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Sustainability Spotlight

Renewable energy is essential to the longevity of our agricultural and food industry. This review focuses on the use of magnetic field to mitigate challenges due to thermal and chemical processes within the industry. In terrestrial systems, magnetic field enhances crop germination and growth cycles through energy-efficient methods. In microalgae cultivation, biomass is promoted and produces valuable bioactive compounds, reducing input. Post-harvest magnetic field interventions enhance food preservation, food safety, and improve product quality. Magnetic field interventions complement efforts made to improve agricultural systems and food security.

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Magnetic Field as a Non-Thermal Modulator in Biological Systems: Mechanistic Insights and Emerging Applications in Food and Agriculture

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Abstract

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Thermal processing methods utilize high heat for food and agricultural production. While this may be an effective strategy to mitigate microbial contamination within food preservation and safety, some drawbacks arise, especially surrounding nutrient preservation. This process may denature proteins or destroy heat-sensitive compounds and promote lipid peroxidation. Chemical preservatives or sanitizing agents may leave harmful residues and increase environmental effects. Current non-thermal methods may only decontaminate surface areas or incur high costs. Magnetic field technology has emerged as a promising non-thermal method acting as a metabolic and enzymatic modulator with potential broad applications. These effects have reportedly increased germination potential, growth kinetics, and nutrient transport in terrestrial plants, as well as improved stress resilience, biomass productivity, and bioactive compound production in microalgae. Additionally, magnetic field has displayed promising bactericidal effects. While magnetic field intervention is effective, the type and exposure duration must be assessed along with potential exposure effects, and challenges related to scalability in industrial applications.

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1. Introduction

Agricultural and food production commonly rely on thermal treatments that risk reducing nutritional quality [1]. Thermal processing promotes protein and lipid oxidation, a process that induces reactive oxygen species (ROS) generation [2], leading to cellular damage, decreased nutritional value, and reduced sensory appeal. Although, alternative non-thermal processing methods have been explored, limitations regarding cost-effectiveness remain [3]. As a result, there is increasing interest in non-thermal technologies due to improved nutrient retention, environmental, and potential cost-effective benefits for food and agricultural production. Accordingly, MF-treatment responses must be examined to highlight key mechanisms involved in the growth of plants and microorganisms, food safety, food processing, and abiotic stress mitigation [4].

Notably, decreases in the Earth's Magnetic Field (MF) have been suggested to negatively disrupt terrestrial growth [5], indicating a need for supplemental treatment. Additionally, MF interventions reduce the need for organophosphate pesticides while lowering anti-nutritional factors, thereby increasing nutritional bioavailability [6]. MF influences electrochemical gradient shifts on the lipid bilayer membrane, which has been reported to enhance germination speed through amplified water and nutrient absorption [7]. MF-induced cellular responses are mediated through biomagnetism, defined as the ability of living cells to generate and interact with their own MF, as well as external field interactions [8]. Pulsed MF (PMF), and static MF (SMF) are the two more commonly used industry types. SMF is characterized by continuous exposure with constant polarity and intensity, whereas PMF involves intermittent, non-continuous exposure [5, 9-11]. Both types are the primary focus of this review.

MF type, strength, duration, distance, and orientation must be optimized [5, 9-11] to achieve desired biological outcomes, as illustrated in **Fig. 1**. MF strengths are classified as weak to moderate (1mT to 1T), strong (1T-5T), and ultra-strong (>5T) [12]. Many studies in food and agricultural processing utilize weak to moderate MF intensities to avoid cellular damage associated with higher field strengths. Although underlying mechanisms are not fully understood, ongoing research aims to uncover the metabolic shifts activated by MF at the cellular level. Importantly, MF exposure drives membrane signaling modulation in species-specific, dose dependent methods rather than as a universal system.

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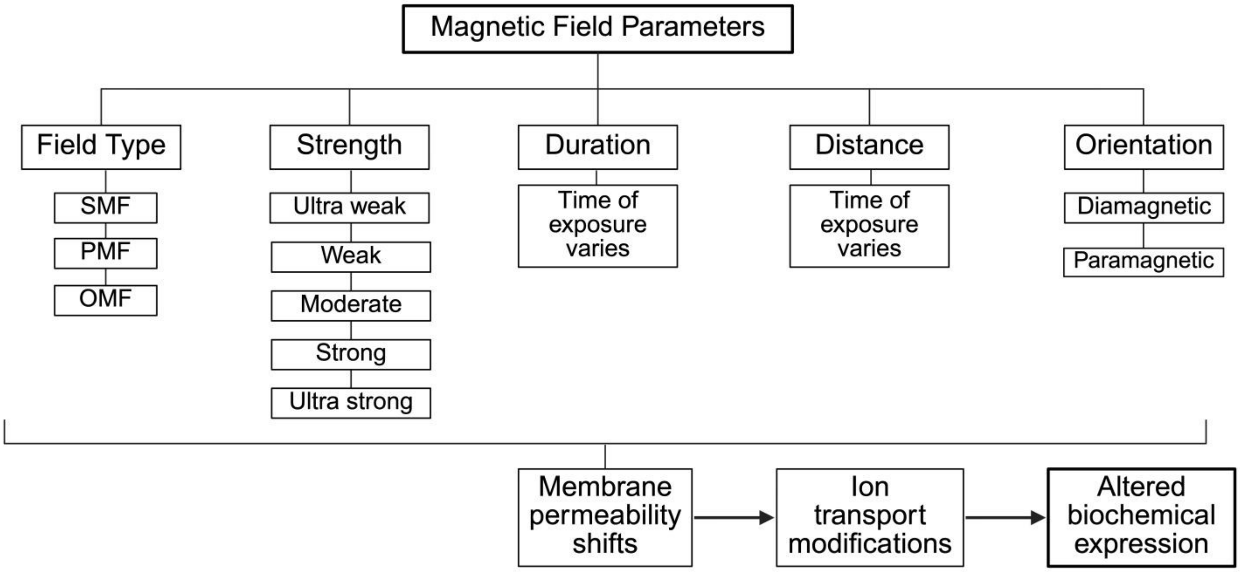

Fig. 1. MF-treatment parameters illustrated in a conceptual workflow, highlighting downstream effects from cellular signaling to biochemical responses.

