PLANT SCIENCE TODAY
Vol x(x): xx–xx
https://doi.org/10.14719/pst.7949

eISSN 2348-1900

REVIEW ARTICLE

Magnetic fields in agriculture: Physiological mechanisms, stress mitigation and future applications

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Received: 26 February 2025; Accepted: 08 June 2025; Available online: Version 1.0: 31 October 2025

Cite this article: Chu HD, La HV , Nguyen BD, Dong GH, Nguyen LV. Magnetic fields in agriculture: Physiological mechanisms, stress mitigation and future applications. Plant Science Today (Early Access). https://doi.org/10.14719/pst.7949

Abstract

Magnetic fields (MFs) have emerged as a promising and eco-friendly approach for enhancing plant growth by modulating key physiological and biochemical processes, including ion transport, membrane permeability, enzymatic activity and stress responses. Research suggests that MF treatments can significantly improve seed germination, enhance seedling vigour and increase crop resilience to environmental stressors, such as drought, salinity and extreme temperatures. In addition, exposure to MFs has been reported to accelerate early seedling development, promote root elongation and stimulate photosynthetic efficiency, ultimately leading to increased plant biomass and yield. However, despite the increasing number of studies investigating the potential of MF applications in agriculture, inconsistencies in experimental protocols, exposure conditions and the underlying mechanisms of plant responses to MFs present significant challenges. The lack of standardized methodologies limits the broader adoption of MF technology in large-scale agricultural systems. Standardizing treatment parameters, identifying optimal exposure conditions and elucidating the molecular mechanisms governing plant responses to MFs are critical areas for future investigation. Furthermore, integrating MF technology into precision agriculture and sustainable farming practices could enhance crop productivity while reducing reliance on chemical inputs. By bridging theoretical insights with applied agricultural practices, MFs hold great potential as a novel tool for improving plant performance, stress resilience and overall agricultural sustainability in the face of global climate challenges. This review synthesizes current knowledge on the effects of MFs in plant biology, highlighting both the reported benefits and existing gaps in research.

Keywords: agricultural applications; magnetic fields; plant growth enhancement; seed germination; stress resilience

Introduction

The growth and development of all organisms on the Earth, including plants, have always been under the influence of the geomagnetic field (approximately 50 to 60 µT) (1, 2). This natural component affects the movement of charged particles within cells, helps plants sense direction for root and shoot development and modulates cellular activities essential for metabolism and adaptation (3). Building on this understanding, the studies have explored the potential of artificially applied magnetic fields (MFs) to enhance physiological processes in plants, leading to improved seed germination, seedling vigor and overall crop productivity (4-9). These effects are believed to be mediated through alterations in ion transport, membrane permeability, oxidative stress regulation and hormonal signalling, which collectively contribute to enhanced stress resilience and metabolic efficiency (10 -14).

Although numerous studies have demonstrated the positive effects of MFs on plant growth and development, the precise molecular and biochemical mechanisms underlying these responses remain incompletely understood (15 -17). One of the prevailing hypotheses suggests that MFs influence plant physiology through an auxin-like effect, promoting key developmental processes such as seed germination, root and shoot elongation and overall biomass accumulation (9, 14, 18, 19). This auxin-like effect may involve enhanced auxin biosynthesis, improved auxin transport within tissues and modulation of auxin signal transduction pathways that regulate cell division and elongation. This growth-promoting influence is believed to arise from MF-induced alterations in hormone signalling pathways, particularly those involving auxins and gibberellins, which regulate cell division, elongation and differentiation (19). For instance, studies have reported changes in endogenous auxin concentrations in radish (*Raphanus sativus*) and sugarcane (*Saccharum* spp.) plants after MF exposure and modulations in gibberellin-related responses in soybean (*Glycine max*) seedlings (20, 21).

Additionally, MFs have been linked to the modulation of reactive oxygen species (ROS) metabolism, playing a crucial role in mitigating oxidative stress and enhancing plant defence mechanisms against environmental stressors, such as drought, salinity and extreme temperatures (11, 22-25). By stimulating antioxidant enzyme activity, including superoxide dismutase, catalase and peroxidases, MFs help maintain cellular redox balance, thereby reducing oxidative damage and improving stress resilience (2, 26-29). However, despite these promising findings, significant variability in experimental outcomes persists due to differences in MF intensity, exposure duration, frequency and plant species specificity across studies (8). The lack of standardized treatment protocols and inconsistencies in research methodologies have led to conflicting results, making it challenging to establish definitive conclusions regarding MF applications in agriculture (2, 30). Thus, a systematic and comprehensive literature review is necessary to consolidate current knowledge and develop optimized strategies for integrating MF treatments into sustainable agricultural practices.

This review aims to comprehensively examine the role of MFs in enhancing plant growth by exploring their underlying mechanisms, summarizing experimental findings and assessing their potential applications in agriculture. It delves into how MFs influence physiological and biochemical processes such as ion transport, membrane permeability, oxidative stress regulation and hormone signalling, all of which contribute to improved seed germination, seedling vigour and stress resilience. By analyzing key studies, this review highlights both the benefits and challenges of MF treatments, particularly the need for standardized exposure protocols and a deeper understanding of the molecular pathways involved. Additionally, it evaluates the feasibility of integrating MF technology into modern agricultural practices to improve crop productivity and resource efficiency. Identifying research gaps and proposing future directions, this review aims to bridge the gap between fundamental research and practical implementation, contributing to the development of sustainable and innovative agricultural solutions.

