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REVIEW ARTICLE

PLANT BIO-MAGNETISM: THEORY AND APPLICATION: A REVIEW

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ABSTRACT

The worldwide climate instability and the growing population are diminishing crop production. Magnetic technologies are found to be efficient therapy tools to increase the plant's tolerance against stresses and diseases, accelerate metabolism, and improve germination and yield. Plant bio-magnetism can play a crucial role in the success or failure of the magnetic remediation technologies. Agricultural plants are affected biologically by the magnetic field, such as germination rate, flowering, and growth, which is called Magneto-tropism. Magneto-tropism is a low-cost and eco-friendly technique to improve the agricultural productivity of essential crop plants. Plants respond to magnetism. The full mechanistic vision is still incomplete, but two assumed physical theories for the magneto-reception mechanism can be considered. The plant bio-magnetism utilization has become a possible choice to minimize the negative impacts of inhibiting factors during growth by activating enzymes, and enhancing the nutrients' and water absorption to stimulate the plant growth and yield. This review presents some early and recent research efforts to postulate definitions, terminology, theories for the mechanism of action, and some applications of the plant response to the magnetic stimulation.

KEYWORDS

Climate Instability, Crops' Production, Magnetic Remediation Technologies, Plants' Tolerance, Plant Bio-Magnetism

1. INTRODUCTION

Some insects and birds can sense accurately a weak magnetic field (MF) due to the presence of fine magnetic particles such as the magnetite within specific body tissues. Tiny marine bacteria are oriented downward at the bottom of the water toward their food supply by the physical spin on their contained magnetic particles. Additionally, some organisms' adaptation to an MF was related to the presence of magnetite entities in their cells (Pessoa et al., 2020). Bacteria called ***Magneto-tactic*** are a miscellaneous category of microorganisms able to orient and migrate along the geo-magnetic field (GMF) lines. Several behavioral tests have revealed a magnetic alignment related to the GMF as a tracking response in different living such as insects, amphibians, fishes, and mammals. Possibly, the environmental MF biologically affects the energy necessary for spinning the biogenic tiny magnetite moieties discovered in various human tissues. Environments deficient in a GMF are expected to generate reactions in living (Maffei, 2014). The Ferritin protein stores the iron (Fe) in the living organisms that also have been isolated from mammals, bacteria, and plants. It is composed of a protein shell that surrounds a Fe-containing core. The inner diameter of the protein shell is about 80Å, which is thus the maximum size of the Fe aggregates, which is possibly packed partially by hydrated ferric oxide phosphate-complexes. Studies of the horse ferritin core have presented a super para-magnetism characteristic for super paramagnetic particles depending on its contained amount of Fe. The Fe-core of the bacterial and mammalian ferritin exhibits dissimilar magnetic behavior (Bauminger and Nowik, 1989).

On another hand, magnetic properties are standard for Co, Fe, and other metals, which are found in some plants such as peas and wheat in different concentrations, possibly due to the magnetic susceptibility (MS) of these plants. Peas showed a higher MS than wheat due to having much more Co and Pb per unit mass. Plant tissues contain traces of Fe as a micronutrient in 10–200 ppm range. Higher susceptible grains contain greater Fe concentration within the varieties of one plant genus. The phyto-ferritin protein stores Fe as a ferric hydroxide similar to ferrihydrite, which was assumed to add to the pedogenic Fe mineral accumulations in soils. In addition, the magnetic techniques are applied in the ecological circumstances affected by transport, deposition, and transformation of magnetic grains of magnetic minerals, mainly Fe-compounds (Table 1). The MS of surface soils in industrial regions exhibits anthropogenic pollution by coal-burning power plants and the steel industry related to heavy metal content in fly ashes as well as pollution due to plant leaves' deposited and/or encapsulated magnetic particles, including lianas, shrubs, and trees (Chen et al., 2022; Jelenska, 2008). The natural fires and burn-up of C3 or C4 plants may increase the soil MS. It may be attributed to higher Fe_2O_3 concentration in the C4 plant than that in the C3 plant (Lu et al., 2000). Fire-induced magnetism of the plant ash perhaps originates as of thermally transformed Fe in the organic and inorganic particles that concentrate in plant mass basis when the matter is burned. They can include weakly magnetic ferric oxide/oxy-hydroxide minerals (e.g., ferrihydrite, goethite, and hematite) and strongly magnetic phases such as magnetite or maghemite. The Fe encapsulated in ferritin and other organic components may convert into ferromagnetic phases through plant burn

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up (Till et al., 2021). Research about the magneto-biological effects that may occur at the physiological level is insufficient.

Table 1: Some examples of types of magnetic materials

Type	Example
Ferromagnetic High susceptibility ~>100	Iron (Fe), Cobalt (Co), Nickel (Ni), Gadolinium (Gd), Dysprosium (Dy), Erbium (Er), Holmium (Ho)
Ferrimagnetic High susceptibility ~>100	Fe_3O_4, $MnFe_2O_4$, Ni Fe_2O_4, $PbFe_{12}O_{19}$
Paramagnetic Susceptibility small positive (10^{-5} – 10^{-3})	Aluminum (Al), Oxygen (O2), Hydrogen (H), Sodium (Na), Platinum (Pt), Air
Anti-ferromagnetic Susceptibility small positive (10^{-5} – 10^{-3})	FeO, MnO, NiO, CoO, MnS, MnF_2
Diamagnetic Susceptibility small positive (10^{-6} – 10^{-5})	Copper (Cu), Phosphorus (P), Magnesium (Mg), Mercury (Hg), Zinc (Zn), Silicon (Si), Bismuth (Bi), Water, Protein