2. Methodology regarding article selection process

Initial literature searches included the following keywords, either separately or in combination: “magnetic field” OR “static magnetic field (SMF)” OR “pulsed magnetic field (PMF),” combined with “seed germination,” “plant growth,” “microalgae,” “abiotic stress,” “food production,” “sustainable agriculture,” “biomass composition,” “MF and food preservation,” and “MF and bactericidal effects.” Inclusion criteria for selected articles emphasized biological or physiological effects of magnetic fields (MF) on plants or microalgae. Research related to seed germination, growth enhancement, stress tolerance, and biomass and nutrient production were prioritized. Additionally, articles were selected based on clearly defined experimental conditions, including field strength, exposure time, and measurable outcomes relevant to food and agricultural production. The authors prioritized peer-reviewed journal articles and more recent publications to reflect current trends in the field. The primary time frame considered was 2010–2026, with the inclusion of a limited number of earlier foundational studies from the early 2000s. Exclusion criteria included non-English publications, studies lacking primary experimental data, and research focused exclusively on clinical applications not directly relevant to food, agriculture, or microalgal systems. A screening process was conducted by first evaluating titles and abstracts for relevance, followed by full-text review of selected articles. Duplicate records were excluded, and additional relevant studies were identified through citation tracking of key publications. The review scope was then narrowed to the following main application areas: seed germination and

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seedling vigor, microalgae cultivation, abiotic stress alleviation, and food preservation, as these represent the most impactful and well-studied domains in sustainable food production. Articles were retrieved through databases including ScienceDirect (Elsevier), Google Scholar, ACS Publications, and Academic Search Premier (EBSCOhost), as well as additional resources accessible through the University of Connecticut's Online Library Services. This review is intended as a structured narrative review. While it does not follow full systematic review protocols, efforts were made to ensure transparency and reproducibility in the literature selection process.

3. MF Interactions at the Cellular Level

Primary MF interactions at the cellular membrane have reported to induce changes in ion transport, enzyme modulation, and gene expression. Cellular membrane permeability affected by MF [13, 14], influences membrane voltage and polarization through diamagnetic interactions [15, 16], where strong MF gradients may contribute to ion shifts within those voltage-gated channels [15]. Notably, intracellular Ca^{2+} ions are critical in cellular signaling and gene expression [17], where MF potentially modifies homeostasis [16], further influencing downstream biological interactions. It is suggested that the MF interacting with ionic currents at the embryonic cell membrane modulates ionic concentrations and osmotic pressure across the membrane, thereby, increasing membrane permeability. This may enhance metabolic activities associated with seedling germination and growth [18].

Building on these mechanisms, SMF of moderate intensity has been reported to influence both cell morphology and plasma membrane properties across a range of cell types [19]. MF exposure may also alter kinetic energy within the lipid bilayer, thereby stimulating cellular signaling and promoting growth [5]. These effects have been associated with antioxidant system activation, protein oxidation, and altered gene expression. MF-mediated modulation of antioxidant pathways may function through ROS signaling cascade, leading to metabolic modifications [2, 20]. When MF influences proteolytic activity, improvements in seedling germination cycles are observed [11]. Furthermore, dose-dependent MF-treatment exposure alters cellular biochemical interactions, resulting in increased plant length and leaf surface area [10].

In a study investigating SMF combined with hydropriming, enzymatic activity of dehydrogenases, and α-amylases were altered, improving plant productivity compared to unprimed and untreated seedlings [21]. Collectively, these enzymatic and hormonal responses suggest that MF exposure effects extend beyond primary signaling and influence regulatory pathways. Importantly,

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phytohormones, including auxins and cytokinins, directly relate to germination initiation and growth regulation [22].

Beyond terrestrial plants, MF may interact with magnetotactic microorganisms, such as cyanobacteria or microalgae, which orient in response to the Earth's MF **[Fig. 2b]**. MF does not produce uniform distribution throughout the cell, as distance, configuration, exposure duration, and strength influence intracellular field distribution [20, 23]. Collectively, MF may mediate enzymatic, hormonal, and stress response pathways by enhancing cellular resilience and growth kinetics [3].

Peptide bonds, helical structures, and microtubules exhibit anisotropic diamagnetism, defined as direction-dependent opposition to the MF within biological structures. Orientation relative to the external MF stimuli influences diamagnetic response at both the molecular and cellular levels, thereby influencing overall biological behavior [24]. This suggests that direction-dependent responses can influence MF-induced metabolic outcomes in microorganisms.

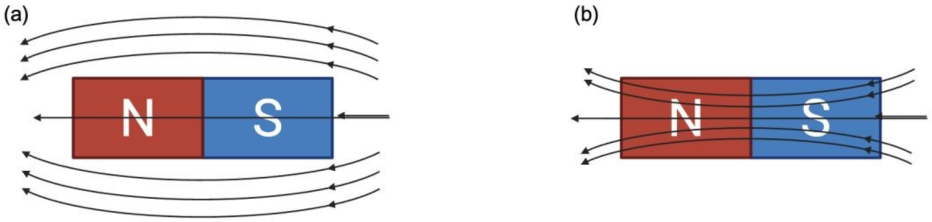

Fig. 2. Representation of (a) oppositional diamagnetic forces and (b) oriented paramagnetic forces

These mechanisms can be conceptually integrated as a framework beginning with MF exposure, followed by membrane-level interactions that trigger cellular signaling responses, and ultimately reporting physiological outcomes characterized by stimulatory, inhibitory, or neutral effects depending on the extent of metabolic engagement, highlighted in **Fig. 3**. The proposed mechanistic framework provides a basis for interpretation of MF-induced physiological outcomes, particularly during seedling pre-treatment and germination cycles.

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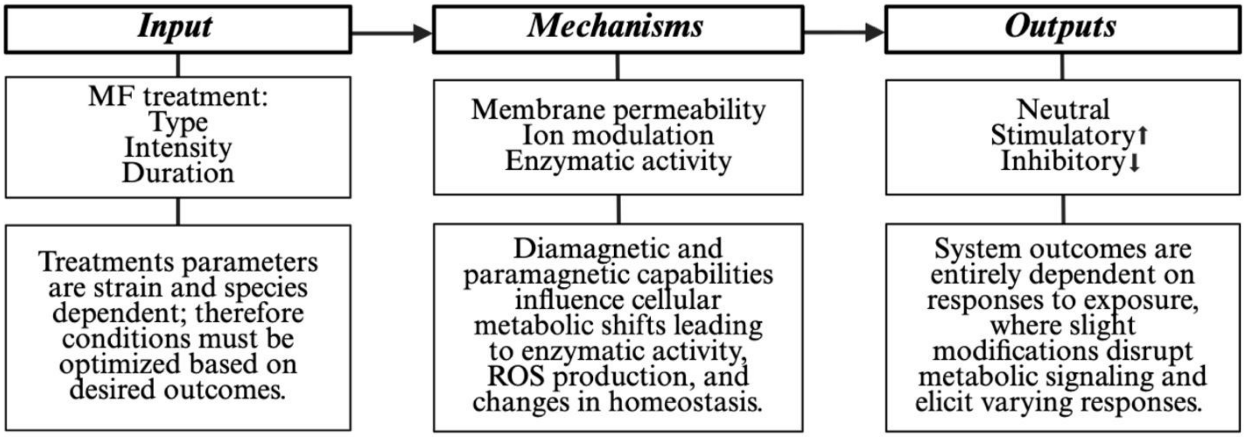

Fig. 3. Indication of the input of MF treatments with resulting mechanisms and reported potential outcomes.