Possible Mechanisms of the Magnetic Field's Influence on Plant Growth and Development

Ion transport and membrane permeability

One of the most widely accepted hypotheses regarding MF effects on plants involves the modulation of ion transport [such as calcium (Ca^{2+}), potassium (K^+) and hydrogen (H^+)] and membrane permeability (31). The Lorentz force, which acts on charged particles moving in an MF, is believed to alter the movement of Ca^{2+}, K^+ and H^+ across cellular membranes (32). These ions play crucial roles in signal transduction, osmoregulation and nutrient uptake (33, 34, 35). Research indicates that exposure to MFs can enhance the activity of ion channels and proton pumps, leading to increased nutrient absorption and improved water balance in plant cells (12, 36, 37). This effect may explain the enhanced germination rates and early seedling vigour observed in magnetically treated seeds, as increased ion flux can accelerate metabolic processes necessary for seed activation (8, 38). For example, a study demonstrated that exposing soybean seeds to pulsed MF at a strength of 1500 nT, with frequencies of 0.1, 1.0, 10.0 and 100.0 Hz for 5 hours daily over a 20-day period, led to a notable increase (20 %) in germination rates (39). The most significant improvements were observed at 10 Hz and 100 Hz, indicating that these frequencies were particularly effective in enhancing seed performance (39). Additionally, MF treatment positively influenced several germination-related characteristics, including water absorption, germination speed and seedling elongation, as well as increases in fresh and dry biomass (21). Furthermore, vigour indices (seedling length and dry weight) of the treated soybean seeds showed considerable improvement under controlled laboratory conditions, suggesting that MF exposure could serve as a biostimulant for enhancing early plant growth and development (8, 14, 21).

In addition to influencing ion transport, MFs have been shown to affect the biophysical properties of the plasma membrane, including its fluidity and permeability (31). The plasma membrane comprises a lipid bilayer embedded with proteins that regulate transport and signal transduction (40). Exposure to MFs has been suggested to induce changes in membrane lipid composition, altering the degree of lipid saturation and the organization of phospholipid molecules (9, 14). These modifications can affect the flexibility and stability of the membrane, making it more permeable to ions and small molecules. Some studies have proposed that MFs influence the phase behaviour of membrane lipids, leading to increased lateral diffusion of proteins and enhanced transport activity (11, 41). Since sterol-rich membrane domains regulate ion transport and signalling, MF-induced changes in lipid organization could influence plant physiology. By altering the balance between liquid-ordered and liquid-disordered membrane regions, MFs may impact protein mobility and function, contributing to enhanced plant growth and stress responses (42).

Additionally, membrane fluidity changes can impact membrane-bound enzymes' activity, such as ATPases and kinases, which regulate ion gradients and energy transduction (16). Increased membrane permeability facilitates ion exchange, enhancing nutrient uptake and metabolism. This effect is particularly relevant during seed germination and early seedling growth, where rapid ion flux is required for metabolic activation and cell expansion.

Modulation of reactive oxygen species metabolism and antioxidant defense

Recent studies suggested that MFs can modulate ROS metabolism and enhance the antioxidant defense system, thereby improving plant stress tolerance and overall growth (15, 31, 43). Exposure to MFs has been reported to influence ROS generation by altering electron transport processes in mitochondria and chloroplasts of plants (25). During energy conversion in these organelles, electron flow through the electron transport chain naturally generates ROS, which may interact with MFs that alter the stability and reaction rates of free radicals and charged biomolecules, thereby influencing the redox balance (25, 31, 44). Additionally, MFs have been shown to influence nicotinamide adenine dinucleotide phosphate (NADPH) oxidase activity. Some studies suggest that MF exposure may downregulate NADPH oxidase activity in plant systems such as *A. thaliana* (3, 12) and soybean (3, 12), leading to reduced ROS accumulation and preventing oxidative damage in plant tissues (3, 12). Conversely, in some instances, MFs may transiently increase ROS levels, triggering adaptive stress responses that enhance plant defence mechanisms. For example, a previous study demonstrated that treating soybean seeds with static MFs of 150 and 200 mT for one hour resulted in elevated ROS production. This included superoxide anion, hydroxyl radicals and hydrogen peroxide in both embryos and hypocotyls of germinating seedlings (22). Research indicates that the ROS increased under MF treatment was mainly due to cell wall peroxidase activity, while antioxidant enzymes like SOD and APX were suppressed in hypocotyls. Despite this, seedlings had higher germination rates, longer shoots and greater biomass than controls (22). This finding aligns with the hypothesis that MFs can fine-tune ROS production to serve as an environmental stimulus, priming plants for improved stress resilience (31, 43). The controlled increase in ROS levels likely functions as a signalling mechanism that strengthens cellular defence responses, potentially through the activation of pathways involving mitogen-activated protein kinases or transcription factors, such as NONEXPRESSER OF PR GENES1, thereby promoting improved growth and enhanced tolerance to environmental stressors. The modulation of antioxidant defence mechanisms under MF exposure is summarised in Fig. 1.

