Enhancement of maize seeds germination by magnetopriming in perspective with reactive oxygen species

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Abstract. The utility of stationary magnetic field (SMF) for biostimulation of seeds and associated physio-biochemical changes in maize (Zea mays L.) var. HQPM.1 was studied under laboratory conditions. Magnetopriming improved germination related parameters like percentage of germination, speed of germination, seedling length, fresh weight, dry weight and vigour indices. Among the various parameters seedling length and vigour Index I were the most improved parameters (up to 72 to 59% respectively) after magnetopriming. Two doses (200 mT for 60 min and 100 mT for 120 min) were further taken to understand the involvement of reactive oxygen species (O\(_2^\cdot\), \(\text{OH}\) and H\(_2\)O\(_2\)) and antioxidant enzymes in the magnetoprimed seeds as they were best in improving germination related parameters. Enhanced germination in magnetoprimed maize seeds was coupled with enhanced reactive oxygen species content. Peroxidase (both cytosolic and wall bound) activity was enhanced and superoxide (both cytosolic and wall bound) activity was reduced in the embryo and the eight-day-old seedlings from magnetoprimed seeds. Obtained results indicated that magnetopriming can be effectively used as a biostimulant for seed germination and the impact of SMF is biochemically identified in context with reactive oxygen species.

Keywords: Biostimulation, magnetopriming, reactive oxygen species, seedling growth.

INTRODUCTION

The pursuit for an efficient and economical technique to develop quality-sowing seed has been an interest of industry and academics. Among the various priming techniques explored, magnetopriming has attracted an increased attention in the past few decades, as it is ecofriendly and cost effective. The majority of the obtained results show that the magnetic field acts as a biostimulant and causes enhanced germination and growth. Mung beans and water convolvuluses seeds when treated with electromagnetic field enhanced germination (Jinapang et al., 2010). Germination enhancement was optimum for the mung beans at 100 mW/1h power duration level, while for water convolvuluses the optimum germination power-duration level was 1 mW/2 h. Enhanced germination rate, seedling growth and development in cucumber by magnetic field pre-treatment was reported by Yinan et al. (2005). The effects of electromagnetic irradiation on seed vigour of maize hybrids, as well as the response of each genotype were assessed by Zepeda-Bautista et al. (2009) and reported that pre-sowing treatment increases corn seed vigour through emergence rate, establishment percentage, and dry mass of seedling aerial part, according to the combination of radiation intensity, time and genotype. Reduced mean germination time and enhanced germination were obtained by exposing tomato...
seeds to stationary magnetic field of 125 and 200 mT for different duration (Martinez et al., 2009). Plethora of literature is available on the effect of magnetic biostimulation of seeds using stationary magnetic field (Shine et al., 2011ab; Bhagwan et al., 2012; Thomas et al., 2013; Kataria et al., 2015; Kataria et al., 2017).

Extensive research has revealed that the effects of magnetopriming treatments depend on the magnetic field strength, duration of exposure (Wittekind et al., 1990), the physiological condition of the organism involved, and the environmental conditions (Weaver, 1993; Gutzeit, 2001). Pertinent literature on magnetopriming shows that most of the work in this field is limited to studying only the germination related parameters of primed seeds with a few exceptions. Under laboratory and field conditions, SMF strength of 200 mT (60 min) was proved to be best for improving different seedling parameters of maize (Shine and Guruprasad, 2012; Vashishth and Joshi, 2016); however biochemical and biophysiological changes associated with enhanced germination after magnetopriming has not been addressed in case of a cereal crop like maize. Therefore the present study was carried out with the objective of understanding the biochemical and biophysiological changes associated with magnetic biostimulation of maize seeds during germination.

MATERIALS AND METHODS

The breeder seeds of maize (Zea mays L.) var. HQPM.1 were collected from Indian Agricultural Research Institute, New Delhi, India. Seeds of uniform size and shape without visible defects and malformation were selected and stored in a desiccators having anhydrous calcium chloride. Seed moisture content was determined by oven drying seeds at 95°C to constant weight (Walters, 1998). Moisture content (%) was calculated as (W1-W2/W1) x 100, where W1 was the initial weight of the seed and W2 was the final weight of the seed after drying. Moisture content was 8.2% in the seeds used for all treatments and experiments.