4. MF effects on plant growth and development

4.1 Seedling pre-treatment

MF demonstrates promise as a seedling pre-treatment, improving germination rates, growth kinetics, and dried biomass yield [5]. Beyond growth promotion MF exposure has reported enhanced stress tolerance, reduced pesticide dependency, and applications in microalgae cultivation [25]. Collectively, MF-treatment represents an ecologically and economically viable strategy for improving plant functional properties relevant to food and pharmaceutical applications [26]. Conventional seedling pre-treatments often rely on environmentally hazardous chemicals [22], highlighting MF pre-treatment to enhance enzymatic activation, using non-hazardous properties. Notably, maize seedlings exposed to SMF exhibited 171.41% and 157.15% increased germination rates under 180 mT for 3 min and 120 mT for 6 min, respectively, compared to a 0-treatment control, which had a neutral effect. Additionally, antioxidant activity also increased, thus improving the seedlings nutritional value [5] and broadening its applications. In contrast, PMF-treatments reported greater biomass yield compared to SMF in maize seedlings [9]. Outcome variation can be attributed to mechanistic differences between MF types, with SMF providing continuous exposure and PMF providing intermittent exposure. Differences in ion flux recovery rates may further contribute to species response.

Several studies have been conducted on various seedling type, such as tomato, wheat, maize, barley, chickpea, soybean seeds, and more. These investigations have identified several factors that can significantly impact the effects of plant development under MF-intervention. MF induced responses on germination or growth of different plant species are summarized in **Table 1**. There

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is a consensual opinion that MF influence on germination speed and seedling vigor could be related to the changes in cell growth, cell structure, and gene expression [19, 24, 27] which varies among species. The internal electric field of biological systems can be influenced by the resonating behavior of MF, stimulating the activity of proteins, such as enzymes [28].

Table 1. Summary of representative outcomes, including both stimulatory and inhibitory results reported. **Note:** Please refer to the respective reference for experimental details. Abbrev.: 'h per d' refers to hours per day, and mT refers to millitesla.

Plant Species	**Treatment**		**Effect on germination, growth, and development**	**Reference**
	Type of MF	**Field strength**		
Sunflower seed (*Helianthus annuus*)	SMF	0-250 mT in steps of 50 mT for 1-4 h (hour) in steps of 1 h per day	Increased germination rate, germination speed, seedling length, and dry weight were observed compared to the unexposed control. Germination speed increased at 50 mT (2, 4 h), 100 mT (1 h), 150 mT (3 h), 200 mT (1, 2 h), and 250 mT (2, 3 h). Shoot length decreased at 100 mT (1, 3, 4 h), 150 mT (4 h), and 200 mT (1 h), while increased shoot length was observed at 2 h under 50, 200, and 250 mT (decreasing significance).	[29]
Lettuce seed (*Lactuca sativa* var. *capitata L.*)	SMF	440, 770, and 1000 mT for three exposure times (1, 2, and 3 h)	Increased osmolyte accumulation, secondary metabolites, and ROS scavenging activity; increased shoot length (1 T, 3 h) and root length (0.44 T, 3 h); no significant inhibition observed in growth, antioxidant activity, or chlorophyll content.	[30]
Cherry tomato seed (*Lycopersicon esculentum* L.)	SMF followed by PMF	SMF dose of 100 mT for 30 min followed by PMF dose in the cycles of 2, 3, 5 or 6 min on and off	Improved yield performance was observed, accompanied by increased superoxide anion and hydrogen peroxide levels. Root length was unaffected under SMF, while shoot length increased. Vigor index increased in most SMF and PMF-treatments except PMF (6 min). PMF (6 min) reduced germination percentage and shoot length. Germination percentage increased in all other SMF and PMF-treatments except PMF (6 min), while decreases were observed under SMF at 50 and 150 mT (30 min).	[31]

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Soybean seed (*Glycine max* L.)	SMF	200 mT for 1 h	Enhanced tolerance against UV-B stress during seed germination and early seedling growth of soybean. Inhibitory effects reporter in same conditions in cucumber seedlings.	[32]
Sunflower seed (*Helianthus annuus* L.), garden cress seed (*Lepidium sativum* L.) and garden radish seed (*Raphanus sativus* L.)	PMF	0.1 µT and 100-200 Hz at 30 min	Earlier germination process, but no changes in germination duration from control across all seedling groups. Increased macronutrients content in sprouts, such as calcium, magnesium, phosphorus, and sulfur.	[33]
Soybean seed (*Glycine max* L.) and maize seed (*Zea mays* L.)	SMF	200 mT for 1 h	Enhanced germination percentage and stimulated early seedling growth parameters (root and shoot length, and vigor indices).	[34]
Soybean seed (*Glycine max* L.)	SMF	200 mT for 1 h	Enhanced root nodules, biomass, yield, pigments synthesis, photosynthetic rate, carbon and nitrogen metabolism, leghemoglobin and hemechrome content in root nodules. Stimulatory effects observed in seed weight, rate of photosynthesis, and transpiration rate compared to the control, notably internal CO_2 concentrations and chlorophyll content were inhibited compared to the control.	[35]
Pisum sativum L. (pea)	SMF	30 and 85 mT for 15 sec	Increased amylolytic enzyme activity and phytohormone levels were associated with enhanced seedling growth and dry weight. No significant differences were observed across doses; however, SMF-treatments exhibited greater stimulatory effects compared to the control.	[22]
Zea mays L (maize)	PMF	60, 120, and 180 mT, each applied for 3 min and 6 min	Germination speed increased at 120 and 180 mT (3 min) and at 120 mT (6 min), with no significant change at 60 mT (6 min). Field emergence increased at all strengths and durations (3 and 6 min), except 60 mT (6 min), which showed no significant effect.	[5]
Solanum lycopersicon L. (tomato)	SMF	20-60 mT for 20 min per day for 48 days (+/- MF with and without flooding index)	Improved germination through shorter cycles in all treatments compared to the control. Neutral effects observed in underground roots under 20 mT.	[36]

