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Review

Electromagnetic Field Treated Irrigation Water for Agricultural Reuse: Physicochemical Mechanisms, Soil Salinity Dynamics, and Crop Responses

Subanky Suvendran [1], Israel Joukhadar [2] and Pei Xu [1,*]

[1] Department of Civil and Environmental Engineering, New Mexico State University, Las Cruces, NM 88003, USA; subanky@nmsu.edu
[2] Department of Plant and Environmental Sciences, New Mexico State University, Las Cruces, NM 88003, USA; icalsoya@nmsu.edu
* Correspondence: pxu@nmsu.edu; Tel.: +1-575-646-5870

Abstract

Electromagnetic field (EMF) treatment of irrigation water has gained attention as a non-chemical conditioning approach to improve irrigation performance under freshwater and saline water conditions. In agricultural applications, EMF treatment is typically applied by passing irrigation water through or near inline magnetic or electromagnetic devices before soil application. Unlike desalination technologies, EMF does not remove salts in irrigation water; it is hypothesized to modify water-soil-ion interactions that influence infiltration, solute mobility, and mineral precipitation kinetics. However, the existing evidence remains fragmented across experimental scales and treatment configurations, with inconsistent reporting of EMF exposure conditions, limited field-scale validation, and uncertainty regarding the underlying mechanisms. This review critically evaluates experimental evidence, proposed mechanisms, and limitations of EMF-treated irrigation water, with particular attention to soil salinity management and its integration with unconventional water reuse. Across laboratory, greenhouse, and limited field studies, EMF-treated irrigation water is most consistently associated with altered wetting behavior and downward salt redistribution, with lower surface-layer salinity reported under selected conditions. However, long-term salt accumulation and groundwater impacts remain unquantified. Reported crop responses include improved ionic balance, enhanced growth, and water productivity, although responses vary among experimental conditions. These outcomes may involve changes in water movement, solute transport, and mineral precipitation behavior, although the contributions of individual mechanisms remain uncertain. EMF treatment cannot substitute for desalination where salinity exceeds crop tolerance thresholds; however, it may serve as a complementary conditioning step within integrated reuse frameworks that combine partial desalination or blending with soil amendments to improve the soil compatibility of unconventional waters. Most available studies involve freshwater or saline/brackish irrigation, with limited direct evidence for reclaimed wastewater applications. Overall, current evidence supports EMF primarily as a condition-dependent modifier of soil–water–salt transport rather than a universally effective treatment. Further research requires standardized treatment reporting, replicated field trials, salt mass balances, and energy and cost assessments.

Keywords: electromagnetic field treatment; soil salinity dynamics; unconventional water irrigation; root zone; desalination; crop productivity

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1. Introduction

Soil salinization and agricultural water scarcity are increasingly constraining crop productivity in arid and semi-arid regions, where irrigation is essential but freshwater availability is limited [1–4]. Salinity stress reduces plant water uptake through osmotic effects, disrupts nutrient balance via ion toxicity, and degrades soil structure under sodic conditions, collectively leading to yield losses and long-term land degradation [5–7]. At the same time, expanding reliance on unconventional water sources (i.e., non-traditional supplies beyond conventional freshwater), including brackish groundwater, reclaimed wastewater, and treated industrial wastewater, has intensified the need for integrated strategies that improve irrigation water usability while maintaining soil health [8–10]. Current water management research has therefore increasingly emphasized the efficient allocation and optimization of limited irrigation water resources [11]. Quantitative approaches, such as Monte Carlo simulation, have also been applied to account for uncertainties in agricultural water availability and allocation decisions [12].

To enable the safe agricultural use of these unconventional waters, treatment is often required to reduce salinity and other water quality constraints. Among available treatment technologies, reverse osmosis (RO) is widely applied for desalinating brackish waters and can effectively reduce total dissolved solids (TDS) to levels suitable for irrigation. However, its agricultural deployment is limited by high cost and energy demand, membrane fouling and scaling, concentrate disposal, and operational complexity [13–15]. These constraints have motivated interest in complementary, low-energy approaches that do not replace desalination but may enhance water-soil–plant interactions, particularly when complete salt removal is economically or environmentally impractical. Within this need for complementary, low-energy water management approaches, electromagnetic field (EMF) treatment has emerged as a physical conditioning technique of increasing interest. Unlike chemical or membrane-based treatments, EMF is proposed to modify physicochemical properties of flowing water, influence ion transport behavior, and alter crystallization kinetics.

Initially investigated for industrial-scale control, EMF treatment has more recently been explored in agricultural systems, where reported benefits include enhanced seed germination, improved vegetative growth, increased water productivity, and partial alleviation of salinity stress [16–23]. Agricultural and water treatment applications employ a variety of static magnetic field (MF) and time-varying electrically induced electromagnetic field (E-EMF) device configurations, including permanent magnets, magnetic rings, solenoid coils, and electromagnetic core systems, each generating distinct field geometries and exposure conditions that may influence ion transport and crystallization behavior (Figure 1). Static MF systems typically employ permanent magnets that generate constant magnetic fields around flowing water, whereas E-EMF systems utilize electrically induced time-varying magnetic fields generated through solenoid coils or electromagnetic cores. These configurations differ in electric and magnetic field geometry, field stability, frequency characteristics, and exposure dynamics, which may influence ion transport, crystallization behavior, and treatment efficiency under different treatment and hydraulic conditions [18,24–26]. Terminology used in the literature varies according to the field source and treatment configuration. The terms “magnetized water” and “magnetically treated water,” frequently used in agricultural studies, describe water following MF exposure and do not represent a separate treatment mechanism. For consistency, this review uses EMF as an overarching term encompassing both MF and E-EMF water-conditioning approaches, while the specific terms MF and E-EMF are retained when the treatment configuration is known.

