RESEARCH PAPER

Magneto-Priming as a Sustainable Strategy for Enhancing Plant Bioactive Compounds: Mechanisms and Applications in Health Promotion

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ABSTRACT

The rising global prevalence of chronic diseases such as diabetes, cardiovascular disorders, and neurodegenerative conditions has intensified the search for sustainable, plant-based therapeutic strategies. The global demand for sustainable agricultural innovations that enhance both crop productivity and nutritional quality has accelerated interest in magneto-priming — a novel, eco-friendly pre-sowing technique that exposes seeds to static magnetic fields. Magneto-priming has demonstrated remarkable potential to improve seed germination, stress tolerance, and the biosynthesis of secondary metabolites with therapeutic relevance. Exposure to magnetic fields induces subtle physiological and biochemical changes that regulate ion transport, redox homeostasis, and gene expression, leading to the upregulation of enzymes involved in phenolic and flavonoid biosynthesis. These modulations enhance the accumulation of therapeutic metabolites including phenolics, flavonoids, carotenoids, and alkaloids, thereby elevating antioxidant and antimicrobial potential. This review synthesizes recent advances highlighting how magnetic field exposure modulates biochemical and physiological pathways in plants, leading to the accumulation of phenolics, flavonoids, carotenoids, and other bioactive compounds with strong antioxidant, antimicrobial, and antidiabetic activities. Collectively, magneto-priming offers a promising biotechnological avenue for developing climate-resilient crops with enhanced nutraceutical and therapeutic value, bridging agriculture with preventive healthcare.

Keywords: Magneto-Priming, Bioactive Compounds, Diabetes, Cardiovascular Disorders, Antioxidant

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1. *Introduction*

The global pursuit of sustainable and resilient agricultural practices has intensified the search for innovative, sustainable and environmentally beneficial technologies that have the potential to enhance both crop productivity and nutritional quality. In this search, magneto priming, a seed treatment involving exposure to a static magnetic field, has emerged as a promising, eco-friendly method for enhancing seed germination, plant vigour, and the biosynthesis of bioactive compounds with therapeutic relevance.[1] Magneto-priming techniques utilise static electromagnetic stimuli to modulate biochemical pathways and physiological responses within the plant systems, which could help in enhancing the stress tolerance and elevating the levels of secondary metabolites such as phenolics, flavonoids, and antioxidants. [2]–[4]

In the context of growing global health challenges, the role of plant-derived bioactive compounds (phytochemicals) in disease prevention has garnered substantial attention. Phytochemicals such as flavonoids, phenolic acids, alkaloids, terpenoids, and carotenoids are naturally occurring compounds in plants that possess antioxidant, anti-inflammatory, antimicrobial, and antidiabetic properties. The therapeutic potential of these phytochemicals against chronic diseases such as cardiovascular disease, diabetes, cancer, and microbial infections has been extensively documented, making them critical components of preventive nutrition and modern phytotherapy.

The concentration and bioavailability of phytochemicals in plants can vary significantly depending on various factors, including genetic, environmental, and agronomic factors. Therefore, the need to enhance phytochemical content in crops will not only help in meeting the nutritional demands but will also help in addressing the increasing global reliance on plant-based disease prevention strategies. Modern agriculture and food systems must therefore explore novel, sustainable techniques that can simultaneously boost crop productivity and nutritional quality.

The biological efficacy of magneto-priming has been attributed to its capacity to influence membrane ion transport, gene expression, and redox signalling during early germination and growth stages.[5] These responses not only improve agronomic traits but also enrich the phytochemical content of crops, thereby aligning agricultural productivity with human health benefits. Recent studies have demonstrated that static magnetic field treatments can significantly enhance the nutraceutical potential and antimicrobial activity of *Momordica charantia* by increasing phenolic content and flavonoid accumulation, without compromising its nutritional value. [2] Similar findings in soybeans (*Glycine max*) report improved photosynthetic efficiency, hormone balance, and yield following magneto-priming, especially under conditions of salinity and oxidative stress.[1], [3]

Chronic diseases such as diabetes, cancer, cardiovascular ailments, and microbial infections are strongly linked to oxidative stress and inflammation. Plant-derived bioactive compounds, particularly polyphenols and antioxidant enzymes, have garnered attention for their role in disease prevention. Magneto-priming appears to potentiate the biosynthesis of such therapeutically relevant metabolites, suggesting a dual benefit: agronomic enhancement and the development of functional foods or phytomedicines. [4], [6]

Despite the growing body of research, the application of magneto-priming to maximise the therapeutic potential of plant-derived phytochemicals remains a relatively underexplored frontier. This review aims to critically evaluate the impact of magneto-priming technology on phytochemical enhancement and its implications for disease prevention and therapeutics. By integrating evidence from recent experimental studies, the review highlights magneto-priming as a transformative tool for bridging the gap between sustainable agriculture and preventive healthcare.

