative parts. Just like in the germination parameters, the influence of EMF on vegetative growth appeared in a similar pattern. Treatment with 180mT magnetic field for 3 min. and 120mT for 6 min. exerted better effects on plant heights and fresh weights which increased by 127.67 %, 122.53 %; and 183.99 %, 169.97 %, at respective levels.

All the treatments showed significant differences ($P \leq 0.05$) on the moisture contents and photosynthetic pigments (Figs. 5 and 6). The highest concentration of chlorophyll *a* was observed for the T_3 (treatment with 180mT magnetic field for 3 min.) and T_5 (120mT for 6 min.), which were 116.70 % and 155.21 % greater than the control group, respectively. At the same EMF levels, chlorophyll *b* contents increase by 108.07 % and 114.03 %, respectively. Total chlorophyll concentrations were more influenced at higher EMF strengths by longer exposure time i.e., at T_5 (120mT for 6 min.) and T_6 (180mT for 6 min.). Here the total chlorophyll contents were increased by 133 % and 159.52 % with respect to the control group. Carotenoid contents showed synchronized pattern with the chlorophyll *a* concentrations. Its maximum concentration was observed at 216.96 % and 192.45 % at T_3 and T_5, correspondingly. As can be comprehended from the results, the genotype FH-1046 exhibited higher physiological performance than YH-5427.

Activities of antioxidative enzymes were enhanced under EMF exposure (Fig. 7). The maximum activities for catalase and peroxidase were observed at the same EMF levels as that of chlorophyll *a*. Catalase activity was the highest, i.e. 105.67 % at T_3 (180mT for 3 min.) and 104.77 % at (T_5) 120mT for 6 min. Peroxidase activity showed the maximum efficiency of 1018.18 % at T_3 (180mT for 3 min.) and 827.27 % at T_5 (120mT for 6 min.). Superoxide dismutase demonstrated higher activity at higher EMF intensities. It showed the optimum performance at 180mT for 3 min. (281.81 %) and 120mT for 6 min. (i.e. 277.27 %).

The magnetic field triggered significant changes ($P \leq 0.05$) in the accumulation of mineral nutrients like Na^+, K^+, and Ca^{2+} (Fig. 8). The application of different EMF treatments significantly altered the concentrations of these nutrients in the stems and roots of both maize genotypes. Statistical analysis revealed that the levels of Na^+, K^+, and Ca^{2+} were high in roots, stems as well as in leaves. The effects of different treatments of EMF were consistent in all elements, however, levels of K^+ abruptly increased manifold in roots (135.67 meq/g at 180mT for 3 min. and 102.33 meq/g at 120mT for 6 min.). Shoot K^+ contents were also considerably much higher as compared to those of Na^+ and Ca^{2+}. Root