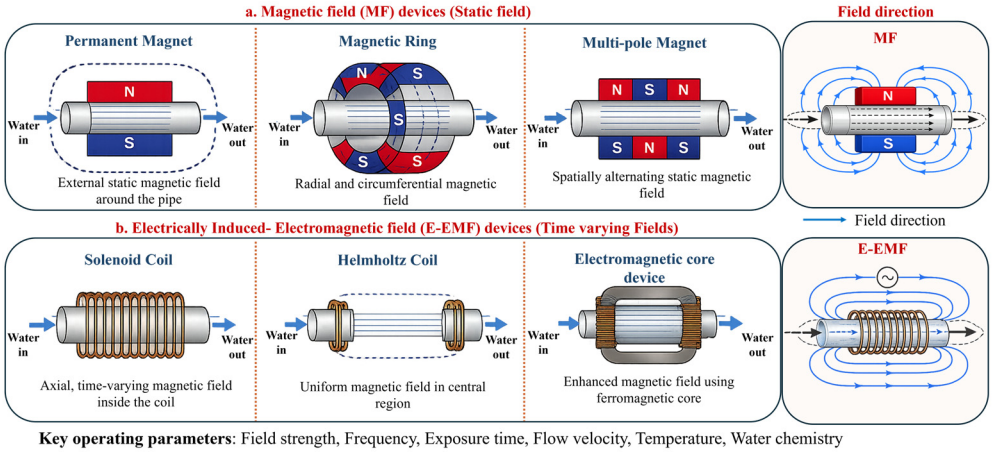


Figure 1. Representative magnetic field (MF) and electrically induced electromagnetic field (E-EMF) devices used for water treatment, illustrating static and time-varying magnetic field configurations and representative field directions around flow-through systems. Static MF devices include permanent magnets, magnetic rings, and multi-pole magnets, whereas EMF devices include solenoid coils, Helmholtz coils, and electromagnetic core systems.

Throughout this review, EMF exposure is considered in relation to a combination of electric or magnetic field strength, hydraulic residence time, and flow conditions. Proposed mechanisms underlying these responses include changes in hydrogen bonding networks, reductions in surface tension, altered ion pairing and hydration, and modified nucleation of sparingly soluble salts such as calcium carbonate and calcium sulfate [18,24,27–29]. However, these molecular-scale mechanisms remain proposed and system-dependent rather than conclusively established. These physicochemical effects are hypothesized to influence wettability, infiltration patterns, nutrient mobility, and salt redistribution within the soil profile. Importantly, EMF treatment does not desalinate irrigation water; rather, its agronomic relevance lies in its potential to modify how salts and water move through soil–plant systems [30–32].

Despite growing interest, outcomes of EMF-treated irrigation water remain highly variable. Reported effects on soil wetting, salt redistribution, nutrient mobility, crop growth, and water productivity depend strongly on EMF field strength, exposure configuration, flow conditions, irrigation water chemistry, soil texture, and crop species [30–35]. Most published studies are short-term laboratory or greenhouse experiments, with limited multi-season field validation. Moreover, inconsistent reporting of EMF parameters and baseline soil-water characteristics constrains reproducibility and cross-study comparison. As a result, EMF water treatment continues to be viewed with skepticism in both soil science and agricultural engineering communities.

Recent work suggests that EMF may be most appropriately considered not as a standalone solution but as a complementary component within integrated water management frameworks. In brackish and unconventional water contexts, EMF conditioning has been associated with downward redistribution of salts below the root zone, improved K and Na in plant tissues, and enhanced soil moisture retention, particularly when combined with organic amendments such as compost [30,32]. These effects indicate potential complementarity between EMF treatment, partial desalination, and soil rehabilitation practices. Hybrid approaches that combine RO for bulk salinity reduction with EMF conditioning to influence transport and crystallization behavior may offer pathways to reduce membrane fouling, improve soil compatibility of blended waters, and enhance crop performance while minimizing energy input.

However, critical knowledge gaps remain regarding mechanistic pathways, the persistence of treatment-induced physicochemical changes after EMF exposure, long-term soil impacts, and economic feasibility. In particular, it is unclear under what water chemistry, soil, hydraulic, and EMF exposure conditions EMF treatment produces meaningful agronomic benefits, how salt redistribution affects subsoil salinity over time, and whether observed improvements can be sustained at the field scale. Interpretation of the available literature is further complicated by differences in experimental scale and treatment configuration, inconsistent reporting of EMF exposure and baseline soil–water conditions, and the frequent attribution of observed soil or crop responses to physicochemical mechanisms that were not directly measured. Consequently, reported responses, hypothesized mechanisms, and effects supported across multiple experimental settings are not always clearly distinguished in existing literature. These limitations make it difficult to determine which reported responses are reproducible, which mechanisms remain hypothetical, and under what conditions EMF treatment may provide practical benefits. Importantly, reported responses are not universal, and negligible or null treatment effects remain plausible under some water chemistry and exposure conditions.