An electromagnetic field (EMF) is a non-quantum field produced by the motion of electrical charges that exert forces on any charged entity in its vicinity. As defined by Maxwell's equations, it consists of two distinct but not separated field components (electric and magnetic) perpendicular to each other. Natural electromagnetic radiation, such as sunlight and atmospheric resonances caused by lightning discharge, differ from a man-made EMF. Anthropogenic EMF is comprehensible, polarisable, and more potent than natural ones. A magnetic sense has been found in many insects, for example, butterflies, beetles, flies, ants and bees, termites, and cockroaches (Thill et al., 2024). Scientists have conducted intensified studies of the bio-magnetism in animals produced due to the heart and brain activities, which produce tiny MF can be measured by sensitive magneto-meters. Since the 1970s, increasing research trials have been started to measure the MF produced by the human body. Normal body tissue is nonmagnetic (MS is small), somewhat due to the weak diamagnetic water as the main component. Paramagnetic ions such as Fe in haemoglobin have a permanent dipole moment that is pretty affect being of a small concentration in the body tissues (Akhalaya et al., 1984). Technologic magneto-meters have been used for ultra-sensitive MF measurements. Magnetic fields from the human brain function ~1 nG, and heart resulting from cardiac action potential are ~1 μG when measured at or near the skin surface (Figure 1) (Im et al., 2017). Developing sensitive magnetometers encouraged the detection of biological magnetic signals to understand the physiological and biological processes with more information about the source of the associated electrical currents. It can help to adapt, image, or restore a human organ or tissue by internal/external MF.

Bio-magnetism is a category of bio-electro-magnetism that is the phenomenon of MF created by living organisms. Magneto-Biology is studying the MF's effects on organisms. Organisms utilize the magnetism in direction-finding, which is known as the magneto-ception. Sometimes, the word bio-magnetism may include magneto-biology for any combination of the words magnetism and biology, such as magneto-astro-biology and cosmology. The electric current induces a MF; similarly, the bio-electric current always induces a bio-MF. Thus, the origin of bio-MF is the same as the origin of bio-electric currents is the bio-electric activity of the tissue. However, the bio-MF arises from the bioelectric fields created by different distributions of the bio-electric source elements. Therefore, the bio-magnetic signals are partially different from the bio-electric signals. A bio-MF can originate from a magnetic constituent or contaminant in the matrix that gives a remanent field, and/or a component at the molecular level possesses a diamagnetic or paramagnetic susceptibility response to an applied field and/or electric current related to the ionic mobility throughout the bio-tissues. Such weak bio-MF could be measured using miscellaneous techniques.

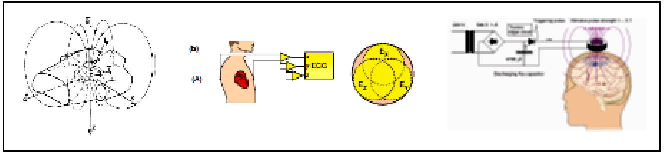

Figure 1 : Simplified drawing of the MF lines of the human heart and brain (Im et al., 2017)

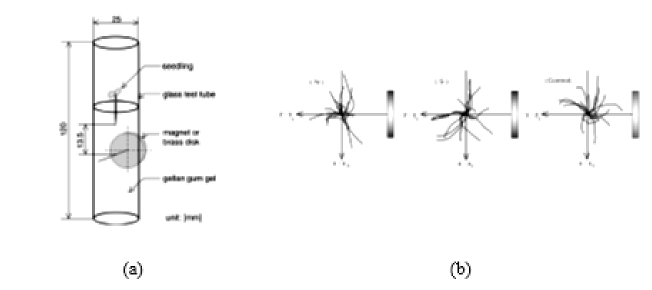

Figure 2 : Radish seedling under the MF effect on the roots' growth directions (a) side view, (b) top view (Yano et al., 2001)

Biologists have asked a question: Since MF is created by the motion of the electrical charges, such as a current of electrons, do the plant's rapid processes during its development involve flowing ions that would create an MF? Biochemical processes, in the form of ionic flows and time-varying ionic distributions, generate electrical currents and time-varying electric fields, producing an MF. In the titan arum, the rapid heating raises the plant temperature as high as 20 to 30 °C. The Titan Arum (Amorphophallus titanium) in the Indonesian tropical forests had been selected for the first experiment on the plant bio-magnetism because it exhibits fast bio-chemical processes and thermo-genic characteristics while blooming with the largest known un-branched inflorescence in the world. Some researchers have tested their magneto-meters using the garden's famous titan arum. The MF from these processes projected along the Earth's MF and measured at the plant's surface was <<~ 0.6 μG. Greater MF detection sensitivity in a more isolated environment was necessary (Corsini et al., 2011). Physicists have continued studying the plant bio-magnetism using more sensitive magnetic detectors and found that the plants may generate no MF greater than a millionth the strength of the MF surrounding us here on Earth. Extremely sensitive MF detecting devices, almost atomic magnetometers based on nonlinear magneto-optical rotation, have been developed to measure near a 10 femto-tesla MF lower than the Earth's MF at the surface (≈ 20 - 50 μT depending on the location).