2. *Principle and mechanism of priming*

The priming of seeds has been widely practised from the traditional to the modern era by seed technologists for commercially utilised seeds. The primary aim of priming was to improve seed vigour by enhancing germination potential and stress tolerance in plants.[7] The International Seed Testing Association (ISTA) has also considered the performance of seeds during germination and seedling production as an essential aspect.[8] The priming of seeds is mainly involves controlled hydration allowing the activation of pre-germinative metabolic processes without permitting radicle emergence. [9] The priming of seeds thus helps in the controlled hydration of seeds before plantation and enhances the speed of germination, vigour, overall germination percentage and uniformity, particularly under stressful environmental conditions. [8]

2.1. *A Brief history of priming*

The word ‘priming’ is related to the enhancement of seed quality by subjecting the seed to various physiological and chemical treatments for the increase in germination rate as well as creating resistance towards abiotic/biotic stress. The history of priming dates back to the ancient era of Theophrastus, who reported that soaking cucumber seeds before planting helped in increasing the rate of germination in his accounts titled Enquiry into Plants. [10] Gaius Plinius Secundus (A.D. 23–79), also known as Pliny the Elder, mentioned the pre-soaking procedure in his encyclopaedia on seed physiology, titled Naturalis Historia. Apart from this, French agronomist and botanist Oliver de Seress and Charles Darwin have also mentioned various methods of seed priming to enhance seed germination.

2.2. *Principle of seed priming*

Seed priming follows the principle of initiating the early physiological and biochemical processes of germination without allowing the radicle to emerge. By carefully hydrating seeds to a controlled level, metabolic activities such as enzyme activation, DNA repair, energy metabolism, and synthesis of nucleic acids and proteins are triggered. These changes prepare the seed for rapid and synchronised germination upon sowing. After this partial hydration, seeds are re-dried to their original moisture content, allowing them to be stored or handled like untreated seeds. The primary goal of priming is to enhance seed performance under both optimal and stressful environmental conditions, thereby ensuring faster germination, uniform emergence, and stronger seedling establishment.

2.3. *Pre-germinative effects of seed priming*

The physiological and chemical treatment of seeds before sowing results in specific metabolic changes in the seeds, providing positive effects on growth. Seed priming initiates critical physiological and biochemical changes even before visible germination begins. The priming of seeds causes the triggering of cellular processes, including the de novo synthesis of nucleic acids and proteins, the production of ATP, the activation of DNA repair and antioxidant activities. These activities mark the onset of pre-germinative metabolism, essential for seed vigor and successful germination. One major focus during this phase is DNA repair, which counteracts damage from oxidative stress encountered during seed maturation, storage, and imbibition. Key DNA repair pathways like Base and Nucleotide Excision Repair (BER and NER), including Transcription-Coupled NER (TC-NER), are triggered early to maintain genomic stability.[11]–[14] On the other hand, reactive oxygen species (ROS), though essential for signalling, can cause damage to DNA, proteins, and RNA. Therefore, a strong antioxidant defence system is vital. Enzymes such as Superoxide Dismutase (SOD), Catalase (CAT), Ascorbate Peroxidase (APX), and Glutathione Reductase (GR) are upregulated during the priming process. These protect cellular components and help maintain redox balance. Overall, seed priming enables seeds to initiate and complete pre-germinative metabolic activities in a controlled manner, enhancing stress resilience, germination speed, and seedling vigour upon sowing.[7][15]

There are various methods for seed priming, which are chosen based on crop needs and environmental conditions, resulting in improved germination, seedling vigour, and overall crop yield in challenging growing situations. The different methods of seed priming include conventional methods such as hydropriming, Osmo priming, chemo priming, biopriming, and halo priming, as well as modern methods such as nano-priming, Nutri-priming, magneto-priming, and thermopriming.

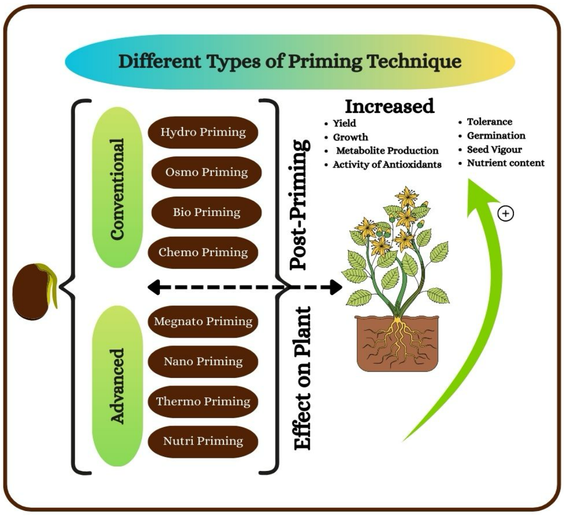

Fig 1: Different types of seed priming methods and its effect.