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Triticum aestivum L. (wheat)	SMF	30 mT, 50 Hz for 30 sec	Neutral effects reported in germination and dry weight. Inhibitory effect on shoot length.	[37]
Cucumis melo L., var Ravi (melon)	SMF	100, 200 mT for 5-20 min	Increase in proteolytic activity, and chlorophyll content. Neutral effect in root length under 100 and 200 mT for 5 min.	[38]
Pisum sativum L. (pea) – aged seedlings	PMF	100 mT for 60 min. total exposure, applied as pulsed intervals: 5 cycles (6 min per pulse), 10 cycles (3 min per pulse), and 15 cycles (2 min per pulse).	Slight increase in germination rate, and significant increase in vigor index in cycles 5 and 15. Inhibitory effects were seen in 10 cycles for germination rate and percentage, as well as seedling vigor.	[11]

As summarized in **Table 1,** MF influences plant physiology and metabolism, eliciting stimulatory, inhibitory, and sometimes neutral responses. This is dependent on the MF type, field strength, exposure duration, and species. SMF and PMF demonstrate variable effects across germination dynamics, seedling growth, biomass yield, stress tolerance, and secondary metabolite production. While many studies report stimulatory effects, studies also highlight the importance of species-specific optimization of MF-treatment parameters due to neutral and even inhibitory effects, indicating desired outcomes are not always present.

These biological differences can be elucidated based on gene expression and phenotype perspective. In a recent study from Anand et al., tomato seeds were exposed to MF at 100 mT for 30 min to examine the changes in hydrogen peroxide synthesis, scavenging capacity, and oxidative signaling pathways contributing to seedling vigor [39]. Based on their results, the use of MF upregulates the relative genes expression involved in the production of hydrogen peroxide, i.e., amine oxidase, superoxide dismutase, and receptor for activated C kinase 1, thereby accelerating the germination speed of tomato seeds. Simultaneously, a higher gene expression of α-amylase and improved enzymatic activity were reported after SMF-treatment at 200 mT for 1 hour per day, leading to stimulated soybean seedlings [32]. While **Table 1** elucidates many benefits for growth kinetics, nutrient transport, and yield, it fails to highlight the limitations in translatability within controlled laboratory settings versus practical applications in the agricultural sector. This must be critically evaluated for logistic and economic purpose. However, this review focuses heavily on the mechanistic benefits of MF for the industry applications.

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4.2 Seed germination and seedling vigor

Vashisth et al. investigated the effects of SMF between 0-250 mT on germination and seedling vigor of sunflower seeds. The effect of MF exposure on germination speed and seedling vigor can be visually illustrated by **Fig. 4 (A)** and **(B)**, respectively [29]. Based on the experimental results of enzymatic activities, α-amylase, dehydrogenase and protease assays, the elevated activities of hydrolyzing enzymes play a significant role in facilitating seed germination, enhancing seedling vigor, and improving root characteristics. In addition to enzymatic activities, charged ions within the cell can respond as endogenous magnets to the external MF-treatment, which leads to accelerated cell metabolism, prompting the cell into its proliferation stage [27], reducing the growth cycle period, indicating enhanced production efficiency.

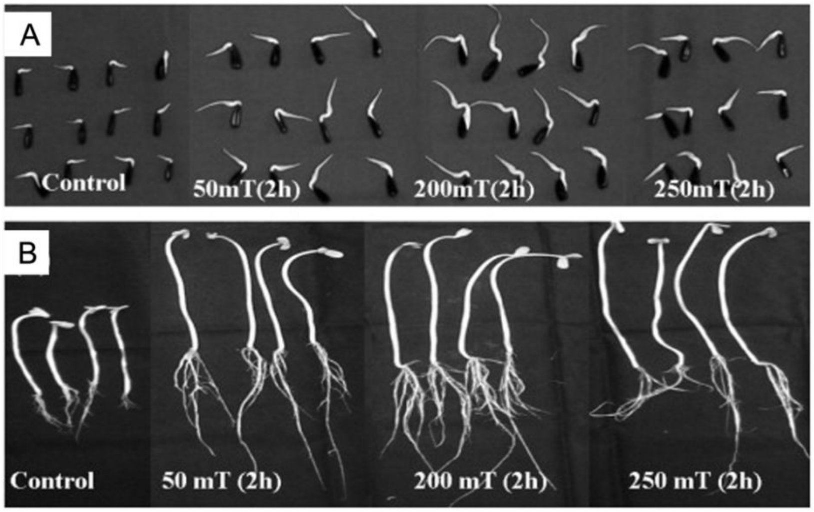

Fig. 4 Effect of MF intervention on (A) speed of germination and (B) seedling vigor of sunflower seeds [29]. This figure is reprinted with copyright permission from Elsevier.

Conversely, seedlings that respond to weak SMF bypass certain photoreceptors required for plant germination, alternatively relying on SMF to support germination, as observed in *Arabidopsis thaliana.* This modulation proves beneficial in low light environments and improving stress resilience [40], potentially increasing its adaptation to climate variability. *Solanum lycopersicon L.* (tomato) has high-water requirements during early growth phases. Ultra-weak or low SMF-treatment improves water conservation and accelerates germination rates in the SMF-treated groups, achieving a 50% increase in germination rate in the 40 mT treatment group. This pre-treatment intervention highlights water conservation and economic benefit [36], through reduced resource needs and faster growth. SMF exposure increased plant hardiness, where several studies observed enhanced seedling development and germination rates under PMF exposure [11], highlighting MF type interactions.

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For example, tomato seeds exposed to SMF improved water transport [36], whereas in *Triticum aestivum* L. (wheat) there was no growth stimulation or nutrient transport response. When the wheat seedlings were subjected to water flooding, no additional resistance was observed compared to the control group [37]. *Cucumis melo L., var Ravi* (melon) exposed to SMF demonstrated enhanced proteolytic activity and subsequently increased germination rates significantly compared to 0-control treatment [38]. PMF successfully revitalized 6-year aged pea seedlings, effectively increasing vigor from 33.66 to 66.22, and germination rates by 6.25%, under 100 mT for 60 min at 6 min in pulsed intervals [11], reinforcing that MF-treatment conditions must be optimized to species-specific requirements **[Table 1]**. Outcome variations based on MF type can be theorized that under PMF there are recovery periods due to intermittent exposure, compared to SMF, which is continuous. While many plant species, including cereals, melon, tomato, maize, and pea benefit from MF-treatment, species-specific pathways are not well understood currently, hypothesizing that enzymatic and antioxidant pathways play a role in signaling mechanisms which result in enhanced germination, stem length, and leaf surface area [38, 41]. Treatment parameters of type, duration, and frequency further complicate the ability to explain these mechanistic responses.