2. Plant Bio-Magnetism

Plants can sense various perturbations and produce various responses known as *tropism* in plants. Plants can sense mechanical, electrical, and electromagnetic stimuli, gravity, temperature, direction of light, insect attack, chemicals and pollutants, pathogens, water balance, etc. Plants of ideal adaptive structures with brilliant sensing abilities based on different types of tropism, such as *chemo-tropism*, *geo-tropism*, *helio-tropism*, *hydro-tropism*, *magneto-tropism*, *photo-tropism*, *thermo-tropism*, *electro-tropism*, *thigmo-tropism*, and *host-tropism*. Plants generate various types of intracellular and intercellular electrical signals responding to such environmental variations. This field has both theoretical and practical significance because these phyto-sensors and phyto-actuators use recent principles of stimulus-response and signals transductions, playing vital roles in plant life (Shabrangy et al., 2021).

For example, the tendrils are thread-like organs that support the hiking plant stems and circumnutate in interstellar. The vertical component of the circumnutation mean velocity vector of cucumber 'Poinset' tendrils' were changed by exposure to weak static MF (1 - 16 mT) with a significant increase of the speediness modulus near the magnet without a certain tendency of its direction. The cucumber tendrils that bear static positive charges have not exhibited the charged body behavior in the MF or magneto-tropic responses. Indeed, tendrils displayed a nastic response to magnetism. The MF may affect specific primary procedures controlling the moving circulation. The cucumber tendrils of specific size and shape were sensitive to weak static MF strength due to particular natural susceptibility to magnetism. This conclusion is because the effect of MF was evident in rainfall at most and field strengths around 16 mT, which is below the values reported to affect plant bodies growing (50 mT to 14 T). It was not sure whether the sensitivity of cucumber tendrils to magnetism was due to some intrinsically significant physiological susceptibility or to their thread-like shape, which would have facilitated the complete penetration of a MF (Ginzo and Décima, 1995).

Magneto-tropism is the plant growth or movement in response to the stimulus produced by the MF in plants. Initial experiments have shown a broad range of effects due to the MF, but the complete physiological mechanism has not yet been elucidated. Agricultural plants are affected biologically (photosynthesis, biomass accumulation activation of crypto-chrome, and shoot growth) under the effect of MFvaried levels as a normal earth environmental feature (Figure 2). Magneto-tropism was studied as an approach to improve agriculture success using the *Arabidopsis thaliana* as a plant model. Under the near null MF, *Arabidopsis thaliana* was found to delay the flowering time by altering the transcription level of three crypto-chrome-related flori-gen genes. The plant also has induced longer hypocotyl length under white light in the near null MF compared to standard GMF and either dark or white light environments. Additionally,the biomass accumulation decreases while the plant switches from vegetative to reproductive growing. The near-null MF under blue light perhaps has caused down regulation of flowering crypto-chrome related genes supposed to be magneto-sensors. In the photo-activation process, blue light hits crypto-chrome and accepts a photon to Flavin, while tryptophan receives a photon by another tryptophan donor simultaneously. Due to the GMF, this combination would rotate from South-pole to North-pole of the earth and convert the two single photons back to their inactive stable states under an aerobic environment. The interactions between signals and magneto-receptor molecules have not been entirely understood. Two mechanisms suggested for perceiving the GMF: crypto-chrome and magnetite, both found in vertebrates and insects. Also, some fish and insects (e.g., the electric eel and the hornet) have specialized organs or cells for sensing electric fields (Thill et al., 2024).

Germination of roots is possible in different directions, perhaps related to the genotype and ecological circumstances, and several root systems have stated magneto-tropism shown by their orientation along the Earth's magnetic vector. More intensive initial growth processes characterizes these seeds. The magnification of the initial growth processes in seeds due to highly forced MF may be caused by inadequate impulse in the earth's magnetism. Non-specific physiological effects in seeds are sometimes because they have no protective mechanism against these abnormal effects in addition to the seasonal variations of reactions of the germinating seeds (Es'kov and Rodionov, 2010). The very low EM may cause morphological changes due to genomic changes with several meiotic abnormalities, including a significant decrease in the genetic recombination and ring bivalent and quadrivalent formation in germinated plant seeds. Cytological irregularities were observed, that are chromosome stickiness, laggards, and micronuclei formation, which differed significantly among the genotypes (Shabrangi et al., 2010).

Most roots of winter wheat and spring wheat varieties have orientated themselves in a plane approximately parallel to the horizontal component of the GMF when grown in stationary pots. They oriented themselves in a plane approximately parallel to the forces' lines of applied MF, which intersected the horizontal component of the GMF at right angles. Critical levels of magnetic intensity may be required for the tropism to occur depending on the type of plant species and varieties. It had been reported early that in Manitoba, the sugar beet roots' orientation was in an east-west direction as well as the lateral roots of some winter wheat varieties showed a tendency to orientate them in a North-South direction with a magneto-tropic or geo-magneto-tropic response. Additionally, it has been observed that the speed of germination and/or growth of several cereals may be dependent on the seeds' orientation relative to the MF force lines. The primary lateral roots of winter wheat frequently grow in a spiral pattern if the plants are turned clockwise horizontally at 90° every day. This behaviour suggests the existence of a 'North-seeking factor' in one primary lateral root tip and a 'South-seeking factor' in the opposite one (Pittman, 1964).

