

Magnetic field treatment on horticultural and agricultural crops: its benefits and challenges

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ABSTRACT

Magnetic field (MF) treatment, as an efficient and pollution-free treatment method, has received extensive attention from researchers and found broad prospects in horticultural and agricultural development. According to relevant studies, mainstream research direction is aimed at utilizing MF treatment to improve the economic traits of horticultural and agricultural crops. MF has positive effects, for example, on seed germination, seedling growth, crop yield and quality and plant tolerance to stress. In recent years, more and more researchers have focused their work on using seed MF or magnetised water (MW) irrigation treatment to improve plant tolerance to salt or heavy metal stresses, to achieve the purpose of soil restoration by plant heavy metal accumulation. In this review, the most commonly utilised MF or MW treatment methods have been described in detail, and the effects of MF treatment on horticultural and agricultural crops have been presented. Furthermore, new prospects for MF treatment and the associated molecular basis have been presented. Since different species or cultivars have different optimal dose requirements for MF treatment, it is still a challenge presently to promote MF treatment use in commercial applications. For successful implementation of MF treatments, it is essential to conduct a large number of screening experiments and more in-depth research on the effects of MF on cultivated plants.

Keywords: crop yield and quality, seed physical treatment, molecular bases of magnetic field treatment, plant tolerance to stress, seed germination, seedling growth

INTRODUCTION

Modern scientific and technological research results show that various life activities in the biological world are accompanied by electromagnetic phenomena. At present, bio-magnetic technology has attracted more and more attention and research interest from professionals and has been widely used in the fields of medicine, agriculture, horticulture, environmental protection and bioengineering (Özdiñç and Yalçın, 2018). In medical science, magnetism has long been popularised to the stage of specific applications and has become an important medical detection method. In agricultural and horticultural areas, magnetic field (MF) effects on crops are being extensively explored.

Seeds/plants chemical treatments, including fertilisers, pesticides and fungicides, bio-stimulants, and so on, are widely used in agricultural and horticultural production. They effectively ensure the crop emergence rate, uniformity of emergence, plant growth rate in the following development stages and crop yield. However, chemical treatment has been controversial from the perspective of environment protection and food safety. More and more chemical reagents are deprecated or prohibited from being used. Under the general trend of environment-friendly agricultural and horticultural production, as an alternative to chemical treatment, physical treatments, such as MF, electric fields,

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microwave, and lasers, have attracted more and more attention (Aladjadiyan, 2007; Chen et al., 2016).

Applying magnetic physical treatment in agricultural and horticultural production has always been a keenly observed method by agricultural and horticultural researchers. The use of artificial MF to treat cultivated crop seeds/plants improves their agronomical characteristics, promotes seed germination and vigour, increases yield, improves crop quality and enhances stress tolerance (Shine et al., 2011; Bhardwaj et al., 2012; Da Silva and Dobránszki, 2016; Kataria et al., 2017; Bahadir et al., 2018; Hozayn et al., 2018; Krawiec et al., 2018; Radhakrishnan, 2018; Anand et al., 2019; Baghel et al., 2019; Hozayn et al., 2019; Kataria et al., 2019; Liu et al., 2019; Menegatti et al., 2019; Alvarez et al., 2020; Kataria et al., 2020; Souza-Torres et al., 2020; Adetunji et al., 2021; Bukhari et al., 2021; Harb et al., 2021; Samarrai et al., 2022). This technology has the advantages of less physiological damage, low cost and easy operation and application. Moreover, it produces no pollution and has a high input–output ratio (Michalak et al., 2019; Nyakane et al., 2019; Abdel Latef et al., 2020; Johnson and Puthur, 2021; Pagano et al., 2023).

Although the main focus of MF application research is in the area of crop commercial trait improvement, still in recent years, more and more researchers have turned their attention to the application of MF treatment in the field of plant stress tolerance improvement. Both magnetopriming and magnetised water (MW) irrigation can enhance the tolerance and vitality of cultivated plants under various environmental stresses (Baghel et al., 2019; Hasan et al., 2020; Hozayn et al., 2021; Kataria et al., 2022, 2023). It ensures not only the ability of plants to survive under adverse stress conditions, but also the accumulation of heavy metals by plants grown in heavy metal soil; thus, it improves the ability of plants to help in soil restoration (Tang et al., 2022; Prajapati and Patel, 2023). MF treatment research in this direction provides great potential for the use of plants for heavy metal soil remediation.

At present, there are many reports in the area of magnetic effects on plants. The research not only involves the positive effects after treatment, but also provides some discussion about its mechanisms. However, there are also reports on some cases when application of MF on seeds was not successful or repeatable. For some crops, only in certain range(s) of the MF intensity and exposure time have caused the positive effects (Araújo et al., 2016; Farooq et al., 2019; Rifina et al., 2019; Sarraf et al., 2020;), while the other ranges have given weakened or even negative effects (Abdani Nasiri et al., 2018; Nair et al., 2018; Florez et al., 2019; Khaledi et al., 2019; Massah et al., 2019; Migahid et al., 2019; Júnior et al., 2020; Afzal et al., 2021). Due to the complexity of the interaction between the used MF and plants, the research of the mechanism is still in the exploration stage and needs further study (Radhakrishnan, 2019). Therefore, an in-depth study of the macroscopic regularity and mechanism of the regulation of plant

physiological activities by magnetic treatment is still an area that needs to be vigorously developed. Meanwhile, the progress in MF treatment research will help reduce the use of traditional chemical reagents in agricultural and horticultural activity. Thus, the method has broad prospects in the development of environment-friendly agricultural and horticultural production and providing food-safety assurance.