However, it is worth noting that the effects of MF-treatments on seed germination and seedling vigor are controversial since the outcome of which could be stimulatory, inhibitory or neutral, species dependent [19]. Adversely, SMF may trigger accumulation of ROS and oxidative stress, resulting in cellular membrane damage, and possibly cell death [39, 42]. MF-treatment stimulated ROS production, activating antioxidant enzyme systems involved in ROS detoxification [30, 43]. Therefore, the consequences of MF interventions are determined by multiple factors, which remains to be uncovered through molecular, biochemical, and physiological responses. Outside terrestrial plant systems, studies in microalgae have reported notable effects of MF-treatments.

5. MF applications in microalgal cultivation and productivity

5.1 Biological modulation in microalgae under MF

Microalgae are eukaryotic, carbon-capturing microorganisms that are photosynthetically efficient [56] and have garnered much attention due to resource-sparing effects [44]. These microorganisms produce protein-rich biomass, bioactive compounds and valuable lipids [45, 46], as a potential food, nutraceutical, or fuel source. MF-exposure initiates biomass accumulation in certain strains as illustrated in **Table 2**, further highlighting the cost-effective potential of this versatile microorganism, as it reduces production cost per gram.

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MF-influenced microalgal metabolism might result in either stimulated or inhibited biomass production depending on the physiological state, cell types (prokaryotic or eukaryotic), exposure time, intensity, and cultivation. Presumably, MF affects microalgal metabolism through enzyme activation, gene transcription, electron spin orientation, and plasma membrane flux alteration [26, 27, 47]. However, these mechanisms are not yet fully investigated and remain controversial, as the evidence for direct effects on the biosynthetic pathways of carbohydrates, lipids, and proteins is limited. In most cases, it appears MF acts as a modulatory signal rather than a primary driver for physiologic response.

5.2 MF effects on microalgal biomass composition

In terms of microalgae-based carbohydrate production, Deamici et al. evaluated the influence of MF intensity (5, 30, and 60 mT) on *Spirulina* sp. cultivation. It was reported that, compared to the system without MF, the treatment condition of 30 mT applied for 24 hours per day for 15 days led to a 133.2% increase in carbohydrate content relative to the control [48]. The observed stimulation may be explained by the activation of starch and sucrose synthase, an enzymatic system involved in carbohydrate accumulation [49].

Lipids extracted from microalgae are a good source of essential fatty acids and could be used as nutraceuticals, food supplements, and food additives [50]. Baldev, et al. investigated the feasibility of using PMF as a viable technique to elevate lipid compounds in *Chlorella vulgaris* using a 35,000 L open raceway pond [51]. The study indicated that MF stimulated energy flow and cyclic electron transfer in photosynthesis promoted lipid accumulation. In addition, MF exposure can activate the generation of Acetyl-CoA in the cytoplasm, which is one of the major steps in fatty acid synthesis [26, 52]. Notably, microalgae, within the same family differ in their fatty acid profiles leading to discrepancies in lipid production. While this represents a viable large-scale cultivation method for lipid production, open raceway ponds present a significant contamination risk, limiting experimental control compared to laboratory-scale closed systems. However, open raceway systems present lower costs compared to photobioreactors, improving economic feasibility [53].

Meanwhile, other studies focusing on microalgae-based protein, may outweigh conventional sources in terms of quality and quantity [54]. Several studies applying MF application during cultivation have reported increased protein-rich biomass. In the work by Bauer et al. and Small et

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al., the MF intensity of 10-30 mT had a significant stimulatory effect on protein production in *Chlorella kessleri* [52, 55]. Beyond the modified protein concentration, another study from Veiga et al. focused on the influence of MF on *Spirulina sp*.-based protein solubility and digestibility [56]. MF-treatment had a limited effect on protein concentration enhancement yet achieved improvements in protein digestibility and solubility, broadening its applications in the food sector. It is speculated that the possible underlying mechanism in MF-induced protein production and physicochemical changes is related to enzyme system alterations, plasma membrane flux, and gene transcription [47].

Chlorella fusca, exposed to SMF at 60 mT for 24 hours per day for 15 days, was observed to enter an exponential log phase with higher biomass yield, compared to the control (exposure of Earth's MF), which entered a lag phase. Notably, a 24.8% carbohydrate increase, relative to the culture control, indicated promising bioethanol production for microalgae-based biofuels [57]. Microalgal-based biofuels provide a renewable feedstock compared to finite fossil fuels [58], and when coupled with carbon-capturing systems [59] microalgae present a promising sustainable approach [53].

Deamici et al, in a 2022 analysis highlighted MF intensity of 30 mT for 24 hours per day in *Chlorella kessleri, Tribonema sp., Spirulina platensis, Chlorella minutissima* exhibited varying effects, respectively, 25% increase in carotenoids, 85.4% increase in protein content, 45.5% increase in lipids, and a 162.9% increase in carbohydrates, compared to controls. MF-treatment on these microalgal species also highlighted negative responses, with *Chlorella fusca* exhibiting a decreased growth rate under varying exposures. Impact on biomass compared to the control group indicates that MF altered plasma membrane properties, enzymatic and antioxidant activities, and gene expression across species. This reinforces the importance of assessing species-dependent requirements for MF exposure based on desired compounds [47]. MF applications have been investigated across many microalgal strains, with wide outcome variability.

Table 2. Mechanisms and biochemical outcomes in various microalgae strains based on MF-treatment parameters
Note: Please refer to the respective reference for experimental details. Abbrev.: 'h per d' refers to hours per day, and mT refers to millitesla.