To address these gaps, this review critically synthesizes and evaluates experimental evidence on EMF-treated irrigation water across laboratory, greenhouse, and field scales, with emphasis on physicochemical mechanisms, soil salinity dynamics, nutrient availability, crop responses, and integration with desalination and compost-based soil amendments. By distinguishing experimentally supported observations from hypothesized mechanisms, identifying sources of variability, and outlining standardized reporting and research priorities, this work aims to clarify the current strength and limitations of the evidence and the conditions under which EMF treatment may warrant consideration within agricultural water reuse systems. In addition, conceptual synthesis figures and decision-support frameworks are presented to summarize proposed EMF interaction mechanisms, implementation conditions, and potential integration pathways.

Literature Search, Evidence Evaluation, and Figure Preparation

This study was conducted as a critical review rather than a systematic review or meta-analysis. Relevant literature was identified through searches of Web of Science and Google Scholar using combinations of keywords including electromagnetic field treatment, magnetic water treatment, magnetized water, irrigation, water physicochemical properties, soil salinity, crop response, water productivity, and agricultural water reuse. The search focused on English-language literature relevant to the physicochemical, soil, and crop responses associated with EMF- or MF-treated water, with additional studies identified from the reference lists of relevant publications. The reviewed literature encompassed publications from 1970 to 2026, reflecting both early investigations of magnetic water treatment and more recent applications in agricultural water management. Studies were considered based on their relevance to MF/EMF water treatment, experimental configurations, and reported physicochemical, soil, or crop responses. Peer-reviewed experimental studies directly relevant to EMF/MF-treated water and agricultural applications were prioritized, while non-peer-reviewed sources were used selectively when they provided relevant information not adequately represented in the peer-reviewed literature. Section 4 discusses selected representative studies rather than an exhaustive compilation of the literature, with the aim of illustrating the historical development of MF/EMF irrigation research, differences in experimental conditions, and variability in reported responses.

Given the substantial heterogeneity in treatment configuration, water chemistry, experimental scale, soil and crop conditions, and measured endpoints, evidence was evaluated qualitatively rather than statistically pooled. Greater interpretive weight was given to

replicated, statistically evaluated, peer-reviewed studies and to findings supported across independent experimental settings. Studies published in journals with limited indexing were evaluated cautiously based on their experimental design, control conditions, replication, and statistical analysis, rather than journal indexing alone. Unreplicated studies, theses, simulations, and studies lacking statistical evaluation were considered relevant but were not treated as equivalent evidence for established agronomic effects. Conference and symposium publications were retained where relevant to the historical development of the technology, but their findings were interpreted cautiously, particularly when replication, statistical evaluation, or independent verification was limited. Numerical results were summarized as reported in the original studies, with consideration of experimental limitations and reported precision. For consistency across studies, magnetic flux density values were standardized to Tesla (T), with values originally reported in gauss (G) converted using 1 T = 10,000 G.

Conceptual figures (Figures 1–3) were developed based on author-defined scientific content and figure layouts, with selected illustrative elements generated using ChatGPT (OpenAI, GPT Image 1.5). These elements included magnetic field (MF) and electrically induced electromagnetic field (E-EMF) treatment devices, reverse osmosis (RO) systems, plants, and soil amendments. Technical instructions regarding device configurations and magnetic field representations were provided to guide the generation of MF and E-EMF illustrations. The AI-generated elements were subsequently reviewed and refined by the authors for consistency with the intended scientific concepts and incorporated into the final figures.