The main aim of this review was to firstly highlight research findings with relevance to seeds or/and plants growing under the influence of a constant or alternating MF and MW and the impact on seed germination, plant growth, yield and their quality in horticultural and agricultural crops, enzyme activity, stress tolerance, and genome stability. Secondly, it was done to elucidate the molecular mechanism regarding the MF interaction based on the existing published results.

METHODOLOGY OF THE REVIEW

As magnetism becomes more and more widely used in agriculture and horticulture, we believe that it becomes necessary to summarise the latest and most-important scientific research results in the related fields and the results of further in-depth research on its mechanism. This could serve as a guide to relevant scientists and will attract more agricultural researchers to pay attention to this field of plant science. By studying selected papers in English and Chinese, we aimed to gain an understanding of past research results and come out with conclusions and recommendations for both the future MF experiments and its applications.

The English literature cited in this paper was mainly obtained through Google Scholar, whereas the Chinese ones came from the collection of the China National Knowledge Infrastructure (CNKI) platform. The searched keywords were ‘effect of MF and MW on plants’, ‘effect of MF on seeds’ and ‘application of MF and MW in agriculture and horticulture’. The present paper consists of five chapters discussing the points of concern for researchers in related fields. These are: ‘Materials and methods of the use of MF treatment’, ‘Plant parameters enhanced by MF’, ‘Molecular mechanisms understanding the response to MF treatments’, ‘Difficulty in application’ and ‘Conclusions and recommendations’. Afterwards, based on the experimental subjects, methods and results collected from the literature, several sub-chapters were further sub-divided into some chapters. For example, in the chapter ‘Plant parameters enhanced by MF’, five sub-chapters were sub-divided, with a focus on explaining the impact of MF on various aspects of plant’s development. They included ‘Increase of seed germination and seeding growth’, ‘Increase of crop yield and quality’, ‘Enhancement of enzyme activity’, ‘Increase of the tolerance to environmental stress’ and ‘Impact on genomic stability’. In each chapter or sub-chapter, representative experimental results, from the collected papers, were elaborated in detail. Their aim

was to provide more specific information for researchers in related fields and to provide an experimental results data foundation for future research and application. The present paper integrated information related to MF with a large amount of data by using a table. Photographs were also used to make the relevant descriptions more concrete and easier for readers to understand. All this allowed us to make final conclusions and recommendations.

MATERIALS AND METHODS OF THE USE OF MF TREATMENT

The MF processing technical parameters, for different methods of using, mainly include: MF intensity, exposure time, frequency of change (for alternating MF), and the number of cutting magnetic lines (for MW). So far, the MF treatment of cultivated crops can be roughly divided into three categories:

- (1) The first method is to treat seeds/plants directly with MF, depending on the experimental design, the processing time ranges from tens of minutes to several days (Hołubowicz et al., 2014; Hozayn et al., 2018; Baghel et al., 2019; Farooq et al., 2019; Jin et al., 2019; Menegatti et al., 2019; Radhakrishnan, 2019; Xia et al., 2020; Bukhari et al., 2021; Himoud et al., 2022). The types of MF that can be used include static MF or varying MF. Static MF is mostly provided by permanent magnets made of alloys such as iron, cobalt and nickel, and it obtains a wide magnetic induction. The varying MF can be obtained according to the MF principle – the alternating current passes through the coil to generate an alternating MF, and the pulsating current passes through coil to generate a pulsating MF. Other types of varying MF are rotating MF, translational MF and gradient MF. Figure 1 shows examples of two devices used in agricultural and horticultural research to generate MF: the Viofor machine which has been patented and previously used in human magnetotherapy (Figure 1, above) and magnets plates (Figure 1, below).
- (2) The second method is to treat seeds/plants indirectly with MF. In this method, the seeds/plants are not directly treated with the MF generated by a machine or a magnet, but through a medium that is magnetised by MF. The most common way to do so is to treat seeds/plants by MW. MW can be obtained by cutting magnetic lines by water flowing through static MF at a constant flow rate. According to the number of times the water flows through the whole static MF, the treated water can be divided into primary MW, secondary MW and multiple MW. MW can also be obtained by statically placing water directly in MF. The placing time ranges from tens of minutes to tens of hours. Then, the obtained MW is used for seed soaking or plant irrigation (Chibowski and Szcześ, 2018; Abobatta, 2019; Cui et al., 2020; Elhindi et al., 2020; Hasan et al., 2020;



Figure 1. Examples of two devices used in agricultural and horticultural research to generate MF: Viofor – patented and used first in human magnetotherapy (above), magnets (below) (Photo X. Xia and R. Hołubowicz). MF, magnetic field.