To counteract ROS toxicity, plants rely on a complex antioxidant defence system composed of enzymatic and non-enzymatic components (Table 1). Enzymatic antioxidants include superoxide dismutase, catalase, peroxidases and glutathione peroxidase, all of which play critical roles in scavenging ROS and maintaining redox balance (45). Among them, increased superoxide dismutase activity in MF-treated plants has been reported in several species such as cucumber (*Cucumis sativus*) and lentil (*Lens culinaris*), suggesting that MFs may upregulate superoxide dismutase expression or enhance its catalytic efficiency (42, 46, 47). Soybean seeds exposed to a magnetic flux density of 2.9 - 4.6 mT for 2.2, 19.8 and 33 seconds exhibited a significant increase in superoxide dismutase activity during germination (26). Notably, superoxide dismutase activity in soybean roots increased by 21.18 % relative to the control at 19.8s exposure, with this effect persisting for up to 72 hours (26). Similarly, studies on plant species have shown that MF exposure can upregulate catalase and peroxidase activity, leading to more efficient ROS detoxification (42). This enhancement may result from increased gene expression, post-translational modifications, or MF-induced conformational changes in enzyme structure that improve catalytic efficiency. Tomato (*Solanum lycopersicum*) seeds treated with varying MF intensities (500 - 4000 Gauss) showed significant changes in these enzyme activities like peroxidase, polyphenol oxidase (PPO), superoxide dismutase (SOD) and catalase (CAT) (48). These findings demonstrated that within the optimal range of 1000 - 2000 Gauss, catalase and peroxidase activity reached peak levels, indicating an enhanced ability to scavenge hydrogen peroxide and other ROS (48). The increase in catalase activity suggests that MF treatment enhances the breakdown of hydrogen peroxide into water and oxygen, while the upregulation of peroxidase activity implies a greater ability to detoxify peroxides and support plant stress responses. However, when the MF intensity exceeded 3000 Gauss, enzyme activity declined, suggesting that powerful fields may have inhibitory effects (48).

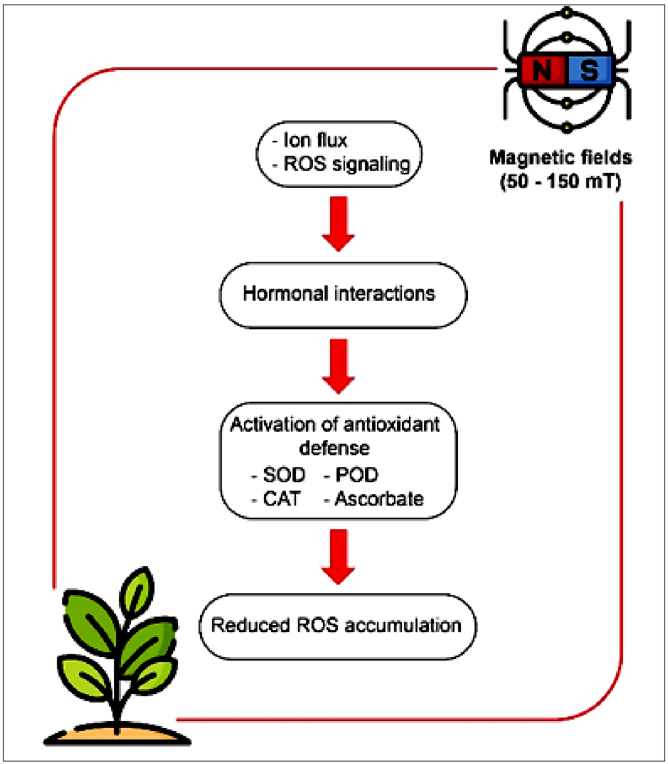

Fig. 1. Proposed mechanism of magnetic field-induced modulation of the antioxidant defence system in plants. Exposure to magnetic fields (50 - 150 mT) initiates changes in ion flux and ROS signalling, which in turn influence hormonal interactions. This cascade activates antioxidant defence mechanisms, including enzymatic antioxidants such as superoxide dismutase, catalase, peroxidase and non-enzymatic antioxidants like ascorbate.

Studies also indicated that MF exposure can increase the biosynthesis and accumulation of the non-enzymatic antioxidant molecules, further enhancing plant resilience to oxidative stress. For instance, increased flavonoid and phenolic content have been observed in MF-treated plants of the grapevine (Vitis vinifera), and also indicates that MFs may activate secondary metabolic pathways such as alkaloids, saponins, flavonoids, flavones and flavonols involved in stress responses (2, 49). The upregulation of secondary metabolite synthesis in response to MFs may be linked to changes in gene

Table 1. Effect of magnetic field on antioxidant enzyme activity in plants.