Magnetic field generation

An electromagnetic field generator “Testron EM-20” (Testron India, Delhi, India) with variable horizontal magnetic field strength (50 to 500 mT) and a gap of 5 cm between pole pieces was used for seed priming treatment (Vashisth and Nagarajan, 2008). The pole pieces were cylindrical in shape, with 9 cm diameter and 16 cm length. The number of turns per coil was 3000 and the resistance of the coil was 16 ohms. A DC power supply (80 V/10 A) with continuously variable output current was used for the electromagnet. A digital Gauss meter model DGM-30 (Testron India) operating on the principle of Hall Effect monitored the field strength produced in the pole gap. The probe made of Indium Arsenide crystal and encapsulated to a non-magnetic sheet of 5 mm x 4 mm x 1 mm could measure 0-2 T with full scale range in increments of 5 mT.

Magnetic treatment

Maize seeds were exposed to a magnetic field of 50 to 250 mT in steps of 50 mT for 30 to 120 min at an interval of 30 min in a cylindrical shaped sample holder of 42 cm³ capacity, made from a non-magnetic thin transparent plastic sheet. Hundred mature and healthy seeds held in the plastic container were placed between the poles of the electromagnet under a uniform magnetic field. The required strength of the magnetic field was obtained by regulating the current in the coils of the electromagnet. A Gauss meter was used to measure the strength of the magnetic field between the poles. At low field (50 mT), from the centre to end of the poles, the variation was 0.6% in the horizontal direction and 1.6% in the vertical direction of the applied field. At high field (500 mT), they were 0.4 and 1.2% of the applied field, respectively. The variation in temperature during the course of seed exposure was 25 ± 0.5°C.

Seed germination

Seed germination was determined by following the method of ISTA (1985). Four replications each with 25 seeds were placed between two layers of moist germination paper, rolled carefully and wrapped in a sheet of wax paper to reduce surface evaporation. They were placed in a seed germinator (Remi Instruments Ltd., India) at 25°C in an upright position. After 8 days, germinated seeds were grouped as normal, abnormal seedling, and dead seeds. Normal seedlings were the seedling with well-developed coleoptiles, mesocotyl and radicle, whereas abnormal seedlings were designated to seedling with stunted radicle with weak/no mesocotyl. Germination percentage was calculated on the basis of normal seedlings. Ten such seedlings from each replicate were randomly taken for measuring seedling length. Subsequently, they were dried overnight in an oven at 90°C and dry weight was measured. Seedling vigor was calculated following Abdul-Baki and Anderson (1973), as: Vigor index I = Germination % × Seedling length (Root + Shoot)

Vigor index II = Germination % × Seedling dry weight (Root + Shoot)

Speed of germination

Hundred seeds in four equal replications were placed on moistened filter paper in Petri dishes and kept in an incubator at 25°C. Radicle emergence from the seed was scored as positive germination. A daily germination count
of the incubated seeds was taken until no more seeds germinated. The speed of germination was calculated following Maguire (1962), as:

Speed of germination = \( \Sigma (n/t) \)

where \( n \) is the number of seeds newly germinating at time \( t \) and \( t \) is days from sowing.

### Spectrophotometric assay of \( \text{O}_2^- \) production

\( \text{O}_2^- \) production was measured by the reduction of Na,3’-(1-((phenylamino)-carbonyl)-3,4-tetrazolium) (4-methoxy-6-nitro) benzene sulfonic acid hydrate (XTT) (Sigma-Aldrich) (Frahry and Schopfer, 2001). Groups of 20 embryos or 20 abraded seedling parts (0.5 cm, from 8 day old dark grown seedling) were incubated in 5 ml of K-phosphate buffer (pH 6.0) containing 500 \( \mu \)M XTT in darkness at 25°C on a shaker. Aliquots were obtained at 15 min interval and absorbance was read at 470 nm by using spectrophotometer (UV-1601: Shimadzu, Nakagyo –Ku, Kyoto, Japan).