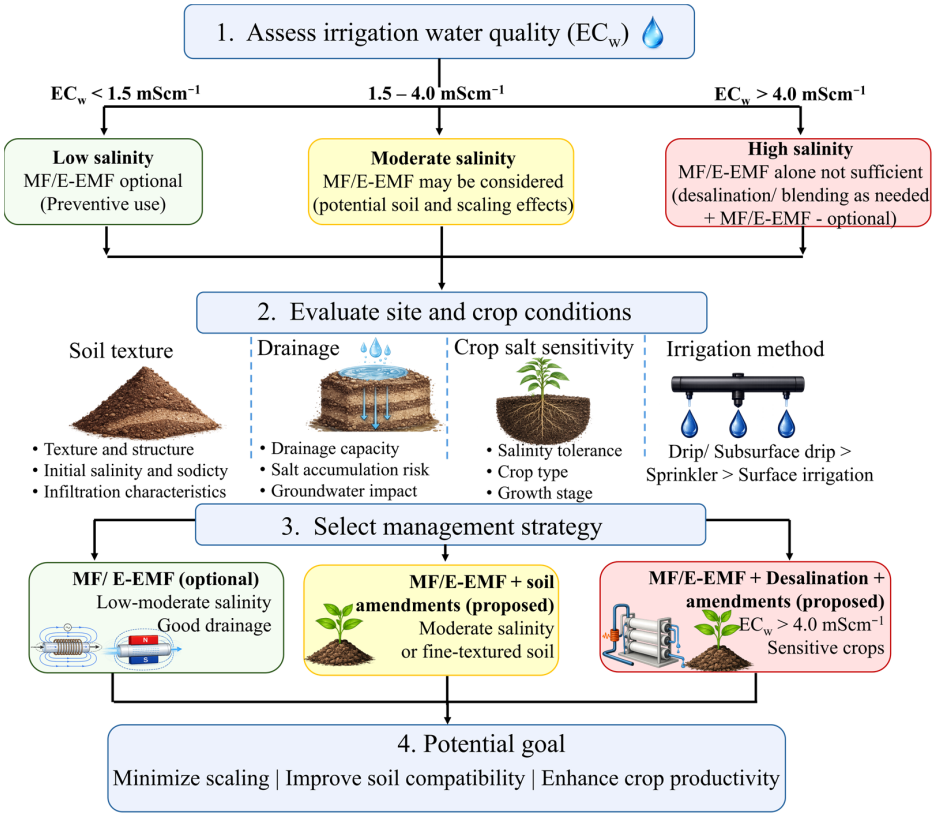


Figure 2. Conceptual framework for future evaluation of MF/EMF treatment in agricultural water management systems. The framework integrates irrigation water salinity, soil and crop conditions, drainage characteristics, and management strategies to identify scenarios where MF/EMF treatment may function as a standalone conditioning approach or where additional interventions such as desalination, blending, or soil amendments are required.

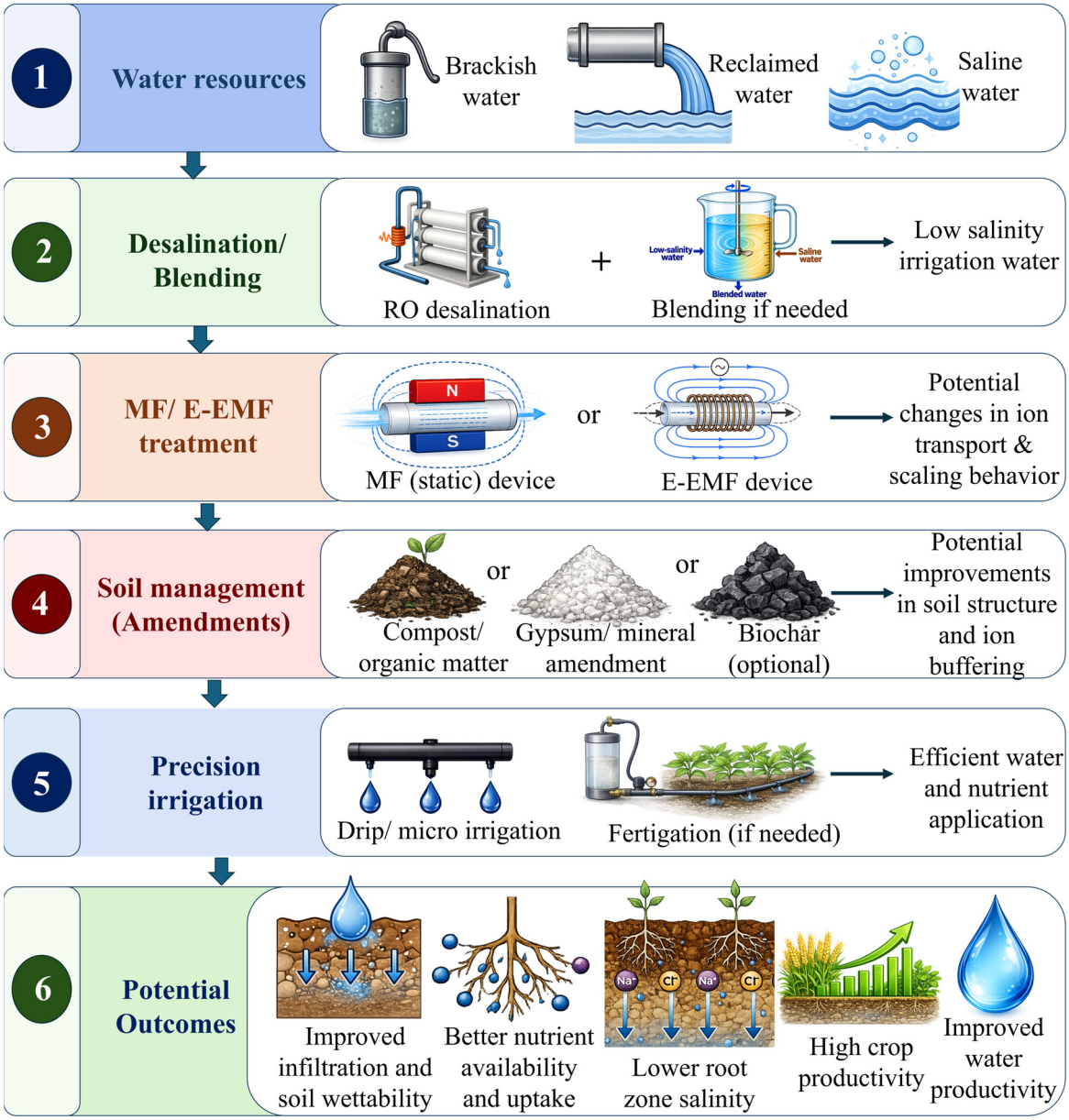


Figure 3. Integrated framework for MF/EMF treatment within agricultural water reuse systems. The framework combines desalination or blending, MF/EMF conditioning, soil amendments, and precision irrigation strategies. In this conceptual system, desalination reduces bulk salinity, MF/EMF treatment modifies ion transport and crystallization behavior, soil amendments improve buffering capacity and soil structure, and precision irrigation enhances water and nutrient delivery efficiency. Collectively, these approaches may contribute to improved soil compatibility, reduced root-zone salinity, enhanced crop productivity, and greater water use efficiency.