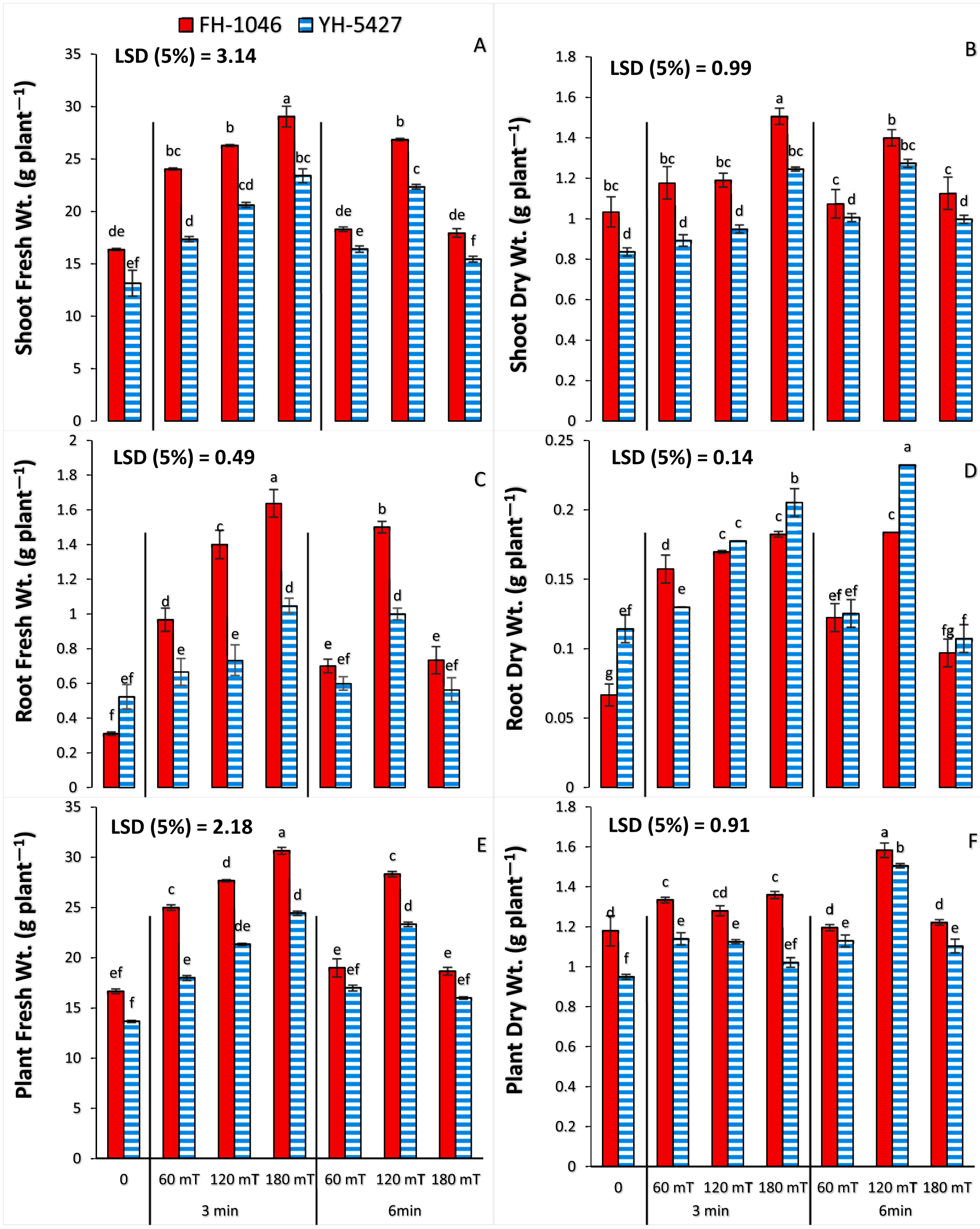

Fig. 4. Shoot fresh (A) and dry (B), root fresh (C) and dry (D), and, total plant fresh (E) and dry (F) weights of maize plants grown from magnetically primed seeds magnetized for different exposure times.

Ca^{2+} accumulation raised only up to 6 meq/g at 180mT for 3 min. and 5.33 meq/g at 120mT for 6 min. The maximum Na^{+} contents were recorded in roots (12.67 meq/g at 180mT for 3 min. and 13.33 meq/g at 120mT for 6 min.).

3.1. Clustered heatmaps

The heatmaps displayed a two-way relationship between EMF treatments and observed traits of maize that assessed interaction based upon the strength of colored rectangular boxes i.e., in Fig. 9. The hierarchical clustering of rows differentiated the combined influence of various traits as modulated by a particular EMF treatment given at a specific interval. The color of the boxes was proportionate to the strength presented along a color gradient. The steel blue was positively correlated while red was negatively correlated. As elucidated from the first and second clusters in the heatmap, most of the seed germination and seedling growth attributes (except chlorophyll and total chlorophyll) were strong positively linked with the 180mT treatment for 3 min. and 120mT for 6 min. in both the cultivars FH-1046 and YH-5427. Cluster 3 contained 60mT and 180mT at 6 min. exposure time in cultivar YH-5427 where most of the attributes were strong negatively influenced. Controls of both cultivars were clustered in cluster four with mostly a strong negative relationship. Cluster 5 mostly had a weak positive relationship between recorded attributes by 60 and 120mT EMF intensity at 3 min exposure time in cultivar FH-1046. A weak negative correlation between plants attributes of cultivar FH-1046 was observed at 6 min. exposure time at 60 and 180mT intensity in cluster six. Cluster 7 grouped cultivar YH-5427 exposed to 60 and 120mT dose level at 3 min. time with mixed weak positive and negative effects.