Samarah et al., 2021; Kishore et al., 2022; Mohamed et al., 2022). When MW is used for seed soaking, it all depends on the species: their soaking time in MW ranges from several hours to tens of hours. When MW is used for plant irrigation, the treatment covers the whole plant-growing period. An example of an experimental design to study the effects of MW irrigation on plants is shown in Figure 2. However, an already-reported result must be taken into consideration wherein MW would not retain its magnetism after leaving the magnetic source (Zamora et al., 2008).

- (3) The third method is composite processing. This kind of comprehensive treatment includes: multiple MF/MW processing, composite treatment with both static and alternating MF and composite treatment with both MF and MW (Sarraf et al. 2020).

The research materials include all seeds, seedlings or plants of agricultural, horticultural and other cultivated plants, for example, maize (*Zea mays*) (Kataria et al., 2017; Baghel et al., 2019; Himoud et al., 2022), rice (*Oryza sativa*) (Chen et al., 2016; Florez et al., 2019), wheat (*Triticum aestivum*) (Massah et al., 2019; Hassen et al., 2020; Selim et al., 2022), triticale (*×Triticosecale* Wittmack) (Alvarez et al., 2019, 2020), barley

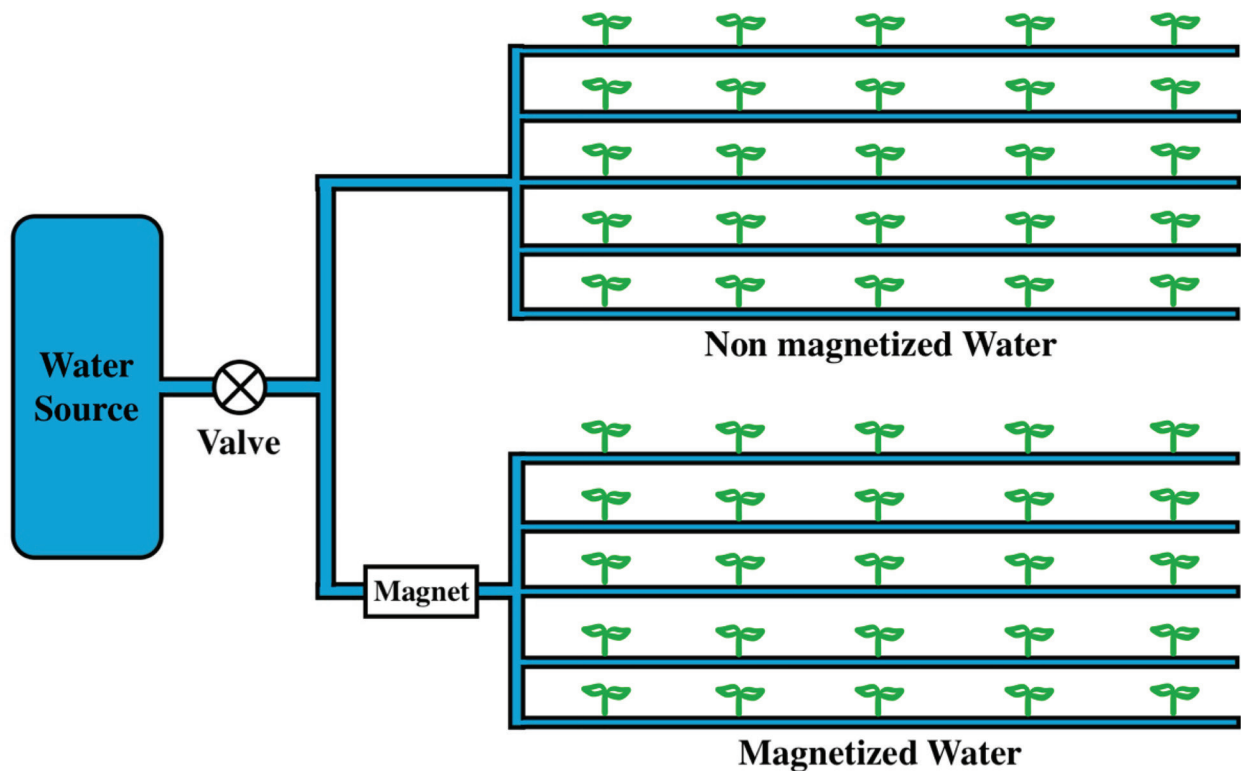


Figure 2. Example of an experiment design for the effects of MW irrigation on plants (Figure X. Xia). MW, magnetised water.