S. No.	Plant species	MF intensity / Exposure	Antioxidant enzymes affected	Observed effects	References
1	Wheat (*Triticum aestivum*)	125 mT, 2 h	SOD, CAT	Increased enzyme activity, reduced H_2O_2 accumulation	(28)
2	Lettuce (*Lactuca sativa*)	100 mT, 3 h	POD, APX	Enhanced enzyme activity and improved oxidative stress tolerance	(29)
3	Soybean (*Glycine max*)	200 mT, 1 h	CAT, APX	Upregulated activity of CAT and APX; improved oxidative defense	(21)
4	Chickpea (*Cicer arietinum*)	150 mT, 2 h	SOD, POD, CAT	Elevated antioxidant enzyme levels under drought conditions	(69)
5	Mung bean (*Vigna radiata*)	100 mT, 6 h	SOD, CAT, APX	Significant increase in antioxidant enzymes; better germination under stress	(68)

expression or the activation of signalling pathways that regulate secondary metabolism (50). Previous studies have shown that MFs significantly boost antioxidant levels in lettuce (*Lactuca sativa*), increasing total phenolics, flavonoids, anthocyanins, ascorbic acid, reduced glutathione and α-tocopherol (29). The most significant increases were observed at 1 Tesla for 2 hours for total phenolics, at 0.77-1 Tesla for 2 hours for flavonoids and at 0.77 Tesla for 3 hours and 1 Tesla for 2 hours for anthocyanins (29). The upregulation of anthocyanins/ flavonoid pigments under MF exposure is a significant adaptive response that enhances plant resilience and overall stress tolerance (51). Similarly, ascorbic acid showed a significant increase, particularly under 0.77 Tesla for 2 hours, reaching 68.31 % higher than the control, while reduced glutathione also exhibited a notable increase of 69.74% at 0.77 Tesla for 2 hours. Furthermore, α-tocopherol (vitamin E), a lipid-soluble antioxidant that protects membranes from lipid peroxidation, was significantly upregulated by MF treatment, with an increase of 164.99 % at 0.77 Tesla for 3 hours (29). These results demonstrate that MF exposure can effectively enhance the non-enzymatic antioxidant capacity of plants, improving their ability to combat oxidative stress and enhance overall physiological (15, 52).

Interaction with plant hormone signaling pathways

Plant hormones, such as auxins, gibberellins, cytokinins and abscisic acid, are critical regulators of plant growth, development and environmental responses (10, 53, 54). Recent research suggests that MF exposure can influence hormone biosynthesis, signaling and crosstalk, leading to enhanced plant growth and resilience (55, 56). The interaction between MFs and plant hormones is complex, involving changes in gene expression, enzyme activity and transport mechanisms that regulate hormone distribution and activity (15).

MFs may induce auxin-like effects, leading to enhanced plant growth and physiological responses. These effects are believed to be mediated through increased auxin biosynthesis, improved transport mechanisms and enhanced signaling efficiency at the cellular level (9, 14). Specifically, the effects of a directional electromagnetic field on radish and sugarcane were investigated (20). The study examined changes in shoot elongation, root proliferation and endogenous indole-3-acetic acid (IAA) concentration (20). One of the key observations was that IAA levels were altered in plants exposed to MFs, with notable variations depending on the duration of exposure and the direction of the applied field. For example, in radish plants, IAA concentrations decreased under MF treatment, particularly at 48 hours of exposure, where auxin levels were at their lowest (3.24 ± 0.47 mg/g) compared to the control (5.82 ± 1.01 mg/g) (20). The decline in auxin levels with increased growth suggested that MF exposure may enhance auxin turnover, either by accelerating its metabolism or by promoting its redistribution to target tissues such as the root system. One possible explanation is that MFs upregulate auxin oxidase, facilitating the conversion of free auxin into storage or degradation forms, thereby preventing excessive auxin accumulation that could inhibit growth (9, 14). This aligns with previous findings that excessive auxin concentrations can suppress elongation and induce ethylene synthesis, leading to growth inhibition rather than stimulation (6, 43). Moreover, this is evident in the root proliferation observed in MF-treated plants of barley (*Hordeum vulgare*), which is typically associated with higher auxin availability in root tissues (43, 57, 58, 59). The increase in lateral root formation and elongation suggests that MFs facilitate auxin redistribution, ensuring an optimal hormonal balance between shoot and root development of *Arabidopsis* (19). Interestingly, an inverse correlation between auxin levels and shoot elongation has been proposed, suggesting that MF exposure may not simply increase auxin production but rather optimize its signalling efficiency in radish (20). The maximum shoot growth (25.65% increase) was observed under 48-hour MF treatment, corresponding with reduced IAA levels, indicating that growth was enhanced due to improved auxin utilization rather than excessive hormone accumulation (20) (Table 2). This finding suggested that MFs might modulate auxin receptor activity or signalling pathways, enhancing auxin perception and downstream gene expression without requiring excessive hormone accumulation (42).

Many studies indicated that MF-treated plants, such as *Arabidopsis* and barley, exhibit enhanced phototropic and gravitropic responses, which are properties of auxin-mediated growth regulation (60, 61, 62). Plants of *Arabidopsis* exposed to MFs show increased phototropic alteration, suggesting that MFs may modulate auxin redistribution in response to light (63). Similarly, enhanced gravitropic sensitivity has been observed in MF-treated roots, likely due to changes in statolith positioning and auxin gradients, allowing roots to reorient more effectively in response to gravity. Numerous studies have demonstrated auxin-like responses in plants subjected to MF treatment, including increased root elongation in soybean, enhanced shoot growth and leaf expansion in tomato (21, 22, 64) and improved vascular differentiation in maize (*Zea mays*), suggesting that MFs may stimulate auxin transport and signaling (23, 38).