2. Physicochemical Basis of EMF-Treated Irrigation Water in Soil–Plant Systems

EMF treatment of irrigation water is postulated to influence soil–plant systems primarily through reported changes in water physicochemical behavior, ion transport, and mineral precipitation kinetics as summarized in Table 1 [17,32,36–45]. Its agronomic relevance lies primarily in altering how water and solutes move through soils and interact with plant roots [46]. The physicochemical responses summarized in Table 1 are highly dependent on experimental conditions, including water composition, dissolved gas content, field strength, exposure configuration, treatment duration, and measurement timing. Some studies report

transient changes following MF exposure, whereas others identify negligible responses, limited reproducibility, or potential experimental artifacts. Consequently, these responses should be interpreted as condition-dependent observations rather than universal properties of EMF-treated water, particularly when extrapolating from simplified laboratory systems to field-scale irrigation.

Table 1. Reported physicochemical responses in water following electromagnetic field (EMF) water treatment under different experimental conditions.

Water Parameter	Reported Response (Study Specific)	Water Type	Potential Implication	Reference
Surface tension	↓ Reported under specific experimental conditions	Fresh, saline	Potential enhancement of wettability, capillary-driven flow in porous media	[37,41,42,47]
Viscosity	Reported ↓ or ↑ (small but measurable)	Fresh, saline	Reduced hydraulic resistance	[39,42,48]
Contact angle	↓ Reported under specific experimental conditions; surface- and exposure-dependent	Fresh	Improved soil wetting	[40,49]
Dissolved gases (O_2, CO_2)	Reported ↓ (depending on treatment and measurement conditions)	Fresh	Increased permeability, infiltration	[36,40,42]
Hydrogen bond dynamics	Reported alterations in H-bond vibrational dynamics and cluster organization	Fresh	May influence interfacial properties, wettability, and diffusion behavior	[50,51]
Electrical conductivity	Minor ↑ or ↓	Fresh/saline	Confirms EMF is not desalination	[32,42,44,48,52,53]
pH	Minor ↑ or ↓	Fresh/ Saline	Reflects CO_2 degassing and carbonate equilibrium shifts; EMF does not chemically alter water	[32,44,52,54]
Zeta potential	Reported ↓	Saline	Reduced colloid stability, enhanced aggregation and precipitation	[55–57]
Crystal morphology/Scaling propensity	Reported changes in nucleation/↓ scaling or clogging tendency	Saline/hard/brackish water	Scaling and clogging mitigation, reduced emitter clogging	[24,36,40,45,58]

Note(s): ↑ indicates an increase, and ↓ indicates a decrease. Reported responses were obtained under heterogeneous experimental paradigms, including static or continuous field exposure, flow-through treatment, post-treatment measurements, and controlled laboratory or simulation studies. The cited studies involved different experimental systems, including bulk water, colloidal suspensions, molecular simulations, and irrigation applications. Experimental configuration and dissolved-gas conditions varied among studies and were frequently not reported. Measurement timing, control conditions, replication, and statistical significance were not consistently documented across studies, and some reported changes were affected by measurement uncertainty or experimental limitations. Therefore, the responses summarized across multiple references should not be interpreted as universally reproducible effects or as directly transferable to field-scale irrigation.

Most agricultural applications employ inline permanent magnets or electromagnetic devices installed upstream of irrigation emitters. Reported field strengths vary widely, while exposure time depends strongly on flow velocity and treatment path length. Consequently, treatment effectiveness is better conceptualized as an EMF exposure dose, defined by field strength, residence time, and hydraulic conditions rather than magnetic intensity alone [25,26]. Inconsistent reporting of these parameters remains a major barrier to

reproducibility. Accordingly, findings from static MF and time-varying E-EMF studies should be compared only when relevant exposure characteristics, including field strength, frequency (where applicable), field geometry, hydraulic residence time, water chemistry, and measurement conditions, are sufficiently documented. Where these parameters differ substantially or are inadequately reported, cross-study comparisons should remain qualitative, and the observed responses should not be interpreted as directly equivalent treatment effects. Furthermore, theoretical calculations of the electric-field (Coulomb) and magnetic-field components of the Lorentz force may provide a complementary framework for comparing the physical interactions associated with different EMF treatment configurations, as demonstrated by Suvendran et al. [59]. However, such comparisons require sufficiently characterized electric and magnetic field strengths, flow conditions, and treatment geometries and should not be interpreted as establishing equivalent treatment effects. Importantly, direct magnetic seed treatment represents a distinct exposure pathway from EMF treatment of irrigation water, as the magnetic field is applied directly to seeds rather than to water before irrigation. Therefore, findings from magnetic seed treatment should not be interpreted as direct evidence of the effects of EMF-treated irrigation water on soil properties or crop responses.