Clustered heatmap for plant attributes (defined from right to left) displayed seven distinct clusters, which provide information about the relationships of data under electromagnetic treatments and seedling

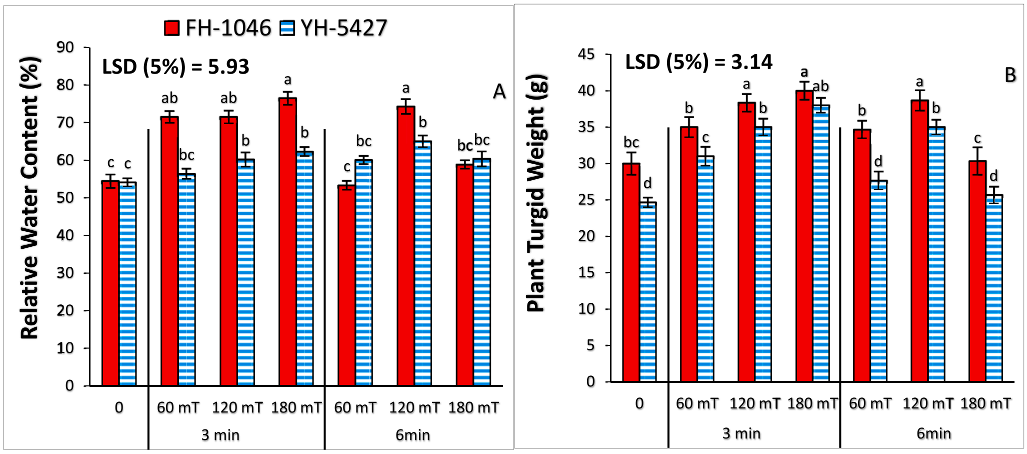

Fig. 5. Relative water content (A) and turgid weight (B) of maize plants grown from magnetically primed seeds magnetized for different exposure times.

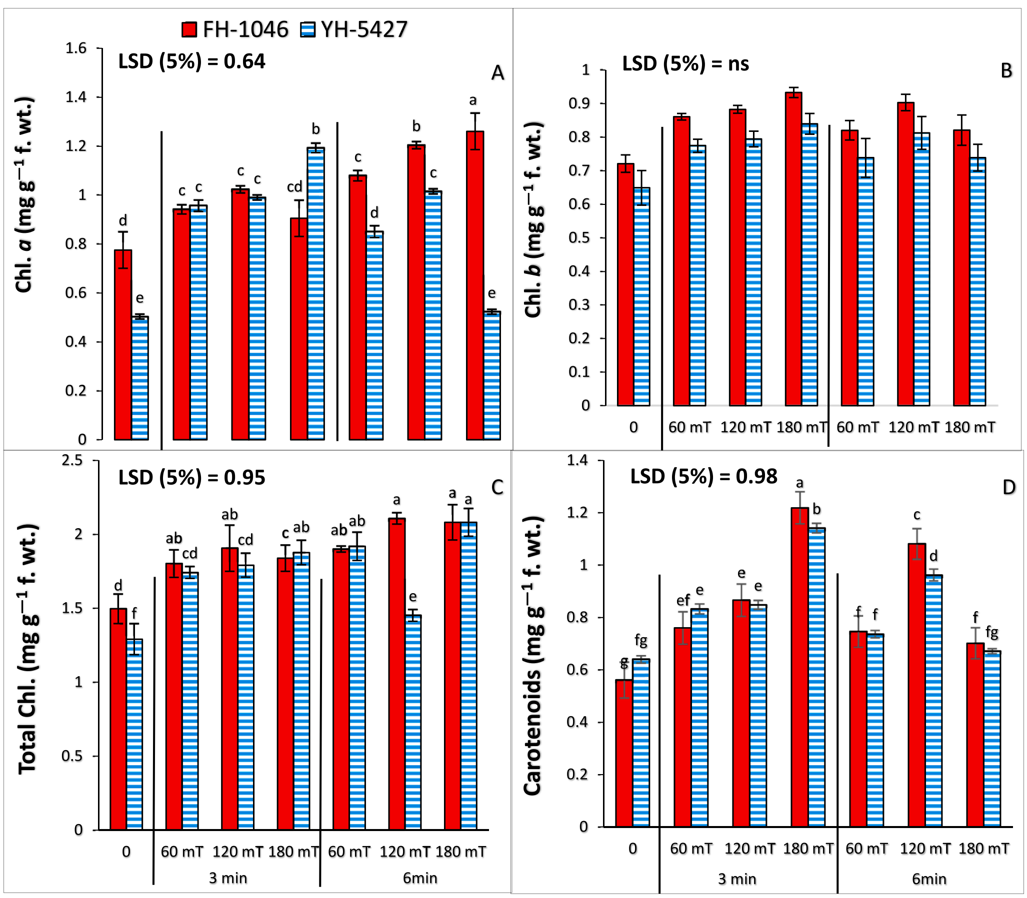

Fig. 6. Chlorophyll *a* (A), *b* (B), total chlorophyll (C) and carotenoid (D) contents of maize plants grown from magnetically primed seeds magnetized for different exposure times.