Table 2. Effect of magnetic field on hormone signalling pathways in plants.

S. No	Plant species	MF intensity / Exposure	Hormones affected	Observed effects	References
1	Radish (*Raphanus sativus*)	100 mT, 48 h	IAA	Increased IAA levels; promoted root and shoot elongation	(41)
2	Soybean (*Glycine max*)	200 mT, 1 h	GA	Stimulated shoot elongation via enhanced GA biosynthesis	(21)
3	Chickpea (*Cicer arietinum*)	150 mT, 2 h	IAA, ABA	Elevated IAA and reduced ABA; improved seedling vigour under drought	(69)
4	Tomato (*Solanum lycopersicum*)	120 mT, 3 h	Cytokinins	Upregulated cytokinin levels are associated with enhanced cell division	(13)
5	Lettuce (*Lactuca sativa*)	100 mT, 6 h	IAA	Improved auxin signalling linked to early root formation	(29)

Triggers of transcriptional reprogramming in plants

MFs, whether static or pulsed, have demonstrable effects on gene expression in plants, particularly in *A. thaliana*. The response to MFs depends significantly on the field's strength, duration, orientation and whether it is static or dynamic. High-intensity static MFs exceeding 15 Tesla were shown to induce substantial changes in gene expression. In a study using transgenic *Arabidopsis* plants carrying a stress-inducible GUS reporter under the Adh promoter, field strengths above 15 T activated stress-responsive genes, notably in root and leaf tissues. Genome-wide microarray analyses revealed that 114 genes were differentially expressed by more than 2.5-fold, including those involved in abiotic stress responses (e.g., heat shock, drought and touch), ion transport and transcription regulation. Conversely, genes involved in cell wall biosynthesis, such as *Xtr7*, were downregulated. These results suggested that strong MFs may impair some aspects of transcriptional machinery or cellular function through mechanisms like magnetic orientation or magnetophoresis (65).

Furthermore, exposure to nanosecond high-amplitude pulsed electromagnetic fields through antennas induced only minimal transcriptional changes (66). A study examining the impact of 30,000 pulses at 237 kV/m in *Arabidopsis* revealed that most stress and redox-responsive genes, including *TCH1*, *ZAT12* and several genes encoding ROS-scavenging enzymes, remained unchanged. There was a late upregulation of *APX1* and *APX6*, two genes encoding ascorbate peroxidases, observed 180 minutes after exposure. This suggests a delayed and limited activation of the antioxidant defence pathways (66).

An emerging transcriptomic study has provided compelling evidence that MFs influence plant growth by modulating gene expression. A time-course microarray analysis in *A. thaliana* revealed that roots and shoots respond differently to changes in the geomagnetic field, with approximately 49 % of geomagnetic field-responsive genes exhibiting opposite regulation patterns in the two organs (43). This organ-specific response underscores the complexity of MF perception and signalling in plants. Genes affected by geomagnetic field exposure were predominantly associated with stress responses, including those linked to redox homeostasis, ion transport and hormone signalling (43). Notably, β-glucosidases (e.g., BGLU21 and BGLU22), redox-related transcription factors such as ERF109/RRTF1 and sucrose transporters (e.g., SWEET10) showed significant expression changes under reduced geomagnetic field conditions, particularly in a biphasic manner (43). Several of the regulated genes are found in chloroplasts and mitochondria, which indicates that MFs may affect organelles responsible for redox reactions and energy conversion. In addition, early-response genes under MF treatment often contain NAC transcription factor binding sites in their promoters. This feature links MFs to the activation of stress-related gene networks.

Potential Applications of Magnetic Fields on Plant Growth and Development

Their influence on seed germination and early growth

Over the years, numerous studies (Table 3) have confirmed that MF exposure positively influences seed germination, emergence and seedling vigour (4, 21, 39, 41, 67-71). One significant finding in this field is that MF exposure enhances germination parameters. For instance, the effects of MF on mung bean (*Vigna radiata*) were investigated and an increase in MF intensity correlated with a linear improvement in germination rate, germination coefficient and water absorption efficiency (68). MF intensities ranging from 87 to 226 mT for 100 minutes on key germination parameters, such as germination rate, germination coefficient and water uptake efficiency, were

Table 3. Effects of magnetic field on seed germination across various plant species.