Laboratory and simulation studies suggest that EMF exposure can induce subtle, often transient changes in bulk water properties, including reduced surface tension and viscosity and altered hydrogen bonding dynamics [31,36,37,40,49,58,60]. Under continuous irrigation, such effects may influence wetting behavior at soil particle surfaces, potentially enhancing lateral water spreading and modifying wetting front geometry, particularly in localized irrigation systems [17,61–63]. In sandy soil under drip irrigation, magnetized water increased wetted soil volume from 2576 cm^3 to 2919 cm^3 and improved irrigation efficiency from 64.07% to 72.62% [62]. A critical uncertainty is the persistence of physicochemical changes after EMF exposure is discontinued. Post-treatment or "memory" effects have been reported in controlled water and electrolyte systems, but their magnitude and duration vary substantially with experimental conditions, including field strength, exposure time, solution composition, dissolved gases, and flow conditions [40,64,65]. For example, Szcześ et al. [65] reported that a conductivity change following 5 min of static MF exposure (15 mT) persisted for 24 h, whereas other studies have reported substantially different persistence times. Such observations are highly dependent on experimental conditions and should therefore be regarded as study-specific memory effects rather than evidence of a characteristic persistence time for MF/EMF-treated water. In particular, the dependence of reported effects on dissolved oxygen and gas–liquid interfacial conditions indicates that persistence cannot be considered an intrinsic or universal property of EMF-treated water [40]. Moreover, most evidence derives from pure water or simplified electrolyte systems, and its applicability to complex agricultural irrigation waters and field-scale treatment-to-application times remains uncertain. This uncertainty is particularly relevant when extrapolating from recirculating or continuous-exposure laboratory and greenhouse systems to single-pass field irrigation, where treated water may experience substantially longer transport times before reaching the soil. Therefore, treatment-to-application time and relevant water chemistry conditions should be explicitly reported and evaluated in future agricultural studies.

Dissolved oxygen may represent an important but insufficiently characterized variable influencing some reported MF-induced changes in water properties. Otsuka and Ozeki [40] observed no detectable change in the properties of vacuum-distilled ultrapure water following magnetic treatment, whereas treatment after exposure of the water to O_2 produced measurable changes in water properties, with the treatment effect evaluated using contact angle. These findings indicate that dissolved oxygen and associated gas–liquid interactions may contribute to some reported magnetic-treatment responses [40]. This issue is particu-

larly relevant to agricultural irrigation because dissolved oxygen can vary with water source, temperature, storage, aeration, and delivery conditions, yet it is rarely characterized in agricultural MF/EMF studies. Consequently, dissolved oxygen should be characterized and reported in future studies to determine whether it contributes to variability in agricultural EMF treatment responses.

At the ionic scale, EMF exposure is reported to affect ion hydration and pairing through Lorentz-force interactions on moving charged species [18,66]. However, this mechanism should be interpreted cautiously because direct experimental evidence linking Lorentz-force interactions to persistent changes in treated irrigation water remains limited. Consistent with the findings of Otsuka and Ozeki [40] discussed above, dissolved gases and interfacial conditions may influence magnetic-treatment responses, suggesting that Lorentz-force interactions alone may not adequately explain the reported changes in water properties. Accordingly, Lorentz-force interactions are considered here as a proposed, condition-dependent mechanism rather than an established explanation for altered ion transport during irrigation. Some studies describe weakened intra-cluster hydrogen bonds and smaller water clusters, whereas others report strengthened or newly formed hydrogen bonds, larger clusters, or expanded hydration layers [39]. These apparently contradictory findings likely reflect, at least in part, substantial differences in experimental conditions and analytical approaches among studies. Investigations have employed different field types and strengths, static versus flowing exposure configurations, treatment durations, water compositions, and experimental or computational methods, making direct comparison difficult. Moreover, changes in ion hydration or local molecular organization should not necessarily be interpreted as persistent restructuring of the bulk water hydrogen-bond network [64,67]. Therefore, current evidence does not establish a universal EMF-induced shift toward either smaller or larger water clusters, and the molecular-scale response appears to be strongly dependent on treatment and measurement conditions. In engineered systems, these interactions have been associated with altered calcium carbonate crystallization kinetics and scale morphology [24,68,69]. When cautiously extrapolated to soil environments, these findings suggest a possible kinetic rather than thermodynamic mechanism whereby EMF conditioning may influence where and how salts precipitate during evapoconcentration, without changing total salt mass. However, this mechanism has not been directly verified in agricultural soils, and observed reductions in surface soil salinity are more directly supported by changes in infiltration and downward salt redistribution. Thus, altered crystallization kinetics should be considered a potential complementary mechanism rather than an established explanation for reduced surface salinity.