3. *Magneto-priming*

In the magneto priming technique, the dry seeds are exposed to a static magnetic field for a long duration of time to enhance and promote the seed germination, seedling vigour, crop yield and stress tolerance potential of the crop.[15]–[17] The techniques have been found useful in the mitigation of adverse effect caused by environmental factors such as salinity, drought, disease and pest on the crop. Magnetically primed seeds exhibit improved germination kinetics, enhanced root and shoot growth, increased biomass production, and more efficient water uptake. This improved water absorption facilitates the early activation of key enzymes such as amylase, protease, and dehydrogenase, which accelerates the germination process and strengthens seedling vigour, even under challenging conditions like drought and salinity stress. Studies have shown that magneto-priming significantly enhances the germination and developmental performance of crops such as maize, broccoli, almonds, soybean, wheat, chickpea and sunflower.[1], [8], [15], [17]–[20].

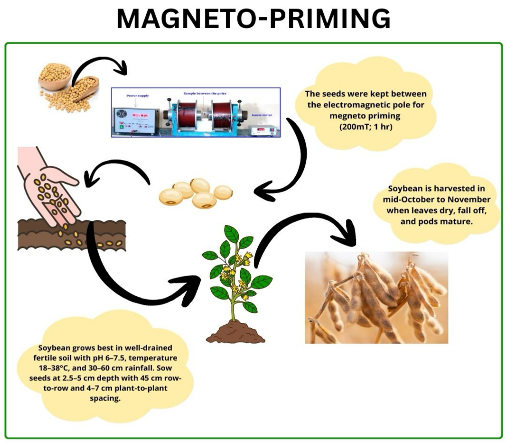

Fig 2:- Process of magneto priming of seeds

3.1. *Impact of magneto priming*

3.1.1. *Effects of Static Magnetic Field on Seed Germination*

The Earth's natural magnetic field, with an intensity of 50-60µT, has an impact on plant growth. The significant evaluated effects of static magnetic field on plants are related to the average germination rate, coefficient of germination rate and water absorption, which have linearly increased. The researchers have observed that a magnetic field has the potential to enhance seed germination by altering biochemical pathways, primarily through increased stimulation of specific proteins and enzyme activities. Magnetic fields are believed to interact with the internal electric fields present in biological systems due to their resonant nature. Since living cells contain electric charges generated by ions and free radicals, functioning somewhat like natural magnets, these elements play a key role in cellular biochemical processes. Applying an external magnetic field can increase ion absorption, thereby potentially boosting the nutritional quality of the seed. Additional studies have suggested that magnetic fields influence ion flow across the embryonic cell membrane, affecting ion concentration and osmotic pressure on both sides. This change alters the water-seed interaction, ultimately improving the conditions for germination.[21]–[23]

In recent research, Anand et al. demonstrated that varying magnetic fields affect gene expression and phenotype in plants. He reported that the key components of the signal transduction pathway are RACK1 (Receptor for Activated Protein Kinase C1) and metallothionein, which is regulated by reactive oxygen species (ROS), that contributes to the accelerated germination observed in magneto-primed tomato seeds (*Lycopersicon esculentum* L. Mill. var. Pusa Rohini).[23], [24]

3.1.2. Effects on Reducing Oxidative Damage

Magneto-priming has been found to play a significant role in minimising oxidative stress in plants by enhancing their antioxidant defence mechanisms. During seed germination, reactive oxygen species (ROS) such as superoxide radicals ($O_2^{-}\cdot$), hydrogen peroxide (H_2O_2), and hydroxyl radicals ($\cdot OH$) are naturally produced through aerobic metabolic processes occurring in the mitochondria, peroxisomes, and the apoplastic space. While ROS play essential roles as signalling molecules in various physiological pathways, their excessive accumulation can facilitate in causing oxidative damage to lipids, proteins, and DNA. To mitigate such damage, seeds have evolved specialised ROS-scavenging systems comprising both enzymatic and non-enzymatic antioxidants. These systems regulate ROS levels, ensuring that they remain within a functional range for signalling without causing cellular harm. Magneto-priming has been shown to enhance these protective mechanisms by upregulating key antioxidant enzymes, including superoxide dismutase (SOD), catalase (CAT), and peroxidase (POD). This enzymatic activation enhances the seed's tolerance to oxidative stress, particularly under adverse environmental conditions such as drought and salinity.[16]