(*Hordeum vulgare*) (Hozayn et al., 2018; Ehtaiwesh et al., 2019; Hozayn et al., 2021), soybean (*Glycine max*) (Shine et al., 2011; Kataria et al., 2017; Özdiñç and Yalçin, 2018; Radhakrishnan, 2018; Kataria et al., 2019, 2020; Michalak et al., 2019), common bean (*Phaseolus vulgaris*) (Da Silva and Dobránszki, 2016; Sarraf et al., 2020), mung bean (*Vigna radiata*) (Nair et al., 2018; Sarraf et al., 2020), faba bean (*Vicia faba* spp. *minor*) (Podleśna et al., 2019), chickpea (*Cicer arietinum*) (Da Silva and Dobránszki, 2016; Samarrai et al., 2022), pepper (*Capsicum annuum*) (Liu et al., 2003), head cabbage (*Brassica oleracea* var. *capitata*) (Cui et al., 2014), Chinese cabbage (*Brassica rapa* subsp. *pekinensis*) (Han et al., 2008), lettuce (*Lactuca sativa*) (Abdel Latef et al., 2020), radish (*Raphanus sativus*) (Xia et al., 2020), tomato (*Solanum lycopersicum*) (Da Silva and Dobránszki, 2016; Souza-Torres et al., 2020), eggplant (*Solanum melongena*) (Cui et al., 2020; Kishore et al., 2022), sugar beet (*Beta vulgaris*) (Faïyad and Hozayn, 2020), sunflower (*Helianthus annuus*) (Afzal et al., 2021; Bukhari et al., 2021), passion fruit (*Passiflora edulis*) (Menegatti et al., 2019) and cotton (*Gossypium* spp.) (Da Silva and Dobránszki, 2016), *Sedum alfredii* (Tang et al., 2022).

PLANT PARAMETERS ENHANCED BY MF

According to current reports, the effects of MF treatment on plants are mainly reflected in the following aspects.

Increase of seed germination and seedling growth

Using MF treatment to improve seed germination is still the main direction of current seed MF treatment research. The mechanism of MF treatment to promote seed germination is related to enhancing enzyme activity in seeds, breaking seed dormancy, accelerating seed water absorption, stimulating protein synthesis in seeds and increasing their respiration rate. (Araújo et al., 2016; Radhakrishnan, 2019; Sarraf et al., 2020). A large number of conducted experiments has proven that MF treatment can effectively increase germination parameters of various plants. Positive effects of MF on agricultural and horticultural crops have been reported, for example, on maize (*Z. mays*) (Baghel et al., 2019; Himoud et al., 2022), rice (*O. sativa*) (Florez et al., 2019; Sarraf et al., 2020), wheat (*T. aestivum*) (Massah et al., 2019; Selim et al., 2022), triticale (*×T. Wittmack*) (Alvarez et al., 2019), barley (*H. vulgare*) (Hozayn et al., 2018; Ehtaiwesh et al., 2019), soybean (*G. max*) (Shine et al., 2011; Özdiñç and Yalçin, 2018; Kataria et al., 2017; Michalak et al., 2019), common bean (*P. vulgaris*) (Sarraf et al., 2020), mung bean (*V. radiata*) (Sarraf et al., 2020), head cabbage (*B. oleracea* var. *capitata*) (Cui et al., 2014), radish (*R. sativus*) (Xia et al., 2020), sunflower (*H. annuus*) (Bukhari et al., 2021), passion fruit (*P. edulis*) (Menegatti et al., 2019) and cotton (*Gossypium* spp.) (Da Silva and Dobránszki, 2016).

In the experiment of MF effects on sunflower (*Helianthus annuus*) seeds, the best result was received

from the 50 mT MF treatment for 45 min. The treated seeds showed higher mean germination growth (100 ± 0.02) and antioxidant activity than the control ones (Bukhari et al., 2021). The experiment on rice (*O. sativa*) seedling length affected by MF treatment showed that, on the 3rd day after sowing, the seedlings chronically exposed to 125 mT and 250 mT MF had bigger length (20.67 mm and 30.61 mm, respectively) than the control seedlings (9.05 mm) (Florez et al., 2019). In the experiment on faba bean (*V. faba* spp. *minor*), seed germination and seedling growth were affected by MF treatment, 85 mT for 15s MF treatment gave the best result. Amylolytic enzymes activity, IAA and GA₃ contents in germinating faba bean seeds and seedlings, which had positive effects on the seedling growth and development, were higher than the ones in the control plants (Podleśna et al., 2019).

In the area of artificial cultivation of wild medicinal plants, large-scale cultivation is often impossible due to the low seed germination rate. However, it was reported in recent years that the seed germination of *Tetrapanax papyriferus* and *Bupleurum chinense* could be effectively increased by MF treatment. The report pointed out that the best treatment combination for *Tetrapanax papyriferus* seeds was MF strength of 1500 GS combined with an electric field strength of 70 kV for 10 min and their germination rate has increased by 52.5% compared with the control seeds (Su and Mo, 2019). After the optimum treatment – 100 mT for 55 min – the seed germination rate of *Bupleurum chinense* increased by 10.5% compared with the control seeds (Zhang et al., 2020). These results laid the research foundation for large-scale artificial cultivation of wild medicinal plants. In an experiment of MF effects on *Salvia officinalis* seeds, it was reported that the treated (15 mT, 5 min) seeds gave longer and heavier (fresh weight) radicles than the control ones. They reached 50.46 mm and 0.11 g, respectively (Abdani Nasiri et al., 2018).