### Electron paramagnetic resonance spectroscopy (EPR) of OH radicals

The OH content in embryos and eight day old seedlings were measured as described by Liszky et al. (2003). coleoptiles/mesocotyl/radicle (0.5 cm) from control and treated seedlings were incubated for 1 h in 15 ml of water and then in 2 ml reaction medium containing 20 mM K-phosphate buffer (pH 6.0), 850 mM ethanol/50 mM α-(4-pyridyl-1-oxide)-N-tert-butylnitrone (POBN) as a spin trapping system. After incubating for 1 h on shaker, EPR spectra of the hydroxyethyl-POBN adduct were measured at room temperature. EPR spectra were recorded using a JEOL JES-FA 300 X-band EPR (Akishima, Tokyo, Japan) spectrometer EPR instruments setting-Microwave power 5 mW, modulation width 0.2 mT, amplitude 8000, field centre 338.092 mT with width +/−5.0 mT, sweep time 4 min and time constant 0.03 s. Hydroxyl radical produced from fenton reaction was recorded as a standard spectra for hydroxyethyl-POBN adduct. All the chemicals used in spin trapping experiments were purchased from Sigma-Aldrich, St. Louis, USA. Hydroxyl radical (OH) production was specifically tested in embryos and eight-day-old seedling using ethanol/POBN spin trap, which reacts with OH and forms relatively stable hydroxy ethyl/POBN adducts (Ramos et al., 1992).

### Hydrogen peroxide assay

Hydrogen peroxide content was determined by measuring the absorbance of titanium-hydroperoxide complex (Mukherjee and Choudhari, 1983). A group of 20 embryos and 0.5 g of 8-day-old dark grown seedling tissue (coleoptiles/mesocotyl/radicle) was crushed in 10 ml of chilled acetone. Concentration of hydrogen peroxide was determined using the standard curve plotted with known concentration of hydrogen peroxide. A standard curve in the range 0 to 10 \( \mu \)M/ml \( \text{H}_2\text{O}_2 \) was used for the calculation of \( \text{H}_2\text{O}_2 \) present in the tissue.

### Enzyme extraction and assay

Superoxide dismutase (SOD) (EC 1.15.1.1) and peroxidase (POD) (EC 1.11.1.7) were obtained from maize seedlings as described by Carpita (1984) with some minor modifications (Kukavica et al., 2009). One gram of tissue was homogenized in 5 ml Tris-HCl buffer (50mM, pH 7.0) containing 50 mM NaCl, 0.05 % Tween-80, and 1 mM phenylmethyl sulfonyl fluoride (PMSF). The homogenate was filtered through two layers of mira cloth and supernatant was centrifuged at 12,000 rpm for 20 min. The supernatant obtained after centrifugation was used for the estimation of cytosolic SOD and POD. The pellet was washed four times with the above buffer without detergent and salt until the pellet was free of cytosolic SOD and POD (tested with reaction mixture of the respective enzyme) and then suspended in 2 ml of 1 M NaCl. Cell wall isolate obtained after centrifugation was digested for 24 h at 4°C in 2 ml of a mixture containing 0.5 % cellulase and 2.5 % pectinase in 50 mM Tris-HCl (pH 7.2) and centrifuged at 10, 000 rpm for 10 min (Lin and Kao, 2001). POD and SOD bound to the cell wall isolates were released by this procedure. The supernatant obtained through this procedure was used for the quantification of wall bound SOD and POD.

Total SOD activity was assayed by the inhibition of the photochemical reduction of Nitro Blue Tetratolzolium chloride (NBT) as described by Beauchamp and Fridovich (1971). One unit of SOD was defined as the amount of enzyme which produced a 50 % inhibition of NBT reduction under the assay conditions (Giannopolitis and Ries, 1977). Peroxidase was assayed by the method of Chance and Maehly (1955). The activity was calculated as change in OD min⁻¹mg protein⁻¹.

Protein concentration was estimated by the method of Lowry et al. (1951) using bovine serum albumin as a standard. All the chemicals for enzyme analysis were purchased from Hi-Media, Mumbai and Maharashtra, India.

### RESULTS

#### Germination characteristics at different magnetic field dose

Magnetopriming of maize seeds resulted in the improvement of the following parameters in the range of
Figure 1. Effect of static magnetic field treatment on different germination parameters of maize seeds. Vertical line above the bar indicates ± S.E.M. Upper symbol indicates the differences vs control. ***, ** and * indicate significance at p < 0.001, 0.01, 0.05 respectively.

0 to 10% for germination, 8 to 58% for speed of germination, 19 to 47% for seedling length, 17 to 72% for seedling fresh weight and 5 to 22% for seedling dry weight, 18 to 59% for vigour index I and 0 to 23% for vigour index II (Figure 1A to G). It was also observed that higher field strength for longer duration (in most of the cases 200 mT for 120 min and 250 mT above 30 min) had a detrimental effect on these parameters. Maximum enhancement of seedling parameters were obtained by 200 mT (60 min) followed by 100 mT (120 min), hence these two doses were further used for understanding the different biochemical and biophysical changes associated with magnetopriming.