growth. The first cluster (rightmost) showed a close relationship between shoot length, chlorophyll *b* contents, shoot sodium concentration and plant turgid weight. The second cluster demonstrated an association of relative growth coefficients with the shoot and root fresh weight, shoot dry weight, relative water content, root sodium concentration, superoxide dismutase concentration and vigour index 2. The third cluster had an isolated position (weak negatively linked) of plant dry weight as it was not linked to any other attributes. The fourth cluster was the largest one exhibiting a correlation between plant height and germination percentage, field emergence index, speed of germination, vigour index 1, number of leaves per plant, root length, carotenoids, catalase, and ions like root calcium and shoot potassium. Peroxidase and root potassium were clustered with root dry weight in fifth smaller cluster. Chlorophyll *a* and total chlorophyll contents were grouped separately in sixth and seventh clusters, indicating their weakest contributory response to the EMF exposure (Fig. 9).

3.2. Principal component analysis (PCA)

PCA analysis demonstrated great variations in germination, growth

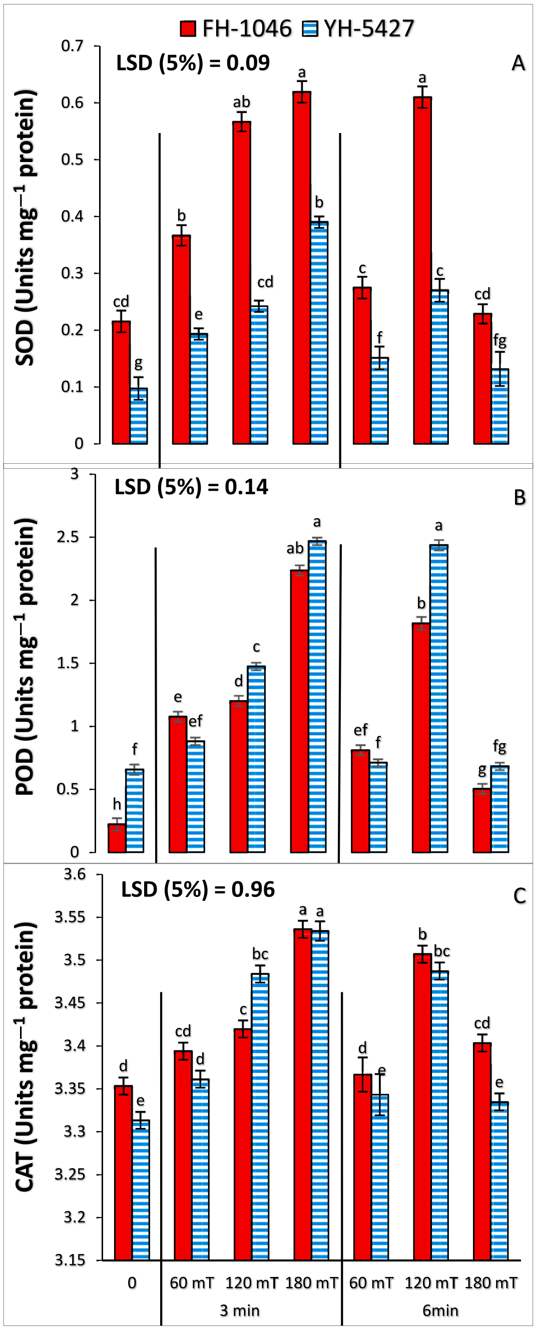

Fig. 7. Superoxide dismutase (A), peroxidase (B) and catalase (C) activities of maize plants grown from magnetically primed seeds magnetized for different exposure times.

and physio-biochemical attributes which were represented in two isolated groups under the influence of electromagnetic fields (Fig. 10). The first and second PCAs axes explicated 76.9 % and 8.7 % (total 85.6 %) variations among treatments and seedlings' growth. The genotype FH-1046 was the major principal contributor to the EMF treatments at 60mT for 3 min. and 120mTfor 3 min. with positive eigenvalues. Several growth attributes were grouped in genotype FH-1046. Relative growth coefficient, vigor index 2, plant fresh weight, superoxide dismutase, and chlorophyll *b* contents were strongly associated with each other in this variety. Other major components correlated in this group included plant turgid weight, relative water content, plant dry weight, chlorophyll *a* and root sodium ions contents.