3. The Geomagnetic Field (GMF) And Gravi-Tropism

The earth is a vast magnet and its GMF is a natural component of the environment that strongly influences on the crops productivity. The electromagnetic radiations from the sun stimulate the growth and development of plants through the photosynthesis process. A modification in the electrostatic balance of the plant system at the cell membrane level increases plant growth. The GMF can affect essential biological functions such as rhythm, orientation, and development. There are significant local differences in the earth's GMF strength and direction. At the earth's surface, the vertical component is maximal at the magnetic pole, ~ 67μT, and is zero at the magnetic equator. The horizontal component is maximal at the magnetic equator, ~ 33μT, and is zero at the magnetic poles. The earth surface ranges between < 30 μT in a region that includes most of South America and South Africa to nearly ~70 μT around the magnetic poles in northern Canada and south of Australia (Maffei, 2014).

Employing MF higher than GMF was studied to improve the seed germination, growth, and harvest of agriculturally essential crop plants, being a low-cost and eco-friendly technique. Proteins involved in primary metabolic pathways were increased in contrast to a significant decrease in proteins with a metal ion binding role, Fe-containing proteins, and proteins included in electron transfer chains in the treated plant tissue. The carbohydrates metabolism, oxidation-reduction, and cell redox homeostasis are up-regulated protein's biological procedures, whereas transformation and protein re-folding are down-regulated procedures. Shoots-specific proteins may be responsible for their stronger response to MF than roots' tissues. The MF changes the regulation of proteins of metal ions binding role during the barley seedling stage with increasing of proteins included in the primary metabolic pathways. The MF may modify the cytoskeleton re-modeling and influence proteins in cell homeostasis, oxidation/reduction, and catalytic activities. This hypotheses provides a vision for proteins responding to MF through the early growth stages and progress (Figure 3) (Shabrangy et al., 2021).

A magneto-tropic response could be observed in the different root-growth patterns for plants grown surrounded by and without a hosted MF. The tropism was first observed in the field, where geo-magnetism is least interfering with or altered in nature by electric power lines, buildings, fence lines, water or gas pipes, or road traffic. The magnetic force lines of the earth, which are orientated in a North-South direction, may be a factor that stimulates the roots of winter wheat to grow in a North-South direction (Pittman, 1962). Primary roots of radish (Raphanus sativus L.) seedlings were exposed to an inhomogeneous static MF generated by a permanent magnet during continuous rotation on a 0.06 rpm clinostat, thus reducing the unilateral effect of gravity. The roots responded tropically to the static MF, with the tropism appearing negative (Figure 2). These roots responded significantly to the south pole of the magnet. A small but insignificant response of the roots to the North Pole has also been observed. Studies have reported that wheat, barley, oats, and rye seeds germinated and matured earlier during 48 h after oriented parallel to the MF than after perpendicularly orientated to the field. The primary roots of radish seedlings curved away from stronger MF when placed under conditions of lateral gravity stimulation. The root curvature was found to be significantly enhanced when roots were exposed to a gradient MF in the vicinity of the South Pole of the magnet (Yano et al., 2001). It was found that the GMF strengthening or weakening can hinder the water absorption and preliminary growth stages. The MS and magneto-tropism in plants were established as a motivational effect of MF on the orientation of roots and progress of plants and the association between the seeds MS and their content of heavy metals. Both pulsing and continuous MFs influence the seeds' germination of the same species. A high-intensity MF changes the water absorption degree and the primitive roots' orientation. The strength of early growth progressions depends on the plant seeds' MS, and the yield depends on the sown seeds' orientation toward the MF vector.

3.1 *Gravi-tropism*

Gravi-tropism is a tendency of plant organs to grow or move towards a specific direction as a consequence of the gravity forces of the earth. Plants are immersed in the GMF so they respond to magnetism as they respond to gravity and sense different light wavelengths or electrical signs. The effect of the GMF on plant evolution is not understood enough, like *photo-tropism* and *gravi-tropism*. The plant can recognize and react rapidly by variable MF via shifting the IR gene expression and phenotypes according to the nature of the magneto-receptor (Maffei, 2014). Indeed, the influential gravity forces dictate many further ecological motivations and reinforce the plant's growth and progress. Crucial roots grow downward seeking water and mineral ions, while shoots grow upward enabling effective photosynthesis. Tropic movements were recorded in plants, such as coiling of tendrils, thermo nastic phenomenon, photo nastic responses, geo-tropism, and day-night activities of plant petals and leaves. The gravi-tropism can be studied by studying Ca^{2+} redistributionsin whole plants.

The *positive* and *negativegravi-tropism* are two different growth configurations: towards and away from the earth's gravity center. Two hypotheses were suggested to explain the gravi-tropism mechanism: the Cholodney–Went and the starch-statolith hypothesis. The Cholodny-Went hypothesis suggests that the gravitropic curvature is due to the lateral auxin transport across the gravistimulated plant organs, resulting in asymmetric growth. According to the starch-statolith theory, the root gravitational sensitivity takes place in the root cap owing to the sedimentation of starch-filled amyloplasts inside the cells in the columella (the central section of the root cap) (Volkov, 2012).

Roots tropism is a vital plant response to adjust their growth direction, which is the gravitational vector on earth as a primary determining factor performing through gravi-tropism and superseding many other tropistic responses to ecological stimuli. A careful use of the term tropism shall be recommended to avoid confusion with the changed root growth direction due to asymmetrical root damage, for example can happen in noticeable chemo-tropism, electro-tropism, and magneto-tropism. Microgravity impacts the cytokinin levels in addition to the essential processes. For example, cell cycle regulation, ribosome biogenesis, and epigenetics. The Cholodny-Went concept may not apply to all roots tropism responses to miscellaneous ecological stimuli, and a prospective study is needed (Muthert et al., 2020).