Effect of magnetic field treatment on reactive oxygen species (ROS) generation

Rate of $O_2^-$ production with XTT assay

Treatment of seeds with SMF increased the production of $O_2^-$ in embryos and eight-day-old seedlings. Magnetic field treatment enhanced $O_2^-$ production up to a 34% in the embryo, 23% in coleoptiles, 57% in the mesocotyl and 31% in radicle over untreated seedlings (Figure 2A to D). The rate of $O_2^-$ production was higher in seeds treated with magnetic field strength of 200 mT (Figure 2A to D).

Electron paramagnetic resonance spectroscopy (EPR) of $^\cdot$OH Radicals

Trend of $^\cdot$OH content after magnetic field treatment paralleled with that of superoxide content. Hydroxyl radical production in the embryo was enhanced up to 26% (100 mT; 120 min) and 39% (200 mT; 60 min) by magnetic field treatment over the control (Figure 3A and Table 1). A similar trend was also observed in the eight-day-old seedlings (coleoptile, mesocotyl and radicle) (Figure 3B, C, D). The maximum difference was observed in mesocotyl (26% by 100 mT (120 min) and 34% by 200 mT (60 min), followed by coleoptile (22 and 31% by 100 mT (120 min) and 200 mT (60 min) respectively) (Figure 3B, C and Table 1).

H$_2$O$_2$ content

H$_2$O$_2$ content was higher in the embryonic axes and eight-
Figure 2. Kinetics of O$_2^-$-formazan production from Na, 3'-[1-[(phenylamino)-carbonyl]-3,4-tetrazolium] (4- methoxy -6-nitro) benzenesulfonic acid hydrate (XTT) from the maize seeds treated with static magnetic field. (A) embryo (B) coleoptile (C) mesocotyl (D) radicle. Vertical line above the bar indicates ± S.E.M of three independent experiments.

day-old seedlings as in the case of O$_2^-$ and OH after magnetic field treatment. The enhancement of H$_2$O$_2$ in embryo was by 13% (100 mT; 120 min) and 48% (200 mT 60 min) over the untreated control (Figure 4).

In eight-day-old seedlings, H$_2$O$_2$ was higher by 16 to 20% in coleoptiles, 39 to 38% in mesocotyl and 19 to 23% in radicle by the magnetic field exposure of 100 mT (120 min) and 200 mT (60 min) respectively over the control (Figure 4).

Taken together, this data shows that O$_2^-$, OH and H$_2$O$_2$ are produced in the germinating maize seedlings and their production was higher in the seedlings that emerged from SMF treated seeds followed by enhanced seedling vigour, than control seedlings. Higher reactive oxygen species were observed in seeds treated with 200 mT (60 min) as compared to 100 mT (120 min).

**Antioxidant enzyme activity**

SOD activity (both cytosolic and wall bound) was reduced in the embryo and eight-day-old seedlings after magnetic field treatment. In case of embryo, cytosolic SOD was reduced by 29% and wall bound SOD was reduced up to 26% after magnetic field treatment (Figure 5A). Amongst the two different treatments, seeds treated with 200 mT (60 min) reduced the SOD content slightly more as compared to 100 mT (120 min). SOD content in eight-day-old seedling followed the same trend as in embryo after magnetic field treatment. The magnitude of reduction in cytosolic SOD content was upto 26% in coleoptiles and 34% in mesocotyl over control seedlings. In case of radicle the magnitude of reduction was much higher (up to 64%) in cytosolic SOD after magnetic field treatment over untreated seedlings (Figure 5B). Wall bound SOD was also reduced in the eight-day-old seedlings after magnetic field treatment. Magnitude of reduction was up to 26, 33 and 20% in coleoptiles, mesocotyl and radicle respectively compared to control. Maximum difference was observed in all cases after treating the seeds with 200 mT for 60 min (Figure 5C).