In cultivar YH-5427, 60, 120 and 180mT for 3 min were grouped indicating 3 min. time interval as the most effective exposure time for germination and growth enhancement in this cultivar. This group included a close association among vigor index2, relative growth coefficient, plant fresh weight, plant dry weight, chlorophyll *a* and *b*, superoxide dismutase content and root sodium concentration. Simultaneously, major principal components in the second subgroup showed a close association among plant height, shoot potassium and calcium concentration, catalase, carotenoids, vigor index 1, POD and root calcium and potassium contents in the same genotype (YH-5427) which contributed toward improvement in germination and growth. Plants grown from un-magnetized seeds of both cultivars were plotted at a distance indicating no significant association with any observed germination, morpho-physiological and biochemical parameters. These results accomplish that both the genotypes responded equally to the electromagnetic fields.

4. Discussion

Plants are immobile and therefore, their growth is strongly impaired by limited resources and environmental constraints. Most scientists undertake impacts of factors like heat, water content, light, and infertility of land on plant growth and development. Conversely, it was postulated in our study that EMF (electromagnetic field) should enhanced plant growth performance when exposed to different intensities and time intervals.

In this study, maize seeds treated with electromagnetic field (EMF) had significantly better germination kinetics than untreated seeds as also reported in earlier studies (Florez et al., 2007). Germination attributes in both cultivars (FH-1046 & YH-5427) were affected in almost similar patterns but their response varied with different treatments of EMF and time of exposure (Figs. 1 and 2). The highest values of germination %age, speed of germination, field emergence index, and germination coefficient were observed at treatment with 180mT magnetic field for 3 min. and 120mT for 6 min., respectively. Maize seeds treated with electromagnetic field (EMF) had significantly greater germination than untreated seeds. Magnetic treatments improved maize germination kinetics. The T_3 (treatment with 180mT magnetic field for 3 min.) and T_5 (treatment with 120mT magnetic field for 6 min.) had the highest germination percentage (171.41 and 157.15 %), speed of germination (174.29 and 151.34 %), field emergence index (177.34 and 150.34 %), and germination coefficient (152.91 and 134.69 %). This led to a significantly higher height of seedlings and more biomass production as compared to control plantlets. In a past study, seed germination kinetics of *Valeriana officinalis* L. were altered under the influence of the electromagnetic field, the rapid protein degradation during the early stages of seedlings (Sara et al., 2013). In another study, pea seeds sprouted more quickly as a result of improved water absorption rate induced by magnetic field treatment (Garcia and Arza, 2001). Molecular mobility of cytoplasmic bulk water and hydration of macromolecules are signs of an increase in water status during seed imbibition in maize seeds after magnetic field treatment. The reason why seeds germinated more quickly was due to the early hydration of macromolecules as well as higher membrane and enzyme activity (Vashisth and Nagarajan, 2010). The electromagnetic field (EMF) influences plant cell membranes and Ca signaling, and magnetic effects in biological systems are most likely connected to changes in membrane-associated calcium flow (Galland and Pazur, 2005). Specifically, when exposed to magnetic fields, the diamagnetic anisotropic features of membrane phospholipids cause the phospholipids to reorient, which results in the deformation of membrane channels. Sodium channels, however, were influenced to a lower extent than Ca channels (Rosen, 2003). These findings clearly imply that the application of EMF can boost the absorption of minerals, which enhances plant development.