Consistent agricultural responses relate primarily to transport processes, including modified infiltration, altered solute mobility, and redistribution of salts within the soil profile. Suvendran et al. [32] reported that E-EMF resulted in lower electrical conductivity in the surface soil layer and progressively higher salinity with depth as compared to non-EMF-treated water-irrigated soils, indicating enhanced downward transport and redistribution of soluble ions rather than net salt removal. E-EMF application also increased soil nitrate (NO_3^-) concentrations, suggesting improved nitrogen mobility and availability within the soil profile under treated irrigation. Similar transport responses have been reported in studies using MF-treated irrigation water. In field plot studies involving sandy soil, magnetized irrigation water enhanced soil salt leaching and reduced the rate of salt accumulation relative to non-MF-treated irrigation water. Soil salt content decreased by 15.0–33.7%, while the increase in soil salt storage within the 0–160 cm profile was 44.99–86.78% lower compared with controls. The lowest salt accumulation rate (4.96%) occurred at a magnetization intensity of 0.3 T, indicating the most effective intensity among those tested under the specific experimental conditions. Magnetized irrigation altered soil ion composition

by increasing the leaching of Na^+, Cl^-, and SO_4^{2-}. Repeated magnetization produced stronger effects than single-pass treatment, with double magnetization at 0.3 T resulting in the largest reductions in the relative proportions of Na^+ (80.90%) and Cl^- (82.36%), confirming intensified downward ion transport [30]. One-dimensional soil column experiments (60 cm soil depth, with sampling points at 5 cm intervals) using magnetized brackish water (TDS 0.2, 1, 3, and 5 $g \cdot L^{-1}$) at a magnetic field strength of 0.3 T showed that magnetization slowed wetting-front migration while increasing cumulative infiltration under drip irrigation conditions. Column experiments using MF-treated brackish water also reported changes in wetting-front migration, cumulative infiltration, water retention, and vertical salt redistribution [31]. The distinction between redistribution and removal refers to the fact that EMF treatment does not directly remove dissolved salts from irrigation water, although it may facilitate salt leaching from upper soil layers to deeper layers or beyond the monitored soil profile under suitable drainage conditions. Collectively, these findings indicate that both E-EMF and MF treatments have been reported to influence infiltration and solute transport, promoting downward salt redistribution within the soil profile.

Noticeable reductions in root-zone salinity arise from salt leaching and redistribution from upper soil layers to deeper layers, potentially beyond the root zone or monitored soil profile, making agronomic benefits highly dependent on drainage conditions and leaching fraction. Recent literature similarly reports enhanced leaching and redistribution of salts under magnetically treated irrigation water [70,71]. Notably, Kaur and Singh [71] observed lower salt accumulation at 30 and 60 cm depths but substantially greater accumulation at 90 cm under magnetically treated saline irrigation, providing direct evidence that reduced root-zone salinity can coincide with increased salt accumulation at depth. In well-drained soils, downward transport can alleviate osmotic stress in the rooting zone, whereas in poorly drained systems salts may accumulate in deeper soil horizons. Therefore, reductions in root-zone salinity should not be interpreted as net system-level desalting unless salts are effectively exported through drainage. Without adequate drainage, long-term redistribution may shift salinity risk from the root-zone to the subsoil and, potentially, groundwater. Recent work on EMF-assisted wastewater reuse likewise emphasizes the need for field validation under different irrigation and drainage systems, including assessment of sodium accumulation, soil permeability, and groundwater contamination risk [72]. Enhanced nutrient mobility has also been reported under both MF- and E-EMF-treated irrigation water, exhibited through improved availability of macronutrients and reduced sodium stress in soils and plants [30,32,73,74]. Wang et al. [30] reported increases of 13.48–63.35% in total soil carbon and 11.73–147.96% in total nitrogen under MF-treated irrigation. However, the study reported total rather than fraction-specific carbon and did not distinguish organic from inorganic carbon. Given the magnitude of these short-term changes, particularly in saline soil where inorganic carbon may contribute substantially to total carbon, these results should be interpreted cautiously and should not be considered direct evidence of enhanced soil organic carbon accumulation or nutrient cycling.

Consistent crop-scale responses have been observed in earlier studies, where magnetic treatment of recycled and saline irrigation water (salinity levels of 1500 and 3000 $mg \cdot L^{-1}$) significantly increased available soil phosphorus and extractable potassium in celery relative to non-MF-treated controls [74]. In addition to these MF-based studies, E-EMF treatment has also been evaluated for its effects on soil nutrient retention. Soil columns irrigated with E-EMF-treated irrigation water exhibited a ~7% increase in soil organic carbon compared with columns receiving non-EMF-treated irrigation water, while compost incorporation in columns irrigated with E-EMF-treated irrigation water reduced NO_3^- leaching by more than 15% [32]. Multi-year field studies combining MF-treated brackish water irrigation with organic fertilizers have reported improvements in soil nutrient status, water-holding capacity,

aggregate stability, enzyme activity, microbial properties, and crop performance [63,75–77]. For example, a three-year field study combining MF-treated irrigation with microbial organic fertilizer reduced soil bulk density by 3.07–11.04%, increased soil porosity by 1.97–14.75%, and increased jujube yield by 3.66–21.38% [63]. A two-year pakchoi field study using magnetized-ionized brackish water with bio-organic fertilizer reported improved soil nutrient status and soil quality, with crop growth, yield, and quality responses varying with fertilizer application rate [76]. Similarly, combined magnetized-ionized brackish water irrigation and organic fertilization in cotton improved soil water retention and salt leaching, soil physicochemical properties, microbial diversity, and crop productivity [75]. In a two-season wheat field experiment under saline soil conditions, magnetic treatment of irrigation water and seeds combined with compost improved soil properties and plant nutrient uptake and increased wheat productivity relative to untreated conditions [78]. Although these studies provide broader evidence for the benefits of combining field-treated irrigation water with organic amendments, further studies are needed to confirm the specific effects of E-EMF–compost integration on nitrate retention and soil carbon. Collectively, these responses may be associated with altered ion transport, improved soil moisture distribution, and enhanced rhizosphere conditions rather than direct changes in irrigation water chemistry, with secondary benefits for phosphorus availability and nutrient use efficiency.