For instance, Bhardwaj et al.[25] reported that cucumber (*Cucumis sativus* L.) seeds exposed to static magnetic fields (SMFs) exhibited increased enzymatic activity of SOD by 8%, CAT by 83%, and glutathione reductase by 77%, compared to untreated controls. Similar positive effects were observed in *Zea mays* and artichoke (*Cynara scolymus*), where magneto-treatment significantly enhanced CAT and ascorbate peroxidase (APX) activities.[26] Hajnorouzi et al.[27] further demonstrated that alternating magnetic field pretreatment promoted maize seedling growth by reducing ROS accumulation; though SOD activity decreased, overall antioxidant capacity increased, suggesting a shift in redox balance toward a more resilient state.

Several experiments on crops such as soybean (*Glycine max*), corn (*Z. mays*), tomato (*L. esculentum*), and lentil (*Lens culinaris*) have consistently reported that magnetic field pre-exposure boosts resistance to environmental stresses such as drought. These studies highlight upregulation of key antioxidant enzymes (APX, SOD, CAT) in both roots and shoots, contributing to the detoxification of ROS and improved stress tolerance. For instance, in lentil seeds, Shabrangi and Majd[28] noted significantly higher SOD and APX activity under drought conditions when seeds were magneto-primed. Moreover, it has been observed that the magnetic fields may interact with membrane-bound ion currents, influencing ion concentration and osmotic balance. These interactions potentially uncouple free radical processes in membranes and modulate cellular oxidative responses. However, findings also indicate that the response to magnetic fields is highly variable and can depend on intensity, duration, and exposure type. In soybean seedlings, Shine and Guruprasad[29] observed an increase in ROS production mediated by cell wall peroxidase after SMF treatment, but a simultaneous decrease in SOD and APX activities in the hypocotyl region. Thus, while magneto-priming generally enhances the antioxidative capacity of seeds and supports improved germination and stress tolerance, its effects can be context-dependent. Field strength, exposure duration, plant species, and developmental stage all influence whether magnetic fields act as beneficial stimulants or harmful stressors.

Table1 : Impact of Magneto-Priming on Seed Germination and Oxidative Damage

Section	Key Findings	Details / Examples	References

Effects of Static Magnetic Field on Seed Germination	Earth's natural magnetic field (50–60 µT) influences plant growth.	• Improves germination rate, coefficient of germination, and water absorption (linearly increased). • Alters biochemical pathways by stimulating proteins and enzyme activities. • Interacts with biological electric fields due to resonant nature. • External magnetic fields increase ion absorption, boosting nutritional quality of seeds. • Affects ion flow across embryonic cell membranes, altering osmotic pressure and water-seed interactions, improving germination.	[21]–[24]
	Gene expression and phenotype modulation.	• Anand et al. showed varying magnetic fields regulate RACK1 and metallothionein (ROS-regulated). • Accelerated germination observed in magneto-primed tomato seeds (Lycopersicon esculentum L. Mill. var. Pusa Rohini).	[23], [24]
Effects on Reducing Oxidative Damage	Magneto-priming minimises oxidative stress by enhancing antioxidant defence.	• ROS ($O_2^{-}\cdot$, H_2O_2, $\cdot OH$) are naturally produced during aerobic metabolism. • Excess ROS damage lipids, proteins, DNA.- Seeds evolved enzymatic (SOD, CAT, POD) and non-enzymatic systems to regulate ROS. • Magneto-priming upregulates antioxidant enzymes (SOD, CAT, POD), enhancing tolerance under drought and salinity.	[16]
	Enhanced enzymatic activity.	• Bhardwaj et al.: cucumber seeds under SMFs showed ↑ SOD (8%), ↑ CAT (83%), ↑ glutathione reductase (77%). • Zea mays and artichoke (Cynara scolymus): enhanced CAT & APX activities. • Hajnorouzi et al.: alternating MF pretreatment in maize reduced ROS, ↑ overall antioxidant capacity despite ↓ SOD.	[25], [27]
	Stress resistance in crops.	• Soybean, corn, tomato, lentil: magnetic pre-exposure ↑ resistance to drought via upregulation of APX, SOD, CAT in roots & shoots. • Lentil (Shabrangi & Majd): ↑ SOD & APX under drought after magneto-priming.	[28]
	Ion interactions and variability of response.	• Magnetic fields interact with membrane ion currents, modulating osmotic balance and free radical processes.	[29]

		• Shine & Guruprasad: soybean seedlings showed ↑ ROS via cell wall peroxidase, but ↓ SOD & APX in hypocotyls after SMF. • Effects are context-dependent, influenced by field strength, duration, plant species, and developmental stage.	