Microalgal species	MF type	Field strength	Biomass and Metabolic Effects	Cultivation platform	Proposed Downstream Effects	Reference

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Chlorella vulgaris	PMF	0.060-0.09 (increments of 0.01) mT at 1 Hz for 4 h per d	Signficant increase in dry weight in 0.07 and 0.08 mT compared to 0.06 and 0.09 mT.	35,000 L open raceway system	Renewable biofuel feedstock	[51]
Chlorella kessleri	SMF	30 and 60 mT for 1h per d, and continuous 24 h per d	Biomass and antioxidants increased by 83% and 185%, respectively under 60 mT treatment at 1 h per d. Neutral effects observed in 30 mT at 24 h per d, whereas 1 h per d showed a slight stimulatory effect in biomass concentration.	2 L photobioreactor	Biofactory for health promoting compounds	[55]
Spirulina sp.	SMF	30 and 60 mT for 24 h per d throughout growth cycle	Increased protein digestibility under 60 mT compared to commercial soy protein. No significant stimulatory effects in biomass under 30 mT	Photobioreactor with 1.8 L culture volume	Improved nutrient bioavailability	[56]
Scenedesmus obliquus	SMF, PMF	SMF at 450 mT for 98 h per d; PMF at 450 mT for 1 h per d	60% increase in superoxide dismutase under SMF in response to MF-induced stress	1 L flasks	Increased antioxidant production	[20]
Nannochloropsis gaditana	SMF, PMF	SMF 98 h per d, PMF for 1 h per d, both at 450 mT	150% increase in superoxide dismutase under PMF in response to oxidative stress	1 L flasks	Production of bioactive molecules, especially violaxanthin	[20]
Chlorella fusca	SMF	30 and 60 mT for 1 and 24 h per d for 15 days	CHO increased 24.8% from control under 60 mT compared to other treatment groups. Inhibitory effect on biomass concentration observed under 30 mT for 24 h per d, whereas 60 mT at 1 h and 24 h per d both showed stimulatory effects on biomass concentration	2 L photobioreactor	Bioethanol production	[57]
Desmonostoc alborzicum	SMF	30 and 60 mT for 24 h per d	Increased pigment production under 30 mT. Improved antifungal and antibacterial effects against Citrobacter	unspecified	Alternative for pigments in food, cosmetics, and pharmaceuticals. Potential	[60]

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			freundtii under 60 mT, whereas 30 mT inhibited *E. coli* k12. No significant inhibition to other tested pathogens.		antibacterial applications.	
Dunaliella salina	SMF	30 and 60 mT for 1 and 24 h per d	Abiotic stress-induced carotenoid and biomass accumulation. No inhibitory effects on carotenoids, chlorophyll content, or biomass concentration reported.	500 mL flask	Biofactory for high-value compounds	[61]

As summarized in **Table 2,** microalgae responses to MF-treatments highlight strain-dependent relationships, as evidenced by differences in biomass and bioactive compound accumulation. Notably, not all studies adopt the same cultivation parameters, especially in terms of scalability, ranging from 500 mL flasks to 35,000 L open raceway systems. These differences in cultivation scale and system design limit the direct translatability of laboratory findings to industrial applications, particularly given the highly controlled nature of small-scale experimental conditions. These differences in cultivation scale and system design limit the direct translatability of laboratory findings to industrial applications, particularly given the highly controlled nature of small-scale experimental conditions. Sarai et al. demonstrated that two MF intensities, 30 and 60 mT, in *Desmonostoc alborzicum* yielded different outcomes. At 30 mT, pigment production was observed, compared to 60 mT, which suggested potential antibiotic applications [60]. Collectively, the findings listed in **Table 2** promotes, again, the importance of species-specific optimized MF-treatments given the diverse metabolic responses and observed downstream effects indicating stress modulation rather than stimulation.

5.3 MF implications for bioactive metabolites accumulation

Further applications of MF have highlighted increased phycocyanin pigment in the cyanobacterium *Desmonostoc alborzicum* at 30 mT and increased antioxidant content at 60 mT. Highlighting how variations in MF strength can yield two distinct, yet valuable outcomes [60]. While phycocyanin is a valuable pigment, certain cyanobacterium produce microcystins, toxic compounds [62] that requires careful evaluations during processing for human safety. Carotenoids, a rich-source of beta-carotene, produced by *Dunaliella salin*a under 30 mT for 24 hours per day increased by 95% from the control of <2.0 mg/L [61]. Notably, consumers are calling for more sustainable, naturally-derived food dyes, rather than artificial food dyes. In this instance

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MF-treatment enhances the applications of microalgae for production of high-value pigments for food, cosmetic, and pharmaceutical industries.

While little research has examined the effects of MF on photosynthetic efficiency of microorganisms, several studies report increased photosynthetic activity following MF-exposure. These reported increases, alongside increased antioxidant systems suggest a role in cellular response signaling as a potential mechanism. For example, *Hordeum vulgare L.* (barley) exhibited increased chlorophyll florescence under MF, where the maximum quantum efficiency of photosystem II (PSII) was expressed, suggesting increased photosynthetic efficiency through potential PSII stimulation. However, at MF strengths over 125 mT, the photosystem production decreased due to ROS generation [63]. While these results are not directly reflective of all photosynthetic microorganisms, potential overlap may exist due to cross-species function of chlorophyll. Importantly, these responses are reflected in cellular adaptation to abiotic stress.

6. MF and stress adaptation in photosynthetic organisms

Previous studies have reported that MF exposure is effective in abiotic stress alleviation regarding drought, salinity, and heavy metal stress [27], thereby improving agricultural plant yield. One specific example is MF exposure ameliorating water stress, by promoting cambium differentiation activity, thereby improving water and nutrient transport [28]. In addition, increased plant cell membrane permeability and free water flow, as well as increased chlorophyll and carotenoid synthesis in leaves can be stimulated with suitable MF-treatment [64]. These MF-induced adaptations in terrestrial systems induce greater stress resistance, and improve growth performance and nutrient composition, thereby improving agricultural performance, and nutritional quality.

Soil salinity, due to concentrated soluble salts in the soil, diminishes soil fertility and nutritional value, posing significant challenges for global agriculture [65]. It interferes with plant growth by disrupting water potential and ion distribution within plant cells, decreasing cellular integrity, ultimately reducing crop yields [66], through poor water and nutrient distribution. MF-pretreatment exhibited positive effects on α-amylase and protease activities, where water-absorption efficiency was enhanced in seedlings. Additionally, biomass accumulation and photosynthetic performance were boosted through MF intervention, especially for salt-stressed seedlings through the maturation stage **[Fig. 5]** [35, 67]. Apart from that, MF intervention alleviated detrimental salinity stress deficits by decreasing levels of flavones, flavonoids, and saponins. Importantly, these secondary metabolites are elevated in the presence of certain abiotic stressors [28]. Furthermore, MF reduces soil salinity-triggered oxidative stress within plant cells and decreases catalase and lipid peroxidation [27]. This suggests yield stability, and more efficient agricultural land use.