Increase of crop yield and quality

To achieve the improvement of crop yield and quality through MF treatment, two common methods have been reported to be used: direct MF treatment on seeds/plants or through MW. These two ways can effectively increase crop germination rate (Baghel et al., 2019; Selim et al., 2022), promote root formation (Ehtaiwesh et al., 2019; Joshi-Paneri et al., 2023), result in seedling robustness (Baghel et al., 2019), increase leaf area (Baghel et al., 2019; Ehtaiwesh et al., 2019; Selim, 2019; Hozayn et al., 2021; Himoud et al., 2022) and enhance stress tolerance (Nyakane et al., 2019; Radhakrishnan, 2019; Sarraf et al., 2020). These are important reasons for increasing yield and quality by MF treatment. Moreover, MW treatment/irrigation can accelerate the substance exchange and nutrient absorption between the root surface and the surrounding soil (Samarrai et al., 2022), improve soil quality (Cui et al., 2020) and

change the community structure of the organisms (Cui et al., 2020), enhance water quality and reduce its salinity impact (Elhindi et al., 2020; Hassen et al., 2020; Samarrai et al., 2022). This way, they achieve the purpose of improving yield or quality. The relevant reports are mainly concentrated on maize (*Z. mays*) (Baghel et al., 2019; Himoud et al., 2022), barley (*H. vulgare*) (Hozayn et al., 2021), wheat (*T. aestivum*) (Selim et al., 2022), chickpea (*C. arietinum*) (Samarrai et al., 2022), soybean (*G. max*) (Joshi-Paneri et al., 2023), mung bean (*V. radiata*) (Nair et al., 2018; Sarraf et al., 2020), sunflower (*H. annuus*) (Afzal et al., 2021), lettuce (*L. sativa*) (Abdel Latef et al., 2020), tomato (*S. lycopersicum*) (Da Silva and Dobránszki, 2016; Souza-Torres et al., 2020), eggplant (*S. melongena*) (Cui et al., 2020; Kishore et al., 2022) and sugar beet (*B. vulgaris*) (Faiyad and Hozayn, 2020).

In the experiment on mung bean (*V. radiata*) nutrients affected by extremely low-frequency sinusoidal MF, different frequencies (10, 50, 100 Hz) of MF were used for the same intensity (1500 ± 250 nT) for 15 days (5 hr · day⁻¹) treatment duration. As a result, all treatment groups showed higher Ca and P contents in seeds and higher Ca content in sprouts compared with control ones. Furthermore, the sprouts, grown from the treated seeds, of two mung bean lines (out of the 5 selected) showed the best total protein content improvement for 8.3% (10 Hz MF treatment) and 7.2% (50 Hz), respectively (Nair et al., 2018). In the experiment of MF effect on sunflower (*H. annuus*), the two methods: seed treatment with 100 mT MF for 10 min and seed priming with 3% moringa leaf extract solution prepared in MW improved the sunflower emergence, growth rate and yield (Afzal et al., 2021). In the experiment done by Joshi-Paneri et al. (2023) on soybean, seed magnetopriming was used. The best yield parameters were received when using MF of the intensity 200 mT for 1 hr. The received maximum enhancements for the so-treated seeds and plants expressed as number of pods per plant, number of seeds per plant, seed weight per plant and 100 seeds weight were 35%, 50%, 53% and 16%, respectively.

Enhancement of enzyme activity

MF treatment can lead to the directional alignment of intracellular carbohydrates, lipids, proteins and other polar molecules and metal ions. It has made the conformation change of the enzymes which contain metal ions of Mg, Zn, Mn, Fe, thereby changed the enzymes' activity (Liu et al., 2003; Han et al., 2008). The study on plants' enzyme activities changed by MF treatment were mainly focused on peroxidase (POD) (Bao and Yun, 2010; Anand et al., 2019; Kataria et al., 2019; Abdel Latef et al., 2020), catalase (CAT) (Anand et al., 2019; Abdel Latef et al., 2020; Harb et al., 2021) and superoxide dismutase (SOD) (Anand et al., 2019; Kataria et al., 2019; Abdel Latef et al., 2020; Harb et al., 2021). Part of the study was also directed

to polyphenol oxidase (PPO) (Abdel Latef et al., 2020), nitrate reductase (NR) (Radhakrishnan, 2019; Kataria et al., 2022, 2023), malate dehydrogenase (MDH) (Júnior et al., 2020), ascorbic acid peroxidase (APX) (Nyakane et al., 2019; Abdel Latef et al., 2020; Harb et al., 2021), glutathione reductase (GR) (Araújo et al., 2016) and other enzymes, and have shown positive feedback.

Plant enzyme activity directly affects various physiological indicators of plants (Nyakane et al., 2019; Radhakrishnan, 2019; Sarraf et al., 2020; Kataria et al., 2022). Therefore, studies on the effects of MF on enzyme activity are usually incorporated in such works. One of the possible mechanisms to get better traits through seeds/plants MF treatment is enzyme activities changes led by MF. They are presented in the next chapter.

Increase of the tolerance to environmental stress

Environmental stress increases the production of reactive oxygen species (ROS) in plants, which then leads to their peroxidative damage. Moreover, oxidative damage initiated by ROS is also the main reason leading to the plant's ageing (Muller et al., 2007; Van Raamsdonk and Hekimi, 2009). POD, CAT and SOD, the main enzymes related to the elimination of ROS in plants, eliminate excessive ROS caused by stress and maintain ROS balance in plants, thereby protecting them from peroxidative damage (Anand et al., 2019; Kataria et al., 2019; Abdel Latef et al., 2020; Harb et al., 2021). MF treatment enhances the plants' ability to eliminate ROS by increasing the activity of the above-mentioned enzymes, thereby enhancing plant stress tolerance and anti-ageing capabilities (Liu et al., 2003; Han et al., 2008; Nyakane et al., 2019; Radhakrishnan, 2019; Sarraf et al., 2020).