4. *Effect of magneto-priming in enhancing the secondary metabolism and therapeutic potential in plants*

The static magnetic field exposure to plants has proved to be a promising strategy in improving the plant growth, productivity and biosynthesis of therapeutic secondary metabolites. Secondary metabolites such as phenolics, flavonoids, alkaloids, terpenoids and other bioactive compounds play a pivotal role in the defence mechanism of plants. Apart from this the bioactive compounds synthesised by plants exhibit significant therapeutic potential in curing diseases. The modulation of plant metabolism through magneto priming not only enhance the accumulation of plant metabolites but it also strengthens their potential towards disease prevention and therapeutics.

4.1. *Antioxidants and Phenolic Compounds*

The mechanism of action of magnetic fields acts as abiotic stress elicitors which influence the enzymatic activity and gene expression concerning the secondary metabolism. Many studies have shown that magneto priming can increase the stimulating activities of phenolics, flavonoids, anthocyanins and carotenoid compounds known for their antioxidant and therapeutic properties. In *Momordica charantia* (bitter gourd), exposure of seeds to a 50 mT magnetic field for 5 s enhanced germination, growth, and leaf chlorophyll content while significantly elevating total soluble phenolics, carotenoids, and flavonoids. High-performance liquid chromatography revealed increased levels of cinnamic, coumaric, syringic, and quercetin derivatives, which directly correlated with enhanced antimicrobial activity against *Staphylococcus aureus* and *Pseudomonas aeruginosa* without affecting the fruit's nutritive value [2]. Similarly, *A. eburnea* (wild almonds) exposed to a 10 mT static magnetic field for several days exhibited elevated phenolic and anthocyanin levels, along with enhanced activities of antioxidant enzymes such as ascorbate peroxidase (APX), guaiacol peroxidase (GPX), and catalase (CAT). This was accompanied by increased proline content and decreased lipid peroxidation, suggesting that magneto priming reinforces cellular antioxidant defence systems and protects membranes against oxidative stress.[18] Recent evidence from *Brassica oleracea* (broccoli), *Glycine max* (soybean), further supports the role of magneto priming in stress mitigation and metabolic enhancement. The treatment effectively counteracted salt-induced inhibition by improving physiological vigour and possibly maintaining osmotic balance, suggesting that magneto priming can sustain secondary metabolite production even under salinity stress and enhance total phenolics and flavonoids, antioxidant enzyme activities, and photosynthetic efficiency [8], [29], [30]

The cumulative enhancement of phenolic and flavonoid content by magneto priming translates into notable therapeutic implications. Increased antioxidant capacity contributes to the mitigation of oxidative stress-related human diseases such as diabetes, cardiovascular disorders, and neurodegenerative conditions. Moreover, elevated antimicrobial properties in magneto primed treated plants like *M. charantia* demonstrate potential for natural antibiotic development.[2] The use of magneto priming in species like broccoli and almond also highlights its role in improving stress resilience and ensuring consistent production of health-promoting phytochemicals even under sub-optimal environmental conditions.[8], [31]

4.2 Flavonoids and Other Secondary Metabolites

Flavonoids represent a large group of secondary metabolites widely distributed in plants and known for their diverse pharmacological properties, including antioxidant, anti-inflammatory, antiviral, and cardioprotective activities. These compounds also contribute to plant defence mechanisms by protecting tissues from oxidative damage and environmental stress.

Magneto-priming has been shown to stimulate the production of flavonoids and other secondary metabolites by modulating metabolic pathways associated with plant stress responses. Studies have reported significant increases in total flavonoids, phenolic acids, and other bioactive compounds following magnetic field treatment. For instance, exposure to static magnetic fields has been shown to increase flavonoid accumulation by up to threefold in certain plant tissues, indicating strong activation of secondary metabolism. [32]

The enhanced synthesis of flavonoids and related compounds under magnetic stimulation is believed to occur through activation of enzymes involved in the phenylpropanoid pathway, including phenylalanine ammonia-lyase (PAL), chalcone synthase (CHS), and chalcone isomerase (CHI). These enzymes play critical roles in the biosynthesis of flavonoids and other phenolic derivatives. Magnetic field exposure has been shown to upregulate the expression of these genes, thereby promoting the accumulation of secondary metabolites. [33]

Apart from flavonoids, magneto-priming may also increase the concentration of other secondary metabolites such as tannins, alkaloids, and phenolic acids, which contribute to the medicinal properties of plants. Enhanced production of these compounds may be associated with magnetic field-induced signalling mechanisms that regulate metabolic flux toward secondary metabolite biosynthesis. As a result, magneto-primed plants often exhibit improved phytochemical profiles and increased resistance to biotic and abiotic stresses.