Elevated concentrations of chlorophyll and carotenoids (Fig. 5) manifested the penetrating power of electromagnetic field at the cell level and its role in triggering physiologically and metabolically

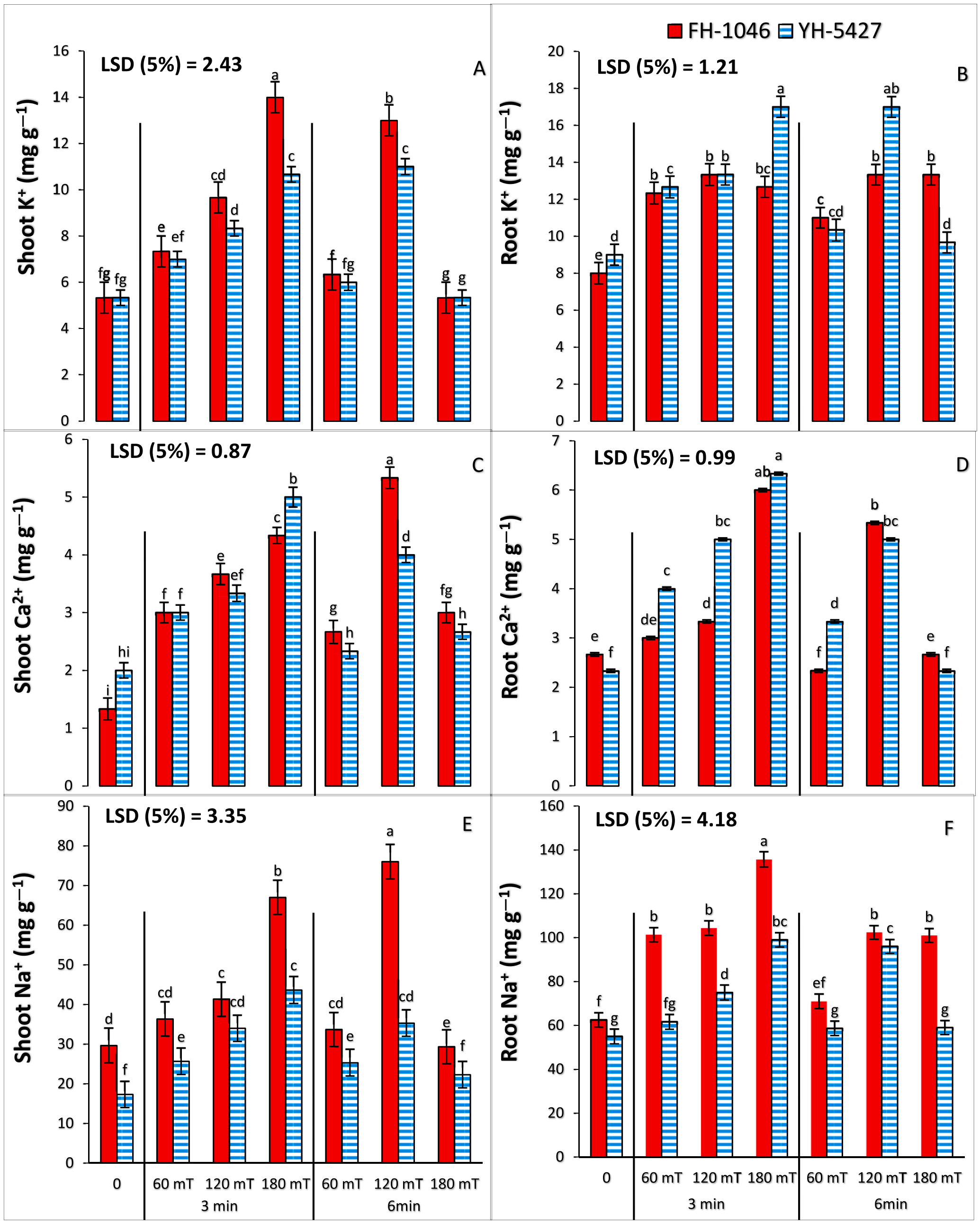

Fig. 8. Shoot (A) and root (B) K^+, shoot (C) and root (D) Ca^{2+}, and, shoot (E) and root (F) Na^+ of maize plants grown from magnetically primed seeds magnetized for different exposure times.

imperative interactions which ultimately appeared in the form of relatively better performance and vitality of the plants. The T_3 (treatment with 180mT magnetic field for 3 min.) and T_5 (120mT for 6 min.) had the highest concentrations of chlorophyll *a*, which were 116.70 and 155.21 % higher than the control group, respectively. Chlorophyll *b* content increased by 108.07 and 114.03 % at the same EMF levels. Larger leaf area and higher water content indicated that photosynthetic machinery was being used effectively and that water use efficiency was improved (Fig. 6). Enhanced uptake and assimilation of water in EMF-stimulated seedlings and rapid trafficking of amino acids and mineral ions across the cell membranes collectively accelerated the physiological processes (Podlesny et al., 2004). In a past study, *Arabidopsis* plants grown in a magnetic field-free chamber failed to develop hypocotyl and flowering was delayed. Moreover, cytochrome regulatory genes were also suppressed in the absence of electromagnetic fields in growing media (Xu et al., 2012).