3.2 *Theories*

Plants respond to the GMF (strong continuous field - alternating field). The GMF is static, homogeneous, and weak (35 µT near equator, 70 µT near the earth's magnetic poles). A full mechanistic vision is still incomplete, but two assumed physical theories for the magneto-reception mechanism can be considered.i) The "radical-pair mechanism" defines the variation of single–triple inter-conversion rates of the radical pair via weak MF. ii) The "ion cyclotron resonance" mechanism states the ions' circulation in a plane perpendicular to an external MF with their *Lamor* frequencies that may interfere with an alternating EMF. The ferrimagnetic minerals magnetite (Fe_3O_4) and greigite (Fe_3S_4) act as magneto-receptors for bacterial magneto-taxis. Magnetite crystalline particles called magnetosomes arrange in chains alongside the bacterium motility axis and generate a permanent magnetic dipole moment that aligns the cells parallel to GMF lines. Every cell holds thousands of magnetosomes analogous to those found in magneto-tactic bacteria. Magnetite particles, which are abundant in the animal kingdom, were supposed to be absent in higher plants. "Botanical magnetite" was detected in disturbed grass cells. Research has shown that phyto-ferritin occurs in plant cells as crystalline magnetite (Fe_3O_4) and hematite (α-Fe_2O_3). Magnetite, probably derived from phyto-ferritin, was also detected in wood ash. Some photosynthetic phytoflagellates can take up inorganic Fe colloids, including magnetite, via phagotrophy. Ferrimagnetic crystals interact more strongly with MF than diamagnetic or paramagnetic particles. When a ferri-magnetic nano-crystal is set to an ion passage, it may generate a spin in a weak GMF that alters the ions' movement across a membrane. Trace amounts of magnetite may be abundant and absorb sufficient energy to supercede thermal background noise (Galland and Pazur, 2005). The ion-cyclotron-resonance and the radical-pair models may explain the MF effect on plants, fungi, and microbes.

Based on the radical pair model, Crypto-chrome, a molecule from the blue light receptor family, regulates the circadian pulse in insects. It is magneto-sensitive and is found in the eyes and brains of most insects and vertebrates and activated by high-energy light, where it acts as a molecular clock. Crypto-chrome would be the magneto-sensor in the light-dependent magneto-reception since crypto-chrome has evolved a significant role in plant behavior, including blue-light reception and regulation, circadian rhythm, and photolyase. In the photo-activation process, blue light hits crypto-chrome and accepts a photon to Flavin, while tryptophan receives a photon by another tryptophan donor simultaneously.

Theories regarding the biological effects of MF state that the movement of the electric charge of an electron, ion, or polarized particle creates an MF around it. The organic matrix constituting living organisms has a polar structure due to various polarized chemical bonds, which may be linked to water molecules, and dissociated mineral salts confer magnetic properties. The ferritin in a plant cell can accumulated more than four thousands of Fe atoms to participate in growth and metabolism. Their spin magnetic moments generate an external MF and together produce oscillations that make energy and re-locate the atoms in the MF direction. Consequently, the plant temperature rises depending on the duration and the frequency of MF treatment. An MF modifies the crypto-chrome and phytochrome mediated plant responses in plants influences the standard affinity of Fe and Co atoms and consumes their energy to continually translocate the microelements in root meristems, resulting in enhanced plant growth (Radhakrishnan, 2019b).

It has been pointed out that a non-uniform MF can displace sensory organelles (statoliths) inside receptor cells, causing a physiological reaction of the plant-tropic curvature. Seedlings stimulated by the MF were oriented with curving in the field, steadily responding to the shift of statoliths alongside the field gradient by pondero-motive magnetic forces. Gravity receptors in plants perceive magnetic forces may act on statoliths via stimulation that exceeds the limit of plant gravity perception sensitivity, causing a plant physiological response (shoots and roots) to appear in a tropistic curving. The higher plants' starch particles (amyloplasts) are capable of the statolith's role. The dense statoliths' transposition in the earth's gravity field decides the upward and downward growth of stems and roots, respectively. Cytoplasm and statoliths differ in density and MS. So, the negative impacts of low micro-gravity on plant growth are possibly mitigated by substituting the gravity with a force of a different physical nature via a gravity stimulation technique for plants using non-uniform MF (Nechitaiio et al., 2001). Twomain theories of gravi-perception were stated. Enormously fast and extensive variations occur in the hormones' concentrations necessary in the saw growth rate response. A second traditional statolith theory postulates that cell particles differing in density from that of the surrounding cytoplasm move under gravity to one side of the cell, resulting in a growth induction. Starch particles in specific cells of some receptor organs may migrate to a lower side of the cell causing quick changes in hormones' distribution. The plant organs' response to the horizontal application of electrostatic gradients has been regarded as firm support for the geo-electric theory (Audus, 1960).

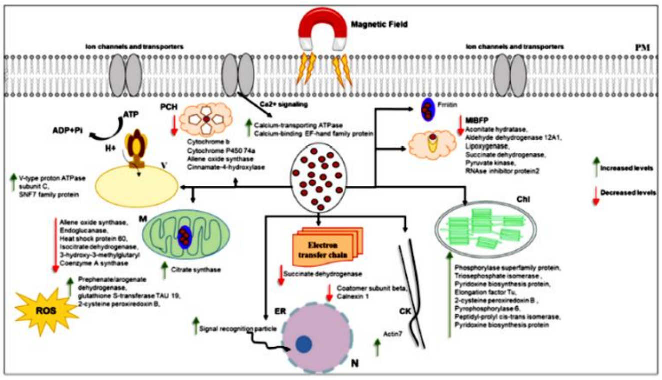

Figure 3 : Hypothetic representation for the MF impacts on organelles by changing proteins, electron transport chains, photosynthesis and metabolism of the cell. The ferromagnetic Fe element directly affects the ferritin and molecules holding heme in their structure. N: nucleus, ER: endoplasmic reticulum, M: mitochondria, MIBF: metal ion binding function proteins, PCH: protein contains Heme, PM: plasma membrane, Chl: Chloroplast, ROS: reactive oxygen species, V: vacuole, CW: cell wall, CK: cytoskeleton (Shabrangy et al., 2021).