4.3 Health-Relevant Phytochemicals

Magneto-priming has also attracted considerable attention for its potential to enhance the accumulation of nutritionally and pharmacologically important phytochemicals in crop plants. These compounds, often referred to as nutraceuticals, possess significant health-promoting properties and play an important role in disease prevention.

One of the most studied examples is isoflavones in soybean, which are well-known phytoestrogens associated with anti-diabetic, cardioprotective, and anticancer activities. Magnetic field treatments have been reported to improve the physiological performance of soybean seeds and may influence the expression of genes related to metabolic and stress-response pathways, potentially affecting the accumulation of health-promoting phytochemicals. [34] Similarly, magneto-priming may enhance the synthesis of glucosinolates in Brassica crops, compounds recognized for their strong anticancer and antioxidant activities. These sulfur-containing phytochemicals contribute to detoxification processes and have been linked to reduced risk of various chronic diseases.[35]

In medicinal and aromatic plants, magnetic field exposure has also been associated with increased production of terpenoids and other bioactive metabolites, which possess antimicrobial, anti-inflammatory, and anticancer properties. For example, magnetic treatment of plant tissues has been shown to induce metabolic shifts that increase the accumulation of pharmacologically important phenolic and flavonoid molecules. [32], [36]

Overall, these findings indicate that magneto-priming can enhance the accumulation of several health-relevant phytochemicals by influencing plant metabolic pathways and stress-response mechanisms. This technology therefore represents a promising eco-friendly approach for improving the nutraceutical quality of crops and medicinal plants.

Further, despite these encouraging results, several challenges remain. Variability in magnetic field intensity, exposure duration, and treatment conditions across studies limits reproducibility and mechanistic interpretation. Most available data are from controlled environments, necessitating validation under field conditions. Moreover, direct biochemical correlation between magneto-primed secondary metabolites and their pharmacodynamic actions, such as DPP-IV inhibition or in vivo antioxidant activity, remains underexplored. Future research should integrate metabolomic and transcriptomic profiling with in vitro and in vivo bioassays to clarify molecular mechanisms and therapeutic relevance.

Magneto-priming acts as a promising physical elicitor capable of reprogramming secondary metabolism and enhancing the biosynthesis of bioactive compounds that exert inhibitory, antioxidant, and antimicrobial effects. Through the upregulation of phenolic and flavonoid pathways, magneto-priming not only improves plant resilience under stress but also elevates the nutraceutical and pharmacological value of crops. Thus, integrating magneto-priming into medicinal and functional plant cultivation offers a sustainable biotechnological strategy for producing high-value therapeutics for oxidative stress and metabolic disorders.

Table 2: Effect of Magneto-Priming on Plant Bioactive Compounds and Their Therapeutic Significance

No.	Plant Species	Bioactive Compound Class	Effect of Magneto-Priming	Therapeutic / Functional Significance	Reference
1.	*Chenopodium quinoa* (Quinoa)	Total phenolics, phenolic acids	Phenolic content increased ~20–26% via activation of phenylpropanoid pathway	Strong antioxidant and anti-inflammatory activity	[33]
2.	*Momordica charantia* (Bitter gourd)	Phenolics, flavonoids, carotenoids, anthocyanins	Magnetic seed treatment enhanced phytochemicals and antimicrobial activity	Anti-diabetic, antimicrobial, antioxidant	[2], [37]
3.	*Calotropis procera*	Phenolics and flavonoids	Static magnetic field increased phenolics (7.5-fold) and flavonoids (3.2-fold)	Antioxidant and anti-inflammatory potential	[32]
4.	*Helianthus annuus* (Sunflower)	Flavonoids, carotenoids	Magnetic seed treatment improved flavonoid and carotenoid accumulation under stress, increased the content of oleic acid	Antioxidant, cardioprotective properties, better nutraceutical properties	[38]
5.	*Solanum lycopersicum* (Tomato)	Carotenoids, chlorophyll pigments	Magnetic treatment increased carotenoid and pigment synthesis	Antioxidant and vitamin A precursor	[39]
6.	*Brassica juncea* (Mustard)	Phenolics and antioxidant enzymes	Magnetic seed exposure enhanced antioxidant capacity	Detoxification and anti-inflammatory benefits	[35]
7.	*Fragaria × ananassa (Strawberry)*	Anthocyanins and phenolics	Magnetic field treatment improved pigment synthesis and mineral uptake	Anti-aging, antioxidant, cardiovascular protection	[40]
8.	*Ocimum basilicum* (Basil)	Essential oils (methyl chavicol)	Magnetic exposure increased essential oil yield and altered secondary metabolism	Antimicrobial, digestive health, anti-inflammatory	[36]