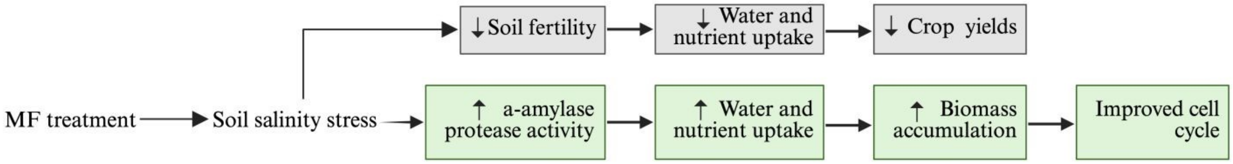

Fig. 5. Mitigation effects of MF seedling treatment to boost overall crop yield

In a recent study by Yang et al., the effect of MF on herbaceous plant phytoremediation under drought stress was evaluated [68]. Based on their study, MF intensities of 30-100 mT applied for 20 min for 7 days alleviated drought-induced detrimental effects. This was evidenced by increased levels of photosynthetic pigments, transpiration rate, and antioxidant enzyme activity. Furthermore, in studies by Selim et al. and Hasan et al., MF-treated irrigation water demonstrated suitability for germination and seedling growth, and drought mitigation to maximize plant productivity [69, 70]. Considerably, water quality can be improved via MF-treatment through modified physicochemical properties, including viscosity, conductivity, refractive index and surface tension due to weakened intra-cluster hydrogen bonds and formation of small, uniform clusters. On the other hand, MF-induced modifications in plant cell membrane size and shape facilitate the entry of water clusters into cells, thereby increasing nutrient absorption and reducing high irrigation requirements [71]. These benefits potentially support crop resilience, and improve water-use efficiency under climate variability.

Regarding microalgae, MF stress has successfully altered antioxidant pathways in *Scenedesmus obliquus*, and *Nannochloropsis gaditana*, increasing their nutritional properties. PMF and SMF induced abiotic stress conditions within these strains, producing different outcomes due to interactions with paramagnetic ions in the cellular membrane. SMF upregulated superoxide dismutase and catalase in *S. obliquus*, where upregulation in *N. gaditana* occurred under PMF-treatment. Inhibitory outcomes were observed under magnetic north configuration, further highlighting the complexities of mechanisms involved in species-specific MF parameter requirements [20]. Antioxidant production was upregulated, and enhanced stress tolerance improved through MF-exposure through the priming of biological stress responses. These observations allow the balance between growth factors and beneficial metabolites to be assessed, and treatment parameters optimized for species-specific requirements. While MF promotes

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biomass and bioactive compound production in microalgae, other microorganisms may exhibit greater inhibitory effects, such as pathogenic bacteria, suggesting a potential ancillary antibacterial treatment.

7. MF Applications in Food Systems and Processing

7.1 Bactericidal properties of MF

Sterilization and decontamination of food and beverage products is essential for preventing foodborne illness outbreaks. According to the CDC, approximately 48 million cases of foodborne illness and 3,000 associated deaths occur in the United States annually [72], placing a significant strain on the public healthcare and economic systems. Thermal methods in food safety are used as a preventative measure to reduce foodborne illness outbreak risks, following regulatory considerations. However, due to the high temperature processes, nutrients and sensory appeal may be compromised, thereby decreasing the product's nutritional value and flavor [73]. Pasteurization employs high temperatures as a sterilization technique. Unfortunately, degradation of certain essential vitamins such as B12, folate, C, E, and A occurs during milk pasteurization [74].

Common non-thermal technologies for food safety include high pressure processing (HPP), UVC irradiation, and cold-plasma treatment [3]. While each technology offers specific advantages, they also present notable limitations. HPP is effective for microbial inactivation through pressure-induced disruption of cellular membranes. However, microbial resistance can occur depending on species, and treatment efficacy may be influenced by food matrix composition and structure [75]. UVC irradiation is becoming widely used for surface decontamination as a result of its damaging effects on microbial DNA and inhibition of replication, but its effectiveness is limited by poor penetration, lack of visibility outside of surfaces, and variability in dose distribution [76]. Cold plasma technology incorporates ionized gas to inactivate microorganisms and is primarily effective as a surface decontamination method, with limitations including restricted penetration into complex food matrices and relatively high initial implementation costs [77]. From an economic perspective, UV irradiation represents a low cost, standardized, and already feasible method for surface level decontamination [76], whereas HPP, although associated with higher operational costs and specialized equipment requirements, is a highly effective non-thermal preservation method [75]. MF technology for commercial use may include costly initial investments, indicating a limitation. MF treatment has been investigated across both liquid and solid food matrices; however, its efficacy is dependent on food composition and selected operational parameters.

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Importantly, further research is needed, as well as comprehensive cost-analysis, and industrial scalability based on realistic processing conditions to establish feasibility.

Importantly, High-strength MF-treatment induces ROS in pathogenic bacterial colonies, including *E. coli, S. aureus,* and *S. epidermis*. While MF treatment reduced more than 50% of bacterial colonies, there was no significant hindrance to bacterial log. This indicates that while this technique may be effective in colony reduction [4], this method would not be ideal for industrial application. Vegetable juice, a popular global beverage, requires food safety interventions that preserve sensory attributes, such as taste profile. Current industrial preservation methods prevent food spoilage but can negatively affect product quality. Treatment of *E. coli* O157:H7, a pathogenic bacterium known to cause disease, organ damage, and even death, with PMF and *Litsea cubeba* (LC) essential oil produced significant bactericidal effects in multiple vegetable juices; cucumber, carrot, spinach, and bitter gourd. A synergistic relationship between LC essential oil and PMF effectively eliminated viable cells by day four without significantly affecting sensory attributes including taste, color, and aroma, highlighting an advantage over conventional chemical preservatives [78].

SMF applied at 5 mT in fresh sea bass demonstrated delayed microbial growth and extended shelf life compared to untreated controls. The treated samples reached total viable count spoilage threshold on day 6, whereas the control reached the same threshold by day 3. Although SMF did not achieve effective bacterial inactivation, microbial growth reduction, and textural properties were improved, indicating potential shelf life extension for seafood [79]. *Listeria monocytogenes* is a food-borne pathogen associated with high fatality risk, partly due to its flagellum assisted motility, enabling greater environmental access. PMF-treatment altered gene expression, leading to decreased motility, function, and metabolism, reducing survival by 1 Log CFU/mL. While these results indicate impaired chemotaxis, and catabolic function, further optimization of MF-treatment is necessary to achieve industry standard sterilization [80].

Calcium polypyrrole nanoparticles exhibited paramagnetic properties that were enhanced in the presence of a SMF at 500 mT, where a 1.7 and 1.2-log reduction was observed in *E. coli* and *S. aureus*, respectively, indicating synergistic efficacy in the combined treatment [81]. While current studies are largely limited to controlled laboratory conditions, this restricts translatability to food processing systems. Especially when viable but non-culturable (VBNC) bacteria are unaccounted as well as many foodborne pathogenic microorganisms during a singular study. In addition, the

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majority of MF studies do not yet assess long-term microbial recovery or resilience, such as genetic transfer, following treatment under real food storage conditions. Currently, MF is not a regulated food decontamination method and lacks standardized regulatory and safety frameworks required to support a consistent validation and commercial implementation. Overall, MF-based interventions demonstrate promising but inconsistent antimicrobial effects in food systems, with current evidence insufficient for regulatory validation as a standalone preservation technology.