S. No	Plant species	Treated plant part	Applied MF intensity (milli Tesla)	Observed effects	References
1	Mung bean (*Vigna radiata*)	Seeds	87 - 226	Accelerated germination time, increased mean germination rate and improved water absorption in response to increasing MF intensity.	(68)
2	Passion fruit (*Passiflora edulis*)	Seeds	200	Enhanced germination, seedling emergence and overall vigour.	(71)
3	Cucumber (*Cucumis sativus*)	Seeds	200	Improved germination characteristics, higher enzymatic activity, increased ROS scavenging and strengthened antioxidant defence during germination.	(46)
4	Soybean (*Glycine max*)	Seeds, seedlings	150 - 200	Increased photosynthetic efficiency, improved germination rate, higher crop yield, enhanced pigment synthesis, greater biomass accumulation, improved nitrogen metabolism and increased root nodulation.	(21, 24)
5	Chickpea (*Cicer arietinum*)	Seeds, seedlings	50 - 150	Faster germination, superior seedling growth and enhanced functional root characteristics.	(69)
6	Wheat (*Triticum aestivum*)	Seeds, seedlings	4 - 7	Increased germination percentage and improved early seedling growth.	(28)
7	Tomato (*Solanum lycopersicum*)	Seeds	50 - 332	Elevated germination rate, stimulated biochemical and molecular pathways regulating hydrogen peroxide homeostasis and improved seedling vigour.	(13)
8	Maize (*Zea mays*)	Seeds, seedlings	200	Improved germination, enhanced seedling growth and increased activity of α-amylase, proteases and free radicals.	(67)
9	Rice (*Oryza sativa*)	Roots, seeds	125 - 250	Enhanced root elongation and stem growth, as well as improved germination kinetics.	(85)
10	Common bean (*Phaseolus vulgaris*)	Seeds, seedlings	130	Enhanced germination and early growth, increased mitotic activity in meristematic cells and higher glutathione peroxidase enzyme activity in leaves.	(28)

evaluated (68). One of the key findings was the direct relationship between MF intensity and germination rate, as the linear increase in germination rate with MF exposure suggests that MFs accelerate the internal biochemical processes involved in seed metabolism and enzyme activation (9, 14). Furthermore, the germination coefficient, which measures the efficiency of germination over time, also increased under MF treatment, indicating that seeds exposed to stronger MFs germinated faster and more uniformly than untreated seeds. Similarly, it was demonstrated that passion fruit (*Passiflora edulis*) seeds exposed to isolated MF treatments exhibited stimulated seed germination, enhanced seedling emergence and improved overall vigour (71). MF exposure has also accelerated germination speed, increased seedling length and enhanced biomass accumulation in various crop species. Studies on chickpea (*Cicer arietinum*) have demonstrated that MF treatment enhances seed germination, seedling growth and biomass accumulation, depending on the MF strength and exposure duration (69). Germination percentage increased by 5 -11 % and germination speed by 80-26 % compared to untreated seeds. Moderate MF intensities (50-150 mT) were effective, while higher intensities (200-250 mT) showed inconsistent results, possibly due to overstimulation or stress effects. Magnetically treated seedlings had 12-34 % longer shoots, 58-90 % longer roots, 38-57 % greater total seedling length and 25-47 % higher dry weight than controls. These findings indicate that MF treatment has the potential to improve seedling performance and overall plant vigour, particularly during the crucial early developmental stages (9, 14). Similar improvements in germination rate and vigour index have been observed in several plant species, including cucumber, lettuce, maize, tomato and radish (20, 23, 29, 38, 41, 72, 73). Beyond germination improvements, MF exposure also influences metabolic and physiological processes in young seedlings. Barley (*Hordeum vulgare*) seedlings exposed to 10 µTesla MF exhibited a significant increase in carbon dioxide emissions (70 - 100 %).

MF exposure enhances seed germination by modulating biochemical processes, particularly by stimulating the activity of proteins and enzymes involved in metabolic regulation (31, 43). This effect is attributed mainly to MF interactions with the internal electric field of biological systems, which occur due to the resonance behaviour of MFs with cellular electric charges (74). When seeds of soybean, maize and artichoke are exposed to an external MF treatment, these endogenous charges experience altered movement and energy states, leading to enhanced ion uptake, improved metabolic activity and increased nutritional value (4, 38, 69, 73). The influence of MF on ion currents within plant cells, particularly across embryo cell membranes, has been a key focus of recent reports, which proposed that MF exposure alters ion flow across membranes, modifying the concentration gradients of essential nutrients and the osmotic potential on both sides of the membrane (31). Among the most affected ions are Ca^{2+}, $K^{+}$and H^{+}, which are critical for signalling, osmoregulation and pH homeostasis during seed germination and early growth (75). MF treatment plays an essential role in early seed activation, as water absorption is a crucial step in breaking seed dormancy and initiating metabolic processes such as enzyme activation, ATP synthesis and macromolecule mobilization (76). When an MF interacts with charged ions present in cellular membranes, it induces changes in ion concentration and electrochemical gradients. This shift in osmotic balance influences the seed's water absorption capacity (77). The enhanced water-seed interaction observed in magnetically treated seeds, as reported in higher plant species, such as the mung bean, chickpea and passion fruit, suggests that MF exposure accelerates germination by optimizing cellular hydration and nutrient transport (68, 69, 71).

Magnetic field applications for mitigating oxidative stress in plants

Extensive research has demonstrated that MF exposure enhances the activity of key antioxidant enzymes, including peroxidase, polyphenol oxidase, superoxide dismutase and catalase, which play a crucial role in neutralizing ROS and reducing oxidative damage in plant cells (31, 43, 78). A study investigated the effects of MF exposure on cucumber seeds and reported a significant increase in antioxidant enzyme activity (46). Specifically, superoxide dismutase activity increased by 8%, catalase activity increased by 83% and glutathione reductase activity was higher by 77 % compared to the control (46). These findings suggested that MF treatment strengthens the enzymatic defense system. Similar experiments conducted on other plant species, including artichoke (*Cynara scolymus*) and maize, further validated these observations (47, 79). Exposure to MFs led to a significant rise in the activities of catalase and ascorbate peroxidase, both of which are essential for scavenging hydrogen peroxide and maintaining redox homeostasis in maize and artichoke (47, 79).