Enzymatic activities play a vital role in the development, growth and maintenance of plants. Our study showed that the magnetic field enhanced the activities of antioxidants and accumulated higher quantities of mineral ions as compared to the control group (Figs. 7 and 8). At the same EMF levels as noted for chlorophyll *a*, the maximum activities of catalase, peroxidase and superoxide dismutase enzymes were observed at treatments with 180mT magnetic field for 3 min. and 120mT for 6 min. An investigation of such biochemical moieties provides an estimate of their impacts on the overall performance of plants. The primary method for changing proteins via electromagnetic fields is the ability of proteins' polar groups to absorb energy and produce free radicals or cause proteins to aggregate and unwind. Free radicals have the ability to interfere with a variety of interactions between protein molecules, including Van der Waals forces, electrostatic and hydrophobic interactions, H-bonding, disulfide bridges, and salt bridges. These interactions affect different levels of protein structure and

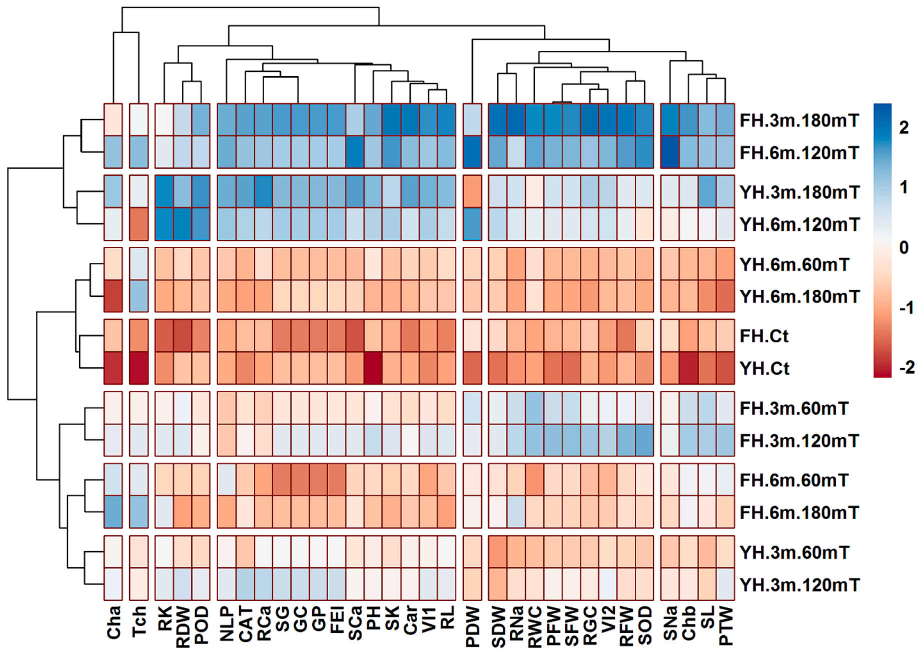

Fig. 9. Clustered heatmap showing clustering of various germination, growth and physiological attributes of maize plants grown from magnetically primed seeds magnetized for different exposure times.