The MF effect on plant tolerance to heavy metal stress can be used in the area of contaminated soil restoration (Prajapati and Patel, 2023). Dissolved organic matter (DOM) in the *Sedum alfredii* rhizosphere mobilises Cd by generating DOM–Cd (organic matter–Cd fraction). In the experiment of soil Cd accumulation by *S. alfredii*, the Cd extraction capacity of DOM from the rhizosphere of the plants grown from MF-treated seeds was higher than that of the control plants, thus increasing the Cd concentrations in the plant tissues. Out of all the treatments, 150 mT MF seed treatment (20 min each day for 1 week) gave the best result. Compared with the control plants, the *S. alfredii* ones grown from treated seeds excreted more DOM in their rhizosphere. Additionally, the hydrophilic DOM fractionation proportion, which presented greater capacity to mobilise Cd in soil, increased from 42.7% (control) to 47.2% (150 mT MF treatment) (Tang et al., 2022). In the experiment of salinity stress, the maize (*Z. mays*) plants, grown from the seeds treated with 200 mT static MF for 1 hr, showed lower H₂O₂ and better photosynthetic performance and bigger yield under all selected salt stress levels (0, 25, 50, 75,

100 mM NaCl concentration) (Baghel et al., 2019). The results of Kataria et al. (2022) experiment on soybean seeds under salinity stress indicated that a balance of abscisic acid (ABA), gibberellin (GA) and auxin (IAA) was maintained by the signalling molecule nitric oxide (NO) in magnetoprimed seeds. It lowered the Na⁺/K⁺ ratio to offset the adverse effects of salinity in the seeds. Magnetopriming of soybean seeds enhanced the NO production by up-regulation of genes of enzymes related to nitric oxide synthase-like (NOS-like) and NR along with their enhanced activities. The enhanced NO production lowered the Na⁺/K⁺ ratio to increase the salt tolerance index in soybean seeds. As a result, magnetopriming increased in the soybean seeds their salt tolerance by 44% in comparison to the check seeds.

The coordination of SOD, POD and CAT can keep free radicals in cells at a relatively low level and enhance the anti-ageing ability of seeds. As the seed ageing time goes by, the activity of above three enzymes in seeds gradually decreases. For the seeds treated with MF, the decreasing trend of these enzymes' activity was significantly alleviated. There are reports that the anti-ageing ability of pepper (*C. annuum*) and Chinese cabbage (*B. rapa* subsp. *pekinensis*) seeds treated with MF was enhanced. In the experiment of accelerated ageing of pepper seeds, the seeds treated with MF (5 times at 100 mT, 2 min each time) showed the biggest promotion in germination capacity after 8 days of the ageing treatment. It increased by 17% in comparison with the control seeds (Liu et al., 2003). In the ageing experiment of multiple cultivars of Chinese cabbage, the result showed the positive effect of MF on seed germination rate. It was bigger than its effect on the germination capacity (Han et al., 2008).

Impact on genome stability

The impact of magnetic treatments on genome stability was investigated by Hozayn et al. (2015) in onion seeds exposed to MF in a static magnetic device. The mitotic index of meristematic cells increased in response to all the tested conditions. However, a concomitant increase in the frequency of chromosomal aberrations, although not lethal, was also observed (Hozayn et al., 2015). Similar results were reported by Aksoy et al. (2010) in wheat (*Triticum baeoticum* subsp. *baeoticum*). Moreover, the authors also reported that some aberrations induced in seeds by their exposure to MF may be transmitted to the next generations, resulting in either defective or beneficial phenotypes (Attia et al., 2014). In a subsequent study, Tajik Esmaeili's team evaluated the genotoxic effect of a low frequency electromagnetic field used to treat fresh and dry bean seeds. Random amplified polymorphic DNA (RAPD) profiles revealed differences between the treated and untreated seeds, thus suggesting that genome stability was affected (Tajik Esmaeili et al., 2017).

MOLECULAR MECHANISMS UNDERLYING THE RESPONSE TO MF TREATMENTS

A deep understanding of the cellular and molecular pathways triggered upon exposure to MF, responsible for the observed biological reactions, is required to provide improved rationale bases for the design of tailored seed invigoration treatments. The current state of the art highlights multiple pathways and targets, disclosed mainly by studies on animal and human systems (Xu et al., 2021).

An intriguing aspect is related to MF perception that has been suggested to occur according to the ‘radical pair mechanism’ (Hammad et al., 2020). Cryptochromes, highly conserved blue light-absorbing flavoproteins acting as photoreceptors during plant development, have been associated to MF perception in plants, flies, and humans. In the presence of MF, cryptochrome modulates ROS levels and, consequently, the cellular redox reactions. This process, conserved in both plants and animals, affects gene expression (Parmagnani et al., 2022a, 2022b).