Theories also suggest that an MF may directly penetrate every cell aiming the magnetic moments present in a biological or plant system, including the electron spin of a free radical, nuclear magnetic moment, orbital magnetic moment, the magnetic moment of *ortho*-water molecules, and Ca^{2+}, Mg^{2+}, K^{+}, etc. ions. These targets become "antennas" inside the sprout system and plant cells. They respond to the influence of the EMF via simple and complex biophysical and biochemical reactions and end by complex adaptive biological phenomena. The strength of the MF makes its effect on the plant either energetic, wave, thermal, or informational. The energy effects alter the rates of reactions and processes mechanism of the plant development. The main factors that affect the EMF influence on plants may include the nature of EMF and the nature of plant internal cell structure. The energy sources commonly used for agricultural plants to obtain high results from the magneto effect are static MF, alternating MF, combined static and alternating, and low- and high-frequency MF. The MF action mechanisms and magneto biological effects are divided into effects from weak (≤100 mT) and strong fields (≥1 T) strength. Large MF amplitudes lead to more significant phase shifts in frequency that do not match the level of the natural frequencies of target ions and molecules and, therefore, do not induce the system quality. Magneto effects are based on the MF stimulus on the elementary chemical processes, including the paramagnetic particles. The biological result of such effects can be categorized into three mechanisms depending on the treatment systems used: 1) Effect on the biochemical reactions that determine the life processes of a plant at the cell level and its growth and development; 2) Enhancing effect on the plant tolerance by increasing fungal and bacterial disease resistance; 3) Modifications in the mineral composition, including the concentration of vitamins, starch, and saccharide components of grain, etc., which affects the nutritional quality of crops and on their storing safety. The low-frequency EMF can induce the vital activity of microorganisms with bactericidal influence suitable for the bactericidal treatment of plant seeds. It may be suggested that the MF affects the oscillation motion of protein structures inside the cell, which promotes the ions' transportation in plant cells and induces complex biochemical processes that activate the cell epigenetic mechanisms. Certain types of chemical and physical bonds are induced. Thus, the EMF affects the macro and micro levels of plant evolution depending on the variety of the plant and its genome. The macro-effects include visible changes, like acceleration or deceleration of growth of plant biomass, morpho-physiological plant parameters, and damage of bacteria on the seed surface. Some studied examples include tomato, wheat, sugar beet, and cucumber (Shibryaeva et al., 2024).

4. Applications

The morphogenetic control through the plant bio-magnetism utilization has become a possible choice to minimize the negative impacts of inhibiting factors during growth and development (Levin, 2003). Among numerous energy sources, such as milli- and micro-wave radiation, UV light, IR radiation, γ-rays, and pulsed electron beams, the EMF was studied to treat seeds to improve the yield of grain, vegetable, feed, and other crops with a simultaneous destructive effect on the harmful phyto-pathogens. The physical pre-sowing activation by magnetization is environment-friendly, secure, and economical compared to chemical approaches. Magneto-biological influences depend on the EMF frequencies, the plant's nature, category, and status, and its reaction capacity for the EMF stimulating energy. Figure 4 and Table 2 present different studies about plant bio-magnetism and some examples of studied plants, respectively. The EMF may activate enzymes, absorption of nutrients and water to stimulate the plant growth and yield. The lateral gravity stimulates the primary roots of radish seedlings to curve away from stronger MF. The root curvature was found to be significantly enhanced when roots were exposed to a gradient MF in the vicinity of the south pole of the magnet (Yano et al., 2001).

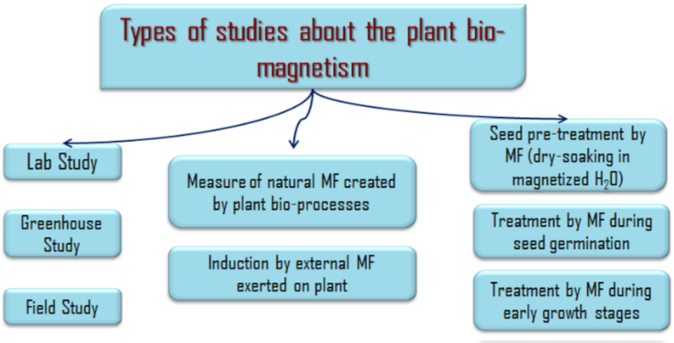

Figure 4 : A chart summarizes some research studies about the plant bio-magnetism

Table 2 : Some examples of different types of studies carried out to reflect the plant bio-magnetism