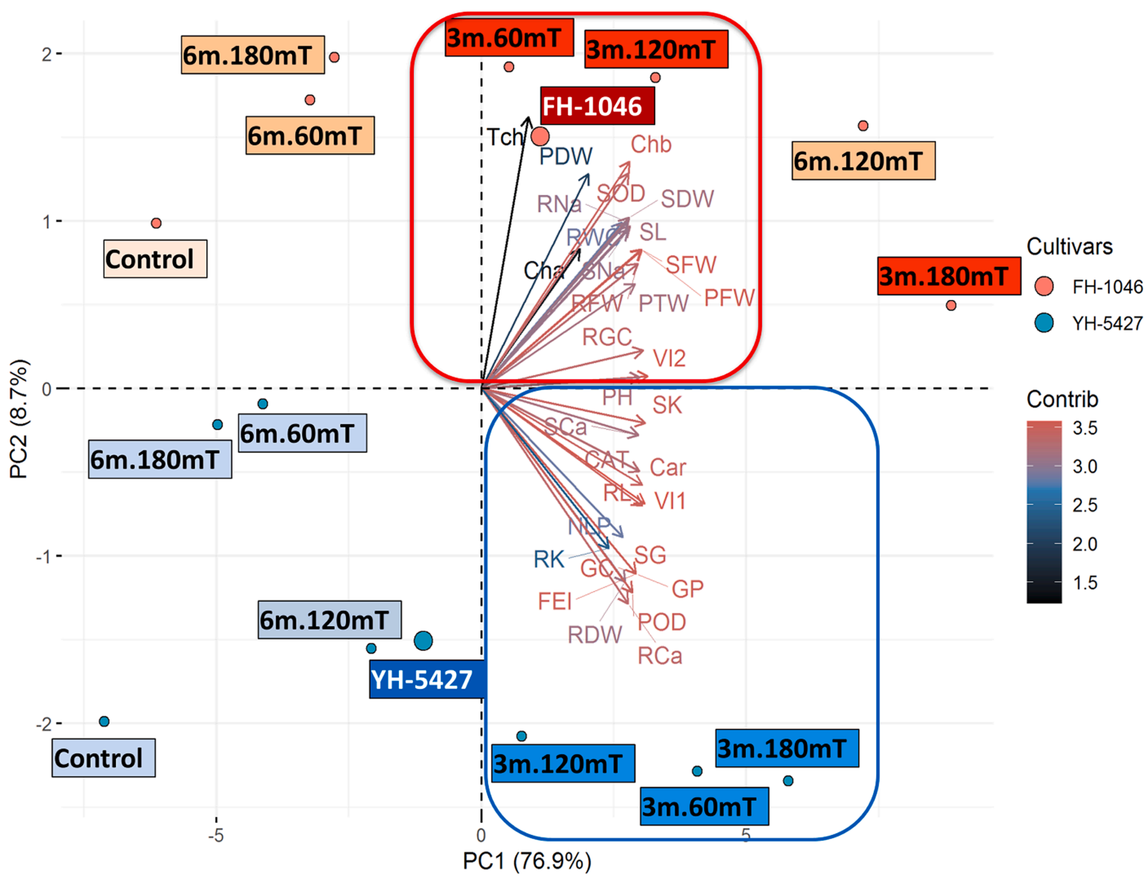

Fig. 10. PCA biplot of various germination, growth and physiological attributes of maize plants grown from magnetically primed seeds magnetized for different exposure times.

functional properties upon exposure to EMF (Wang et al., 2008). Findings exploring the impact of extremely low-frequency electromagnetic fields (EMFs) on plant germination and early growth suggest that the EMF effects correspond to ion cyclotron-resonance frequencies for calcium and potassium ions, changing their distribution and subsequently affecting seed germination and plant growth (Smith et al., 1993). Faster growth of seedlings of maize treated with magnetic field compared to the control seeds, as observed in our study, was supported by the higher overall performance of antioxidant enzymes in magneto-primed seeds than untreated seeds in the control group (Hajnorouzi et al., 2011).

5. Conclusion

Pre-sowing exposure of maize seeds with electromagnetic field resulted in better performance in germination kinetics, biochemical assays, and growth dynamics as compared to the corresponding unmagnetized control group. The close relationship between germination traits and photosynthetic pigments indicated superseding effects of EMF on the growth and development of seedlings. Up-regulation in antioxidant enzymatic activities and mineral ions accumulation also affirmed the positive effects of EMF in enhancing growth attributes and maintaining regulatory processes. Variable responses to different intensities of electromagnetic field treatments were perhaps due to the differential stimulatory nature of EMF in triggering physiological and metabolic pathways. However, pronounced outcomes were observed at 180mT for 3 min. and 120mT for 6 min. of exposure time. Of the two maize genotypes, FH- 1046 exhibited better performance than YH- 5427 at all treatment levels.

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Author Contributions

MFA and MSAA drafted the experimental design and MFA did the experimental work. ARZF analyzed the data and helped the writing of this paper. AS revised the manuscript and corrected the language of the manuscript.

CRediT authorship contribution statement

Muhammad Faraz Ali: Conceptualization, Investigation, Methodology. **Muhammad Sajid Aqeel Ahmad:** Conceptualization, Project administration, Supervision, Writing – original draft. **Abdel-Rhman Z. Gaafar:** Data curation, Resources, Validation, Writing – original draft, Writing – review & editing. **Awais Shakoor:** Formal analysis, Resources, Visualization, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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