In the attempt to explain the impact of MF on biological processes, Binhi and Prato (2017) developed the ‘molecular gyroscope mechanism’ based on the rotation of large fragments of macromolecules or amino acid residues with distributed electric charges in response to MF. The biological effect is related to the reaction yield, the number of gyroscopes that enter this reaction, or those that are in a state of equilibrium. The theoretical model elaborated by Vaezzadeh et al. (2006) is based on the oscillation of ferritin under the influence of MF. A common feature of these models is the hypothesis that the MF energy is absorbed by the cells, affecting the mobility and uptake of ions with important roles in cellular homeostasis.

Information about MF mechanism in plants is still scanty, and the published reports generally focus on the plant response rather than on seed germination. In a recent review, Salentnik et al. (2022) described the effects of MF on plant gene expression, underlining the potential of the technique for applications in the agri-food sector. The few reports, so far contributing to expand the knowledge in plant field, use the model system *Arabidopsis thaliana*. Jin et al. (2019) investigated the impact of static MF on *Arabidopsis* seedling growth and evidenced that root growth was promoted according to intensity and direction-dependent profiles by increasing auxin levels in the root tip. Transcriptomics showed that MF caused upregulation of the *AUX1* gene coding for an auxin influx transporter as well as downregulation of the *PIN3* gene encoding an auxin efflux transporter. The MF-shaped *Arabidopsis* transcriptome revealed up-regulation of genes participating in the flavonoid biosynthetic pathway, cell wall organisation and nitrate transport.

Parmagnani et al. (2022b) explored the transcriptomics and metabolomics of ROS production in roots and shoots of *A. thaliana* plants exposed to MF. Upregulation of several oxygenase-coding genes was observed in the tested tissues, including *AERO2* involved in the oxidative protein folding in the endoplasmic reticulum (Fan et al., 2019) and *GulLO1* involved in the production of the antioxidant and redox molecule L-ascorbic acid (Maruta et al., 2010). Developmental changes in ROS production occurring in MF-treated plants were associated to the upregulation of genes coding for enzymes involved in ROS production, for example, respiratory burst oxidase homolog H, J and G (*RBOHH*, *RBOHJ* and *RBOHG*) (Parmagnani et al., 2022b). Metabolomics provided insights into the dynamics of antioxidant molecule accumulation, such as polyphenols. Furthermore, increased H₂O₂ production in MF-exposed plants was associated with progressively decreased polyphenols levels (Parmagnani et al., 2022b). Kataria et al. (2022) proved in their experiment on magnetoprimered soybean seeds that the enhanced NO production lowered the Na⁺/K⁺ ratio to increase the salt tolerance index in soybean seeds. The enhanced NO production came from the upregulation of genes of enzymes related to nitric oxide NOS-like and NR along with their enhanced activities after soybean seeds magnetoprimering. The *GmNOS-like 2* and *GmNRI* genes can be ideal candidates to be characterised towards their involvement in the NO production in soybean.

The complexity of the molecular networks underlying the response of plant cells to MF has been so far partially disclosed. The mechanisms of plant perception and signalling and related molecular players still need to be defined as well as the downstream targets (effectors) that contribute to the physiological responses (growth, antioxidant protection). Efforts should be expanded to gain insights into the way the seed pre-germinative metabolism reacts at the molecular level to MF treatments. In this way, it will be possible to design more rationale and controlled MF-based protocols for agri-food applications.

DIFFICULTY IN APPLICATION

It is important to note that a large number of research results showed that different optimal MF intensities and exposure time for different cultivated crops, cultivars and target traits were found. The excessive intensity and exposure time will lead to weakened positive effects, and even in some crops – to negative effects (Table 1). As in the table below, listed crops, including agricultural, horticultural and herbal plants, all showed positive effects in certain range(s) of the MF intensity and exposure time, while there did exist the adverse dose, which led to negative effects (Table 1). After studying the table, one should be aware that in the past, many researchers who had tried and failed to use MF or MW in their experiments with plants

Table 1. A summary of positive and negative doses of MF treatment on selected cultivated crops