9.	*Allium ascalonicum* (Shallot)	Ascorbate, glutathione, antioxidant enzymes	Magnetic field exposure enhanced antioxidant defense system	Oxidative stress reduction, improved metabolic health	[41]
10.	*Arabidopsis thaliana*	ROS signaling metabolites	Magnetic field stimulated ROS-mediated metabolic pathways	Regulation of cellular oxidative balance	Pooam et al., 2019
11.	*Lycopersicon esculentum* (Cherry tomato)	Antioxidant enzymes and ROS metabolites	Magneto-priming increased SOD, CAT and APX activity	Protection against oxidative stress and improved nutritional quality	[42]
12.	*Daucus carota* (Carrot)	Mineral nutrients (Ca, K, Mg, S, Cu, Fe, Mn, Zn)	Algal extract and static magnetic field influenced germination and increased mineral content in seedlings	Improved nutritional value and micronutrient enrichment	[43]
13.	Phoenix dactylifera (Date palm)	Mineral nutrients (Ca, Mg, K, Na, Fe, Mn, Zn)	Static magnetic field increased mineral uptake with increasing field intensity and exposure time	Improved nutritional quality and micronutrient enrichment	[44]
14.	*Brassica oleracea* var. *italica* (Broccoli)	Glucosinolates, phenolics	Magneto-priming improved germination and seedling growth under saline wastewater stress	Broccoli bioactives show anti-cancer, antioxidant and detoxification properties	[8]
15.	*Spirulina* sp.	Chlorophyll-a, proteins	25 mT magnetic field increased biomass concentration and chlorophyll content and altered protein profile	Antioxidant, immune-boosting, nutraceutical protein source	[45]

5. *Sustainable Agriculture and Environmental Impacts*

The growing demand for sustainable agricultural practices has encouraged the exploration of eco-friendly technologies capable of improving crop productivity while minimizing environmental damage. Among these emerging approaches, magneto-priming has attracted considerable attention as a non-chemical seed treatment technology that can stimulate plant growth and enhance the accumulation of beneficial phytochemicals without the use of synthetic agrochemicals. Magnetic field exposure has been reported to improve germination, physiological performance, and stress tolerance in several crops, suggesting its potential role in sustainable agricultural systems [46]–[48]

5.1. *Reduced Chemical Inputs*

Conventional agricultural systems often depend heavily on fertilizers, pesticides, and chemical growth regulators to increase crop yield and quality. Although these inputs contribute significantly to productivity, their excessive use can lead to environmental pollution, soil degradation, and health risks associated with chemical residues in food products.[49] Magneto-priming offers a promising alternative by stimulating plant physiological and biochemical processes through physical stimulation rather than chemical treatments. Magnetic fields can enhance metabolic activities, enzyme functions, and nutrient uptake efficiency, thereby reducing the reliance on chemical inputs [48]. Since magnetic treatment does not introduce external substances into the environment, it leaves no toxic residues in soil, water, or plant tissues. Consequently, magneto-priming has the potential to support safer food production systems and promote environmentally sustainable agricultural practices.

5.2. *Energy Efficiency*

Another advantage of magneto-priming is its relatively low energy requirement compared with many modern agricultural technologies. Magnetic treatment devices generally require minimal electrical energy and are applied during the seed treatment stage before planting. This feature makes the technology economically viable and suitable for large-scale agricultural implementation.[50] Furthermore, once magnetic treatment equipment is installed, it can be reused for multiple seed batches without the need for additional consumable materials. This reusability significantly reduces operational costs and improves resource efficiency. Compared with chemical seed treatments that require continuous procurement of reagents, magneto-priming represents a cost-effective and environmentally benign alternative.

5.3. *Climate-Smart Agriculture*

Climate change presents significant challenges for global agriculture by increasing the frequency and intensity of environmental stresses such as drought, salinity, and temperature fluctuations. Developing climate-resilient crops is therefore essential for ensuring food security in the future.

Magneto-priming has been reported to improve plant tolerance to several abiotic stresses by enhancing antioxidant defence systems, enzyme activity, and physiological performance [46], [47]. Enhanced production of protective metabolites such as phenolics and flavonoids can strengthen plant defence mechanisms against oxidative damage caused by environmental stress. By improving stress tolerance and crop resilience, magneto-priming may contribute to climate-smart agriculture, a strategy aimed at increasing agricultural productivity while adapting to climate variability and reducing environmental impacts.

6. *Challenges and Limitations*

Despite the promising potential of magneto-priming technology, several challenges must be addressed before its widespread adoption in agriculture and nutraceutical production.

6.1. *Lack of Standardization*

One major limitation in current magneto-priming research is the absence of standardized treatment protocols. Studies often employ different magnetic field strengths, exposure durations, seed conditions, and crop species, which makes it difficult to compare results across experiments. Establishing standardized parameters will be essential for improving reproducibility and optimizing the effectiveness of magnetic treatments.