Type of study	Type of plant	MF intensity	Reference
Field and greenhouse experiments for monitoring of the roots' magneto-tropic or "geo-magneto-tropic orientation	Winter wheat (*Triticum vulgare* Vill.)	Visual estimation of the root growth direction	(Pittman, 1962)
Greenhouse study: Root growth	Winter and spring wheat (*Triticum aestivum* L.)	Geomagnetic and introduced magnetic stimuli	(Pittman, 1964)
Lab then Field experiments after pre-seeding magnetic treatment	Barley seeds (*Hordeum vulgare* L.), wheat seeds (*Triticum aestivum* L.), Otas (*Avena sativa* L.)	50, 650, and 130 gauss	(Pittman, 1977)
Laboratory treatment and germination	Spring wheat, soybean, maize, sugar beet	16 Hz, 50 Hz homogenous MF, using a magnetic flux density of 5 mT and treatment time of 2 h	(Rochalska and Orzeszko-Rywka, 2005)
Germination incubator	Sunflower seeds (*Helianthusannuus*)	MF 0 – 250 mT in steps of 50 mT for 1-4 h in steps of 1 h.	(Vashisth and Nagaraja, 2010)
Petri dishes were placed in a seed germination chamber	Canola *(Brassica napus)* seeds	MF: for dry pre-treated seeds 10 mT for 4 h - wet pre-treated seeds 10 mT for 2 h	(Shabrangi et al., 2010)
Greenhouse experiment	Titan arum (*Amorphophallus titanum*) Fig. 5	Geometrics G858 magnetometer sensors to measure the MF created by the plant processes, which was found to be projected along the Earth's MF, and measured at the surface of the plant is < ~ 0.6 μG	(Corsini et al., 2011)
Lab study using growth chamber: Pre-sowing magnetic treatments	French marigold seeds	25, 50, 75, 100 and 125 mT for 3 min	(Afzal et al., 2012)
Experimental stimulation by high-gradient magnetic fields	The movement of corn, wheat, and potato starch grains in suspension	A magnetic gradient was generated by inserting a wedge into a uniform, external MF that caused repulsion of starch grains.	(Hasenstein et al., 2013)
Laboratory pre-sowing magnetic treatments of seeds then growing plants under field conditions	Onion (cv Red Creole)	60 Hz full-wave rectified sinusoidal non-uniform MF induced by an electro-magnet at 160 mT for 15 and 20 min.	(De Souza et al., 2014)
Field study after pre-sowing seed MF stimulation,	Bitter gourd (*Momordica charantia* L.)	25, 50, and 75mT generated by an electro-magnet (rectified sinusoidal non-uniform) for 15, 30 and 45 min each	(Iqbal et al., 2016)
Pots experiment for germination of magneto-primed pretreated seeds	Soybean seeds	MF 1500 nT at 10 Hz for 5 h/day up to 20 days.	(Radhakrishnan, 2019a)

Table 2 (cont) : Some examples of different types of studies carried out to reflect the plant bio-magnetism

Lab study: During the germination process	Coffee seeds (*Coffea arabica* L.).	External MF, 10 mT and 28 mT	(Júnior et al., 2020)
Pre-sowing pulsating magnetic treatments sown in disposable glasses	Wheat (*Triticum spp.*) seeds	MF (5, 10, 15 mT for 5, 10, 15 min)	(Hussain et al., 2020)
Laboratory experiments for magnetic treatment then a greenhouse planting experiment, plant irrigation by different magnetically-treated saline solutions	Tomato seeds (*Solanum lycopersicum* cv. Thuraya)	MF (3.5–136 mT) for treating tomato seeds and saline water solution (NaCl: 0, 5, 10, and 15 dS/m) for 20 min	(Samarah et al., 2021)
Glasshouse growing experiment after pre-sowing magneto-priming	Shoot and Root Proteome of Barley (*Hordeum vulgare* L.)	MF: 7mT for 1, 3, and 6 h	(Shabrangy et al., 2021)
Pot experiment after pre-sowing magneto-priming using artificial magnetism treatments	Pea (*Pisum sativum* L.) seeds	MF: geomagnetism and artificial magnetism Artificial Magnetism included South/North magnets arrangements of roots and shoots	(Naseer et al., 2022)

Figure 5: The Geometrics G858 magnetometer sensors are behind the titan arum (Amorphophallustitanum) plant at the University of California Botanical Garden (23/06/2009) (Corsini et al., 2011)

Accelerated seed germination becomes stimulated under an EMF that increases the seed energy and energy diffusion to bio-molecules, thus stimulating the metabolism and increasing the germination with lower costs, especially under abiotic stresses including drought, salinity, and temperature. Magnetic and electric treatments activate the proteins and antioxidant enzymes. For example, static MF 226 mT for 100 min has increased germination rate and decreased malon-di-aldehyde, hydrogen peroxide (H_2O_2), and superoxide (O_2^-) in *Vigna radiate*. Moreover, seed priming at 200 mT has increased the α-trocopherol and ascorbic acid contents while decreasing H_2O_2 in soybean. The free mobility of ions and radicals was optimized without damage to the soil organic matter with no harmful effects on the seed profile, giving better and uniform crop attitudes (Naseer et al., 2022 ; Pittman, 1965). Magnetic treatments were applied for seed priming or by water magnetization. The MFs of 100, 200, and 300mT at the salinity degrees of 4, 8, and 12 dS m^{-1} were studied. Salinity and MF have improved the peppermint plant biochemical compounds, including menthol, menthone, chlorophyll, and proline, as well as the nutrient uptake of N, P, K, Ca, Mg, Fe, and Zn (Miransari et al., 2022).