Additionally, the study found that MF pretreatment promoted maize seedling growth by mitigating excessive ROS accumulation (80). Notably, while superoxide dismutase activity decreased in magnetically treated seedlings, their total antioxidant capacity increased as compared to the control (80). This suggests that MF exposure may optimize antioxidant balance by modulating enzyme activity and effectively counteracting oxidative stress. Similar to animal cells, plant cells respond to MF exposure, with growing evidence suggesting that MFs can modulate cellular oxidative processes and affect free radical dynamics (25, 31, 43). One of the key mechanisms by which MFs influence plant physiology is through the disruption of free radical pathways within cell membranes (31). Membrane lipids are vulnerable to oxidative damage due to free radical accumulation, initiating lipid peroxidation. As lipid peroxidation escalates, ROS accumulate, triggering oxidative stress, which subsequently alters enzymatic activity, gene expression and intracellular calcium release. If left unchecked, oxidative stress can compromise membrane integrity, inhibit cell growth and, in severe cases, lead to programmed cell death. Thus, the ability of MF exposure to regulate ROS metabolism has been observed in several plant species, particularly in major crops, such as soybean, maize and lettuce (31, 43). These effects have shown particular promise in abiotic stress-prone regions, including drought-prone areas and saline agricultural zones, where MF treatments have enhanced stress tolerance and improved yield potential. For example, MF exposure influences oxidative homeostasis in soybean seedlings by increasing ROS production via cell wall peroxidase activity while reducing antioxidant defences in the hypocotyl (81). Specifically, MF-treated soybean seeds exhibited a 45 % increase in cell wall peroxidase activity, while superoxide dismutase and ascorbate peroxidase activities decreased by 27 % and 31 %, respectively, in the hypocotyl (81). Additionally, ascorbic acid levels dropped by 35 % indicating disrupted redox balance and transient oxidative stress (81). These findings suggest that MF exposure induces localized oxidative stress, potentially priming seedlings for improved stress resilience by modulating cell wall metabolism, hormone signalling and structural adaptation (Fig. 2).

Future Direction

The application of MFs in plant production has gained significant attention as a non-invasive, eco-friendly strategy for enhancing germination, growth and stress tolerance (6-8). While substantial progress has been made in understanding how MFs influence plant physiological and biochemical processes, future research and technological advancements will be critical in optimizing MF treatments for large-scale agricultural applications. One of the primary challenges in applying MFs in plant production is the lack of standardized treatment protocols, as their effects vary depending on field strength, exposure duration and plant species (15, 16). Future research should prioritize establishing optimal MF exposure conditions specific to different crop species, while also evaluating the long-term impact of MF treatments on plant health, yield and biochemical composition (17). Additionally, there is a need to develop cost-effective, scalable MF treatment systems that can be easily integrated into modern agricultural practices (1, 70). Advances in precision agriculture and automation may facilitate real-time monitoring and precise application of MF treatments, ensuring crops receive optimal stimulation without adverse effects (82).

Another promising application is the use of magnetically treated water, which improves water structure and solubility, thereby enhancing plant root absorption and nutrient uptake efficiency (70, 82). While studies suggest that magnetically treated water enhances seed germination, accelerates plant growth and improves yield, further research is required to elucidate the molecular mechanisms governing these effects, particularly how MF exposure alters water properties (70). It interacts with soil and plant systems (83). The potential of MF technology in mitigating abiotic stresses, such