In contrast to SOD, peroxidase (both wall bound and cytosolic peroxidase) activity was significantly enhanced by SMF treatment (Figure 6A). An enhancement of 10% (100 mT; 120 min) and 30% (200 mT; 60 min) in cytosolic peroxidase and of 29% (100 mT; 120 min) and
Figure 3. EPR spectra of hydroxyethyl/ α-(4-pyridyl-1-oxide)-N-tert-butyl/nitrene (POBN) adduct diagnostic for OH after magnetic field treatment. Group of 20 embryos or ten abraded hypocotyls (0.5 cm) from control and treated seedlings were used for obtaining spectra (A) embryo: [(1) Spectra from Fenton reaction, (2) control, (3) 100 mT (120 min), (4) 200 mT (60 min)] (B) coleoptiles (C) mesocotyl (D) radicle. [(1) control, (2) 100 mT (120 min) and (3) 200 mT (60 min)]. Each spectra is the representative of eighteen individual spectra.

58% (200 mT; 60 min) in wall bound peroxidase was recorded after SMF treatment at embryonic stage. In the eight day old seedlings the enhancement was up to 22, 44, and 22% in coleoptile, mesocotyl and radicle respectively in case of cytosolic peroxidase (Figure 6B). In case of wall bound peroxidase the enhancement was up to 34% in coleoptile and mesocotyl and 15% in radicle over untreated seedlings (Figure 6C).

DISCUSSION

Magnetopriming is a promising technique for the biostimulation of seeds. In the present study, the magnetopriming improved seedling parameters in maize under laboratory condition. The effect was dependent on the magnetic field strength and time of exposure without showing any specific trend. Obtained results showed that
Table 1. Percentage enhancement in α-(4-pyridyl-1-oxide)-N-tert-butyl nitrone (POBN) spin adduct in maize seedlings after magnetic field treatment.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Embryo</th>
<th>Coleoptile</th>
<th>Mesocotyl</th>
<th>Radicle</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 mT (120 min)</td>
<td>100 ± 00</td>
<td>100 ± 00</td>
<td>100 ± 00</td>
<td>100 ± 00</td>
</tr>
<tr>
<td>100 mT (120 min)</td>
<td>126.45 ± 4.092***</td>
<td>122.23 ± 3.45**</td>
<td>126.97 ± 8.97*</td>
<td>113.74 ± 4.78*</td>
</tr>
<tr>
<td>200 mT (60 min)</td>
<td>139.13 ± 3.99***</td>
<td>131.13 ± 5.27***</td>
<td>134.33 ± 10.43*</td>
<td>124.56 ± 4.77*</td>
</tr>
</tbody>
</table>

Data are the means of ± S.E.M. of eighteen individual EPR spectra. Upper symbol indicates the differences vs. control. ***,** and *, indicate significance at p < 0.001, 0.01, 0.05 respectively.

certain combination of SMF and duration of exposure like 200 mT for 60 min and 100 mT for 120 min are highly effective in enhancing germination related parameters. This observation indicates that the internal energy of the seed responds positively when there is an appropriate combination of magnetic field and exposure time (Bhatnagar and Dev, 1977). Kavi (1983) reported that ragi seeds exposed to 100 mT, changed their internal potential energy and suggested that by selecting a suitable combination of magnetic field and exposure time, it may be possible to obtain higher yield. According to previous reports magnetic field stimulated the shoot development of maize and led to the increase of germinating energy, fresh weight and shoot length (Aladjadjian, 2002; Vashisth and Joshi, 2016). Florez et al. (2007) reported that exposure of maize seeds to SMF enhanced the germination and early growth of seedling. In the present study enhanced germination in magnetoprimed maize seeds were coupled with enhanced production of reactive oxygen species (O$_2^-$, ·OH and H$_2$O$_2$) in treated seeds. Similar kind of results were observed in magnetoprimed seeds of soybean by Shine et al. (2012). The difference in ROS content was observed only in the imbibed seeds and differences in mean ROS were similar in magnetoprimed and unprimed seeds before imbibition (Data not given).

Enhancement of total free radical content was also observed by priming with laser light, magnetic field (Podlesny et al., 2001; 2005) and polyethylene glycol (Naglreiter et al., 2005), followed by enhanced germination characters. In the present study, ROS content was specifically studied after magnetopriming. Furthermore, it is reported that pretreatment of seeds with H$_2$O$_2$ accelerated the germination in a dose dependent manner in maize seeds (Gondim et al., 2010) and scavenging of H$_2$O$_2$ by ascorbic acid reduced the
germination of wheat seeds (Ishibashi et al., 2008). In the present study, enhanced ROS content in the magnetoprimed seeds was beneficial and not detrimental for the maize seeds as in case of ROS accumulation during seed deterioration.