Magnetic frequency strength range 0 - 300 mT have been studied for magneto-primed seeds and resulted in improved seedling rates and sprouting biomass or root growth with enhanced tolerance to biotic or abiotic stresses as a consequence of the activated antioxidant response. Amplified antioxidant enzyme actions of superoxide dismutase, catalase, and glutathione reductase were defined in magneto-primed cucumber seeds. A decreased proliferation of superoxide radicals (O_2^-) in magneto-primed soybean seeds was reported (Ahmed and Kumar, 2020). Usually, soybean seeds were characterized by a low germination percentage below 21% due to seed dormancy. A bio-stimulation of soybean (*Glycine max* L.) seeds germination by exposure of seeds to 400 mT static MF applied for 3, 6, and 12 min together with 10% of algal extract has stimulated the germination of the dormant seeds. It has enhanced the metabolism of plants, their growth, and their development. The field acts on the ions of ferromagnetic elements found in the prosthetic groups of electron transport chain enzymes (e.g, some cytochromes) or enzymes included in the H_2O_2decomposition (catalases peroxidases). The whole protein structures and even tissues may be changed. Cell membranes exhibit many properties of liquid crystal structures, which physical phenomena induced by MF can change. The positive effects of MF depend on the plant kind, the exposure period, the intensity, and the nature of the MF applied (Lewandowska et al., 2019). It has been proposed that an auxin-like effect of an MF on germinating seeds. Auxins or synthetic plant growth regulators have been used to stimulate the ripening of immature fruits. Suggested mechanisms related to this phenomenon may be as follows: (1) an auxin-like character of the MF, or perhaps an auxin-activating mechanism speeds the ripening process; (2)activation and/or acceleration of the enzyme systems enhance respiration; (3) radical formation speed up respiration and thus accelerate ripening. The MF effects are similar to the effects of plant growth regulators, and there are magnetic characteristics of the Fe porphyrin compounds (Boe and Salunkhe, 1963).

Seeds of mustard, radish, cucumber, field corn, and pea were germinated in GMF conditions after soaking, and then subjected to non-homogeneous electro-MF (flux gradient between 1500 and 2000 G). No difference was observed between the control and treated seeds (Majumder, 1979). The French marigold (*Tagete spatula* L.) seeds were exposed to five different magnetic treatments for 3 min each, which resulted in an enhanced germination speed and spread, root and shoot length, seed soluble sugars, and α-amylase activity. A 100 mT MF treatment has maximally enhanced the germination, seedling vigor and starch metabolism compared with the control and other seed treatments (Afzal et al., 2012). The germination of coffee seeds (*Coffea Arabica* L.) after being subjected to magneto-priming magnetic pre-treatment at constant MFs (10 mT and 28 mT) for 6 days during the germination process was significantly enhanced. The cellular membranes became more permeable, and the antioxidant system was activated, promoting fast and more uniform seed germination. The EMF perhaps increases the nutrients' absorption from the culture medium, which is related to cell metabolism and the energy production required for cell division to increase seedling size and development (Júnior et al., 2020). It has been found that the seed's physical properties were improved by increasing the Fe fertilization rate from 0 to 2 L ha^{-1}. The moisture content and the resistance to the breakage of wheat seeds have increased (Feizollah Shahbazi et al., 2015).

Another application of magnetism for botanical systems optimization is utilizing the magnetized water as water is passed through an MF before being used. The MF induces the particle surface charge in the fluid solution that influences the solids' crystallization and precipitation process and significantly motivates the minerals translocations in the irrigated soil. The field can react with charged ions, polar molecules, ion pairs, free radicals, crystalline nuclei, and suspensions either by direct reactions with the charged particles or by stimulus of the MF on certain molecular energy levels, resulting in magneto-kinetic adaptations (Noran et al., 1996). Irrigation with magnetized water enhances plant growth, development, and yield, lessens abiotic stresses increased due to the climate changes, such as drought and salts, and saves the irrigation water (Dobránszki, 2023).

5. Conclusion

The plant bio-magnetism is a natural characteristic mainly related to its contained magnetic moieties and can be stimulated by external magnetism sources. A modification in the magneto-electrostatic balance of the plant system at the cell membrane level by an MF possibly increases the plant growth by affecting the essential biological functions. It can improve the productivity of crucial agricultural crops by activating seeds' germination and growth, being a low-cost and eco-friendly technique. Scientists of physics, botany, and agriculture can share research interests regarding plant bio-magnetism to present an optimized approach for a successful application and a full explanation of the mechanism of MF action on plants. Additionally, non-optimized or out-of-control application of the plant bio-magnetism may lead to harmful results and/or health risks for the food and feed crops due to abnormal growth induction.

Appendix : Definition of Magnetic units The metric system (System International SI) units express magnetic quantities as its primary units the meter (m), kilogram (kg), second (s) and ampere (A). The strength of an MF is usually designated by the value of its *magnetic induction* SI unit (tesla T). It is a secondary unit its value is defined in terms of the force between two parallel wires carrying electrical currents (1 Tesla = 1 newton/ampere-meter), where the newton (N) is the secondary unit of force, equals to 1 kilogram-meter/second. *Magnetic induction* appears in the force law governing the motion of a moving charge in either free space or a magnetic material and in the expression for the spin practiced by a magnetic dipole. The magnetic induction is also known as the *magnetic flux density*, and 1 Tesla = 104 gauss (G) in the cgs system. The unit of the Weber (Wb) describes magnetic flux, and 1 Weber = 1 tesla-meter^2.

Consent For Publication

The author declares her consent for publication.

Author Contribution

The manuscript was edited and revised by the author.

Conflicts Of Interest

The author declares no conflict of interest.

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