7.2 MF Applications in Food Processing Techniques

MF has been explored for non-thermal processing techniques for preservation, yield, rheological, and physiochemical properties. Rice, a globally consumed staple, is prone to retrogradation and thawing instability related to reheating, affecting its quality and texture. Rice starch granules exhibit high water-holding capacity, increasing the potential for microbial contamination and modifications within the starch granular network. Rice starch exposed to PMF, presented with altered hydrogen bonding, decreased gel network, and improved starch stability [82]. Non-thermal preservation for leafy green vegetables offers promising solutions to combat loss and improve overall quality. Integrative therapies with hydrocooling and SMF based on neodymium magnets facilitated increased vegetative cooling, preventing further respiration and enzymatic activity, improving preservation. SMF-based neodymium magnets interacted with water molecules, leading to a faster decrease in temperature compared to controls [83]. By improving post-harvest quality this technique reduces food loss in leafy green vegetables. Furthermore, preservation quality improved, and microbial log reduction was evident in multiple studies under MF-treatment [84]. Non-thermal post-harvest interventions are essential for reducing food waste, as post-harvest losses account for approximately 44% of total waste, with fresh produce experiencing four times higher losses than cereals and pulses [85]. Overall, MF-based non-thermal interventions demonstrate reduction in microbial logs, extended shelf-life, and improved sensory qualities, potentially reducing food waste on a larger industrial scale.

8. Considerations for safety, and regulatory considerations of MF technologies

Potential health and safety risks associated with long-term occupational exposure to static and non-ionizing MF requires careful evaluation. The International Commission on Non-Ionizing Radiation Protection (ICNIRP) issues guidelines for exposure to static MF in occupational and public settings, with more stringent thresholds applied to non-occupational exposure and individuals with implanted medical devices. These guidelines are primarily designed to prevent acute biological effects associated with high-intensity exposure rather than to address

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uncertainties related to prolonged or repeated low-level exposure [86], such as those in occupational settings.

In this context exposure is distinguished between incidental, and short-term interactions which may involve different risk considerations depending on field strength, duration, and proximity to the MF source. Prolonged exposure, through industrial settings, may require additional precautionary measures than current standardized compliance to prevent significant risk. Falsaperla et al., proposed principles of exposure mitigation to include training and implementation to reduce unnecessary exposure, especially in the context of medical devices. Effectively training employees through safety parameters, implementing shields, and personal protective equipment improves biological risk factors and reduces prolonged exposure to MF [87].

While human data is limited in effectively elucidating biological interactions of MF exposure, various animal models provide mechanistic interpretations for potential biological translatability. For example, adult zebrafish are magnetosensitive organisms that exhibit cognitive disruptions at exposure levels as low as 0.015 mT, suggesting alterations in neural processing under weak MF-treatments [88]. Similarly, Yang et al. investigated rotating MF exposure at 200 mT over 10 months in female C57BL/6 mice and observed no significant changes in body weight, agility, and visceral fat deposition. However, significant differences in serum lipid values were detected, including increased pro-inflammatory omega-6 fatty acid levels. Out of the 18 inflammatory cytokines tested, only IL-28 was elevated in the RMF-treatment group. These results indicate that while no physical changes were observed, subtle immune modulation is occurring [89]. Neurological modulation has been observed in rodent models. Exposure of Wistar rats to MF-treatment at 2 mT over 5 days indicated neurological signaling of nitric oxide (NO) was upregulated with neuronal modulation rather than neurotoxic effects. Notably, NO acts on hormone release, neurotransmission, and intracellular signaling [90]. These findings underscore the ability of MF exposure to influence signaling pathways within the central nervous system. Collectively, these studies highlight the complex and exposure dependent relationship between MF, paramagnetic ions within cells, and systemic biological responses. The variability in observed outcomes across species, underscores importance on strict occupational safety assessments protocols, with continued investigation into the long-term effects of MF-exposure especially related to proximity in humans.

MF applications are emerging in agricultural and food processing contexts, however there are not currently standardized occupational safety frameworks specific to food industry applications. In

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the U.S., OSHA does not provide in-depth MF-specific exposure limits for guidance for non-ionizing radiation exposure, which is generally addressed through other governing bodies. At the international level, the International Commission on Non-Ionizing Radiation Protection (ICNIRP) provides exposure limits for static and time-varying MFs. However, these guidelines are not specific MF in food processing and production systems. Further highlighting the need to establish specific safety protocols to ensure MF occupational exposure risks are well-managed.

9. Research Limitations

While many studies exist on MF applications within controlled laboratory conditions, there is still a limited number of research that reports MF as translatable to commercial or industrial food and agricultural applications. This limitation is particularly evident in studies involving complex food matrices, where experimental conditions are controlled rather than representative of real-world applications. Additionally, there is a lack of standardized experimental design across studies due to variations in MF strength, exposure, and conditions, which reduces the ability to compare findings across these studies. Additionally, relatively few studies evaluate long-term stability such as microbial recovery, or regrowth following MF-treatment under long-term storage conditions. These gaps limit the ability to fully assess scalability, reproducibility, and feasibility of MF-based technologies within agricultural and food systems.

10. Future Directions

MF technologies present an emerging non-thermal approach for agricultural production, microalgal cultivation, and food processing and food safety. MF-exposure in plant and microalgae systems have been associated with enhanced germination rates, altered enzymatic activity, improved stress tolerance, and increased biomass productivity. In controlled experiments, MF-based interventions have demonstrated promising bactericidal effects against specific foodborne pathogens, and reduced spoilage in specific food matrices such as beverages and seafood, with minimal effects on sensory attributes. However, MF responses are highly dependent on exposure parameters, field strength, duration, and species and strain. Underlying mechanisms remain unclear and require further evaluation. MF technologies are not yet within standardized regulatory frameworks for food safety applications. These gaps restrict the current scalability of MF-technologies into practical applications. Future research should focus on standardized methodologies, food matrix evaluation, long-term antimicrobial and antibacterial efficacy, pilot-scale industrial studies, and techno-economic assessment. Addressing these limitations will be

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essential in determining the feasibility of MF as a reliable and scalable tool for sustainable food and agricultural applications.

CRediT

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Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data availability is not applicable to this article, as it is a review article and no datasets are generated.