Antioxidant enzymes which are responsible for maintaining cellular homeostasis, respond differently to magnetopriming. SOD which is responsible for the detoxification of $\text{O}_2^-$ was reduced, POD which is responsible for detoxification of $\text{H}_2\text{O}_2$ was enhanced by magnetopriming. Peroxidase is a bifunctional enzyme which can oxidize various substrates in the presence of $\text{H}_2\text{O}_2$ and also produce ROS. It exists either in ferric form ($\text{Fe}^{3+}$ - peroxidase) or in a labile perferryl form of peroxidase ($\text{Fe}^{3+}\text{-O}_2^-$ $\text{Fe}^{3+}\text{-O}_2^-\text{peroxidase}$), which is also designated as compound III (Yokota and Yamazaki, 1965). Conversion of peroxidase from ferric form to perferryl form requires $\text{O}_2^-$ (Chen and Schopfer, 1999), which is probably provided by the NAD(P)H oxidase present in the plasma membrane (Liszkay et al., 2004). Peroxidase transformed in to the perferryl state by $\text{O}_2^-$ catalyzes the generation of $\text{OH}$ from $\text{H}_2\text{O}_2$ (Chen and Schopfer, 1999). SOD prevents the generation of $\text{OH}$ by scavenging $\text{O}_2^-$ and thereby inhibiting the conversion of peroxidase from ferric form to perferryl form. The enhanced $\text{OH}$ in the magnetoprimed maize seeds was apparently due to the enhanced POD and reduced SOD content. Preliminary experiments conducted to establish the role of ROS in seed germination of magnetoprimed seeds also showed, scavenging superoxide using Mndesferal $\text{OH}$ by urea or that inhibition of peroxidase using KCN reduced the germination related characters of magnetoprimed seeds (Schopfer et al., 2001). $\text{OH}$ generated in the first days of germination contribute to

Figure 5. Effect of static magnetic field treatment on superoxide dismutase (SOD) in maize. (A) embryo (B) cytosolic SOD (C) wall bound SOD of eight day old seedling. Vertical line above the bar indicates ± S.E.M. Upper symbol indicates the differences vs control. ***, ** and * indicate significance at $p < 0.001$, $0.01$, $0.05$ respectively.
the breakage of the seed coat and subsequent cell elongation, cleavage of various polysaccharide and there by the mobilization of stored food (Schweikert et al., 2000) and non-enzymatic cell wall loosening (Chen and Schopfer, 1999). High levels of ROS (O$_2^-$, OH and H$_2$O$_2$) are produced in the leaf expansion and root elongation zone of maize (Rodriguez et al., 2002; Liszakey et al., 2004). H$_2$O$_2$ acts as a signaling molecule and regulates the catabolism of ABA and biosynthesis of GA for faster germination (Liu et al., 2010). The ROS generated in the seed germination is involved in endosperm weakening, protection against pathogen, Ca$^{2+}$ signaling, gene expression, redox regulation, hormone signaling, cell wall elongation etc. (Bailly et al., 2008; El-Maarouf Bouteau and Bailly, 2008). In our study, enhanced germination characters were followed by enhanced ROS production in maize seeds. On the other hand enhanced ROS content followed by enhanced antioxidant enzymes (POD) may also prevent the excess accumulation of ROS, thereby preventing the oxidative damage in germinating seeds.

CONCLUSION

In conclusion, exposure of seeds to stationary magnetic field for a particular duration acts as biostimulant for maize seeds. Maximum enhancement in germination characters were obtained by treating the seeds with 200 mT (60 min) and 100 mT (120 min). The enhanced germination in magnetoprimed seeds was followed by enhanced ROS content, POD activity, but reduced SOD activity. Treatment of seeds with 200 mT (60 min) showed maximum response in germination related parameters and also exhibited maximum free radical content. The different response of antioxidant enzymes after magnetopriming may contribute to the enhanced
level of ROS in these seeds. Increase in ROS and maintenance of their levels for promotion of rapid growth in magnetoprimed seeds also explains the faster rate of germination. SMF treatment influences the physiological and biochemical process in the seeds and thereby contributes to better vigor and improved crop stand.

REFERENCES


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