Crop (genus/cultivar)	Method	Selected parameters	Positive dose	Negative dose	Reference
Lentil (<i>Lens culinaris</i>)	Seed MF treatment	Seedling growth, lipid peroxidation and antioxidant enzymes activity	20 mT, 20 min.; 20 mT, 25 min.	50 mT, 30 min.	Harb et al. (2021)
Sunflower (<i>Helianthus annuus</i>) FH620	Seed MF treatment	Final emergence rate and mean germination time	50 mT, 45 min.	80 mT, 30 min.; 100 mT, 15 min.	Bukhari et al. (2021)
<i>Lathyrus chrysanthus</i>	Seed MF treatment	Seed germination	125 mT, 24 h; 125 mT, 48 h	125 mT, 72 h	Bahadir et al. (2018)
Soybean (<i>Glycine max</i>) JS-335	Seed MF treatment	Percentage and speed of germination	200 mT, 60 min.	250 mT, 90 min.; 300 mT, 90 min.	Shine et al. (2011)
Medicinal sage (<i>Salvia officinalis</i>)	Seed MF treatment	Radicle length	15 mT, 5 min.	3 mT, 5 min.; 30 mT, 5 min.	Abdani Nasiri et al. (2018)
		Radicle dry weight	15 mT, 5 min.; 30 mT, 5 min.	3 mT, 5 min.	
Sunflower (<i>Helianthus annuus</i>) Armoni	Seed MF treatment	1000-achene weight (yield of the plants grown from MF treated seeds)	100 mT, 10 min.	150 mT, 10 min.	Afzal et al. (2021)
Wheat (<i>Triticum aestivum</i>) Alborz	Seed MW treatment (distilled water)	Seed germination	400 mT, 30 min.; 600 mT, 30 min. (MF treatment on water sample)	500 mT, 30 min. (MF treatment on water sample)	Massah et al. (2019)
		Shoot length, root length and seedling vigour index	400 mT, 30 min.; 500 mT, 30 min. (MF treatment on water sample)	600 mT, 30 min. (MF treatment on water sample)	
Mung bean (<i>Vigna radiata</i>) line NM94	Seed MF treatment	Protein contents in sprouts	10 Hz, 1500 nT $\pm$ 250 nT; 100 Hz, 1500 nT $\pm$ 250 nT (all for 5 hr $\cdot$ day ⁻¹ for 15 days)	50 Hz, 1500 nT $\pm$ 250 nT (5 hr $\cdot$ day ⁻¹ for 15 days)	Nair et al. (2018)
Coffee (<i>Coffea arabica</i>) Catuai Vermelho 144	Seed MF treatment	enzyme activity - EST	28 mT, 6 days	10 mT, 6 days	Júnior et al. (2020)
Alfalfa (<i>Medicago sativa</i>)	Seed MF treatment	Growth parameters, protein contents and enzymes activity	0.75 mT, 30 min $\cdot$ day ⁻¹ , for 4 days	1.5 mT, 30 min $\cdot$ day ⁻¹ , for 4 days	Khaledi et al. (2019)
Ryegrass (<i>Lolium perenne</i>) Accent	Seed MF treatment	Seed germination capacity	1000 Gs, 30 min.; 1500 Gs, 30 min.; 2000 Gs, 30 min.	2500 Gs, 30 min.	Wang et al. (2010)
Head cabbage (<i>Brassica oleracea</i> var. <i>capitata</i>) Wanfeng	Seed MF treatment	Seed germination	1000–3500 Gs, 1–6 min.	Over 3500 Gs, over 6 min.	Cui et al. (2014)
Cauliflower (<i>Brassica oleracea</i> L. var. <i>botrytis</i>) Xueling 1	Seed MF treatment	enzyme activity - POD	3000 Gs, 8 hr	3500 Gs, 8 hr; 3500 Gs, 12 hr	Bao and Yun (2010)
Cucumber (<i>Cucumis sativus</i>) Shandong Mici	Seed MF treatment	Seed germination capacity	0.5 T (5, 10 min.); 1.0 T (5, 10 min.); 1.5 T (5, 10 min.)	2.0 T (5, 10 min.)	Yu and Zhang (2010)

EST, esterase; MF, magnetic field; MW, magnetised water; POD, peroxidase.

had never reported it. Some of these old experiments could be repeated today when our technical equipment is much better than before. Moreover, many of such reports were published in other-than English languages and, therefore, could have been missed by ones who only follow papers published in English. Another serious difficulty that came from this review is lack of one main way of using MF in practical agriculture and horticulture as it had affected various organs of plants. Therefore, for some species, cultivars and target traits, only by a large number of screening experiments to determine the best treatment conditions, can MF treatment achieve the purpose of effectively improving the target traits of plants.

CONCLUSIONS AND RECOMMENDATIONS

In recent years, the application of magnetism in agriculture and horticulture has been paid more and more attention to, especially in the field of MF treatment on both seed germination and the physiology of seedlings. In the application research of MF effects on seeds, for certain species and cultivars, only after a large number of screening tests to determine optimal dosage, can we achieve positive effects and income improvement. This is the main challenge we currently face for the commercial MF application in plants.

In the current application research of MF effects, much of the work, so far, has focused on how to improve economic traits and increase economic output. At the same time, more and more researchers have moved their attention to using seed MF treatment or MW irrigation to improve the plant stress tolerance under salt or heavy metal stresses, in order to achieve the purpose of soil restoration by plant heavy metal accumulation. At present, there have been many reports that MF treatment can successfully improve plant tolerance to various environmental stresses. They have all proved the potential of MF application in this area and provide new environmentally friendly ideas for soil restoration and environment protection. In addition, there are also reports on MF effect on seed anti-ageing ability, which imply that the magnetic treatment may also have a technical potential applied to seed storage.

On one hand, the future research direction is still to study in-depth the mechanism of MF effects on seed germination and cultivated crops growth promotion. It would help us to understand or even effectively predict the possible improvement of the crops' parameters enhanced by the treatment. On the other hand, further research and development on the use of MF to improve plant stress tolerance are needed to achieve the application in soil remediation and environment protection on a large scale. Through these two aspects of further study and development can we make MF treatment more effective and targeted in agricultural and horticultural production and environment restoration.

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X.X., R.H. and A.B. – conceptualization. X.X., A.B., G.P., A.M. and A.P. – resources. X.X., A.M. and A.P. – writing – original draft preparation. X.X. and A.B. – writing – review and editing. R.H. and A.B. – supervision. X.X. – project administration. All authors have read and agreed to the published version of the manuscript.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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