6.2. *Mechanistic Uncertainty*

Although numerous studies have reported positive physiological responses to magnetic field exposure, the underlying cellular and molecular mechanisms remain incompletely understood. Several hypotheses have been proposed, including effects on ion transport, enzyme activation, and reactive oxygen species signalling. However, further research using advanced molecular techniques such as transcriptomics, proteomics, and metabolomics is needed to fully elucidate the biological mechanisms involved.

6.3. *Field-Scale Validation*

Most studies investigating magneto-priming have been conducted under laboratory or greenhouse conditions. While these experiments provide valuable insights into plant physiological responses, their applicability under large-scale field conditions remains relatively unexplored. Environmental variability, soil properties, and crop management practices may significantly influence the effectiveness of magnetic treatment. Therefore, long-term field trials and large-scale validation studies are required to determine the practical feasibility and economic benefits of magneto-priming in commercial agriculture.

7. *Conclusion*

Magneto-priming has emerged as a transformative and eco-sustainable technique that bridges modern agricultural biotechnology with preventive healthcare. By exposing seeds to controlled static magnetic fields, this technology activates a cascade of physiological and biochemical processes that enhance germination, stress tolerance, and the biosynthesis of secondary metabolites with significant therapeutic potential. An enormous amount of evidence demonstrates that magneto-primed plants exhibit elevated concentrations of phenolics, flavonoids, carotenoids, and other phytochemicals that contribute to enhanced antioxidant capacity and disease-modulating effects. These bioactive enrichments not only strengthen the plant's intrinsic defence mechanisms but also improve their pharmacological efficacy against oxidative stress-related disorders.

The enhanced antioxidant enzyme activities—such as superoxide dismutase (SOD), catalase (CAT), and peroxidase (POD)—observed in magneto-primed species like *Momordica charantia*, *Brassica oleracea*, and *Glycine max* indicate the role of magnetic fields in regulating redox homeostasis and mitigating cellular oxidative damage. Importantly, the elevation of phenolic and flavonoid content under magnetic exposure has been correlated with increased inhibition of dipeptidyl peptidase-IV (DPP-IV), a key therapeutic target in type 2 diabetes mellitus. This link underscores the potential of magneto-priming not only in improving crop nutritional profiles but also in generating plant-based biomolecules with direct pharmacodynamic activity against metabolic disorders.

In conclusion, magneto-priming represents a frontier innovation that unites sustainable crop production with human health benefits. Through the targeted enhancement of plant secondary metabolism, antioxidant activity, and enzyme-modulating potential, this technology provides a powerful, low-cost, and environmentally safe strategy for developing functional foods and therapeutic crops. Continued interdisciplinary research integrating plant physiology, biotechnology, and pharmacology will be essential to translate magneto-priming from experimental success to large-scale agricultural and biomedical applications.

8. Future Prospects

Magneto-priming has shown remarkable potential in enhancing plant growth, secondary metabolism, and therapeutic efficacy, its practical application is still in its infancy. The future of magneto-priming research lies in decoding the molecular mechanisms that govern magnetically induced metabolic reprogramming. Integrating advanced *omics* platforms—such as transcriptomics, proteomics, and metabolomics will be pivotal in elucidating the gene–enzyme–metabolite networks modulated by magnetic fields. Such integrative analyses can identify specific biomarkers and regulatory nodes responsible for the upregulation of phenolics, flavonoids, and DPP-IV inhibitory compounds, providing a mechanistic foundation for targeted interventions.

Furthermore, field-scale validation under diverse agro-climatic conditions is essential to establish reproducibility, dose–response relationships, and long-term stability of enhanced metabolites in post-harvest systems. The development of standardized magnetic exposure devices and optimized treatment protocols tailored for different crop species will accelerate the technology's adoption in sustainable agriculture. Combining magneto-priming with complementary techniques—such as nano-priming, biofertilizer integration, or nutrient fortification—could synergistically boost bioactive synthesis and stress resilience.

9. Conflicts of Interest

The authors declare no conflict of interest

10. Abbreviations

1. International Seed Testing Association: - ISTA
2. Base Excision Repair: - BER
3. Nucleotide Excision Repair; -NER
4. Receptor for Activated Protein Kinase C1: - RACK1
5. superoxide dismutase: - SOD
6. Catalase: - CAT
7. Peroxidase: - POD
8. Reactive Oxygen Species: - ROS
9. Ascorbate Peroxidase: - APX
10. Glutathione Reductase: - GR
11. Dipeptidyl Peptidase-IV:- DPP-IV

11. References

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