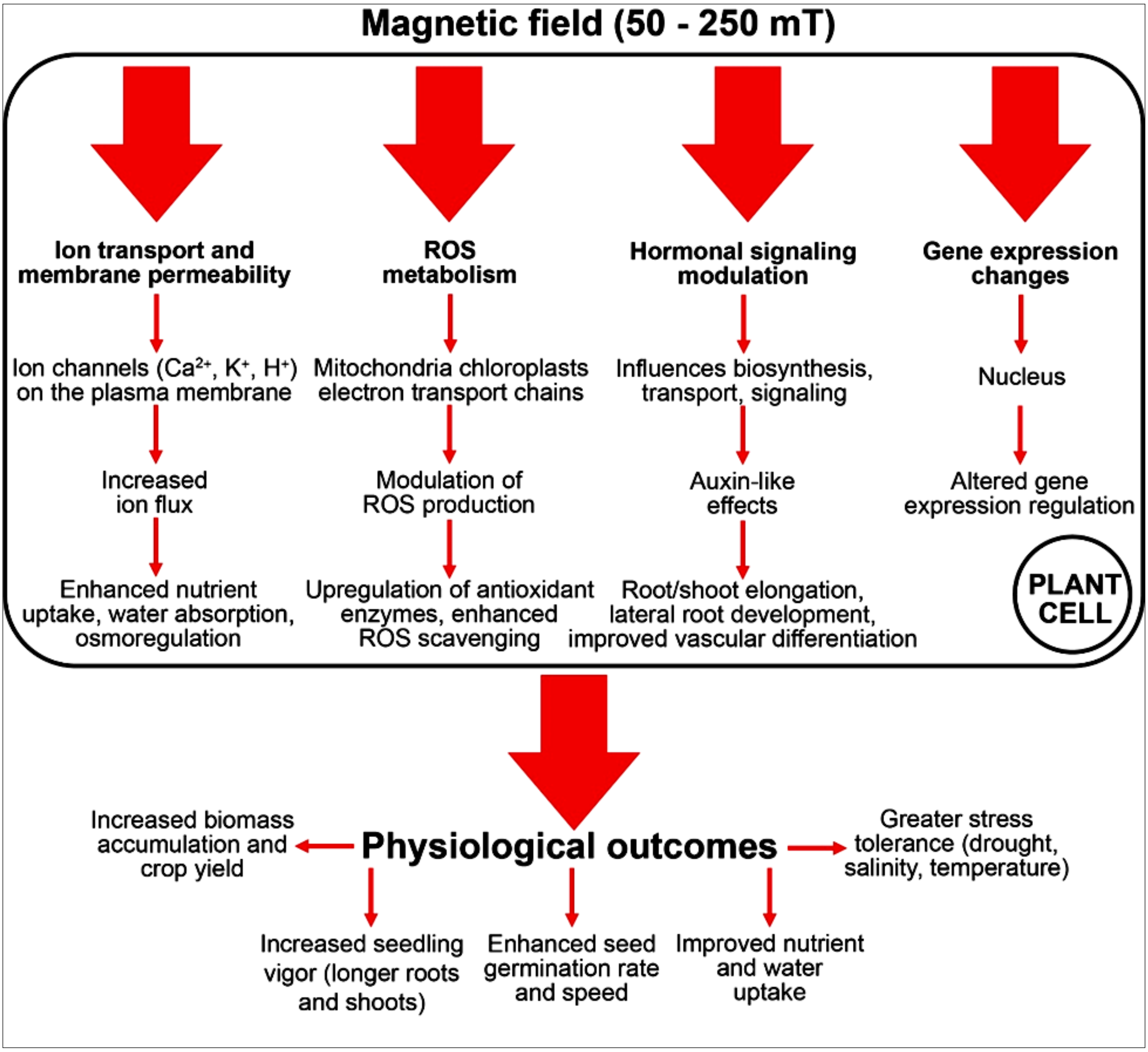

Fig. 2. Schematic representation of the physiological effects of magnetic field exposure (50 - 250 mT) on plant cells.

as drought, salinity, extreme temperatures and heavy metal toxicity, is another crucial area for exploration (8, 42). Future applications could include enhancing drought tolerance by improving root development and water retention, mitigating salinity stress through sodium ion regulation and antioxidant enzyme activation and alleviating heavy metal toxicity by modifying ion transport and detoxification pathways (22, 24, 42, 84).

Integrating MF technology with sustainable agricultural methods, such as organic farming and hydroponics, could reduce dependence on chemical fertilizers and strengthen overall crop resilience (8). However, despite growing evidence supporting the benefits of MFs, the molecular and biochemical mechanisms underlying these effects remain largely unexplored. Future research should focus on analyzing gene expression changes in MF-treated plants using advanced omics technologies (genomics, transcriptomics, proteomics and metabolomics), investigating how MFs modulate plant hormone signaling networks, particularly those involving auxins, cytokinins, gibberellins and abscisic acid and determining their influence on plant-microbiome interactions, as soil microbes play an essential role in nutrient cycling and stress adaptation (43). To transition MF applications from laboratory research to large-scale agricultural implementation, it is imperative to ensure their commercial viability and accessibility to farmers. Future applications could include MF-based seed treatment technologies to enhance seed vigour and uniform germination, integrating MF-treated irrigation systems in commercial farms to improve water-use efficiency and nutrient uptake and designing MF-based controlled environment agriculture systems, such as greenhouses and vertical farms, to optimize plant productivity(21, 28, 46, 70).

Conclusion

This review has highlighted the potential mechanisms through which MFs influence plant physiology, including their impact on ion transport, membrane permeability, ROS metabolism and hormone signalling pathways. Experimental findings demonstrate that MF treatments can enhance seed germination, promote early seedling vigour and mitigate oxidative stress, suggesting their potential for improving crop yield and stress tolerance. However, despite the growing body of research supporting these benefits, several challenges and concerns remain. These include the risk of overexposure, potentially leading to physiological disturbances, inconsistencies in plant responses across species, unknown long-term ecological impacts and the economic feasibility of large-scale implementation. To fully realize the potential of MF technology in agriculture, future studies must address these risks while focusing on optimizing exposure parameters, elucidating molecular mechanisms and developing cost-effective application systems. Bridging the gap between fundamental science and field-level implementation, MF technology could become a valuable tool for enhancing plant performance and sustainability in the face of global agricultural challenges.

Authors' contributions

HC conceived of the study, participated in its design and coordination and drafted the manuscript. HL contributed to the literature review and synthesis of key findings. BN assisted in organizing content and refining the manuscript structure. GD provided expert insights and contributed to critical revisions. LN reviewed and edited the manuscript for clarity and coherence. All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interests to declare.

Ethical issues: None.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the author(s) used Grammarly and Quillbot to edit grammar. After using this tool, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

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Peer review: Publisher thanks Sectional Editor and the other anonymous reviewers for their contribution to the peer review of this work.

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