A molecular dynamics simulation of a highly idealized model membrane system under a continuously applied magnetic field reported changes in water flux through aquaporin channels [79]. This computational result demonstrates a possible field–membrane interaction under the specific simulated conditions but should not be interpreted as experimental evidence of MF effects on aquaporin function or plant water uptake under agricultural conditions. However, plant water absorption is biologically regulated through aquaporins and osmotic gradients [80], and current agricultural evidence is insufficient to establish a direct MF effect on root membrane physiology. Any agronomic influence on plant water uptake may instead arise indirectly through changes in soil hydraulic properties and boundary-layer transport rather than direct modification of root membrane physiology. Overall, available evidence indicates that EMF-treated irrigation water affects soil–plant systems primarily through coupled physical and transport mechanisms, including modified wettability and altered solute mobility, and redistribution of salts and nutrients within the soil profile. Consequently, EMF treatment is best viewed as a kinetic modifier of soil-water-ion interactions rather than a transformative water quality technology.

While altered wetting behavior, salt redistribution, and emitter clogging mitigation are consistently observed outcomes of EMF-treated irrigation, proposed molecular-scale mechanisms (e.g., hydrogen bond restructuring or ion hydration changes) remain partially speculative and system-dependent. The agronomic relevance of EMF treatment is therefore better supported by macroscopic transport observations than by persistent modifications of bulk water structure. Furthermore, the occurrence of reported soil responses across studies with differing treatment-to-application conditions is not readily reconciled with the variable and sometimes transient post-treatment effects discussed above. This discrepancy further cautions against attributing field-scale responses solely to persistent changes in bulk water properties and highlights the need to investigate alternative or longer-lived processes, including mineral nucleation and precipitation kinetics.

3. Effects of EMF-Treated Irrigation Water on Soil Moisture, Salinity, and Nutrient Dynamics

EMF-treated irrigation water has been reported to alter soil moisture dynamics, salinity distribution, and nutrient behavior, with observed responses primarily associated with changes in infiltration patterns and solute transport within the soil profile. As a result,

observed soil responses may reflect coupled hydraulic and geochemical processes, including changes in wetting behavior, downward redistribution of salts, and shifts in nutrient availability and retention in the rhizosphere. This section synthesizes experimental evidence describing how EMF-treated irrigation water influences soil water storage, salinity gradients, and nutrient mobility across laboratories, columns, and field scales.

3.1. Soil Moisture Distribution, Infiltration, and Salinity Dynamics

Multiple studies report altered soil moisture patterns under EMF-treated irrigation, particularly under drip and localized irrigation systems. MF-conditioned water is commonly associated with increased lateral wetting and more uniform moisture distribution around emitters, often accompanied by modest reductions in vertical percolation depth [81]. These responses may be associated with changes in water–soil interfacial behavior and wettability; however, direct attribution to specific physicochemical changes such as reduced surface tension remains uncertain. Importantly, these quantitative responses were obtained under different soil textures, salinity levels, magnetic exposure conditions, and experimental scales. Differences in control treatments, replication, and statistical significance reporting further limit direct comparisons among studies; therefore, the reported values should be interpreted as study-specific observations rather than universally applicable effects of EMF-treated irrigation water.

Experimental evidence consistently indicates that EMF-treated irrigation water alters soil moisture distribution with depth and modifies wetting-front dynamics, rather than increasing total water input [31,45,82–85]. Column and field studies report that soils irrigated with MF-treated water exhibit higher moisture content in the root zone compared with non-MF controls, with moisture varying systematically with depth [86]. In sandy loam soils irrigated with MF-treated water (0.07–0.36 T), soil water-holding capacity increased by approximately 25%, and soil matric potentials were less negative than in non-MF-treated soils, indicating reduced energy required for plant water uptake and enhanced moisture retention [86]. Field experiments across slightly, moderately, and heavily salinized soils demonstrate that MF-treated irrigation water significantly alters soil water-salt distribution, increasing soil water-holding capacity, enhancing salt leaching, and reducing salt content throughout the monitored 0–100 cm soil profile, with effects most pronounced in slightly saline soils. Among tested magnetic intensities (0–0.5 T), irrigation at 0.3 T produced the strongest soil response, increasing soil water content by 33.2–56.2% and improving desalination rates by 29.2–50.4% relative to the control, confirming the strong dependence of MF effectiveness on both soil salinity level and magnetic field intensity [87].

Under saline conditions, MF of irrigation water substantially enhanced soil wetting and irrigation performance, with subsurface drip irrigation achieving a markedly larger wetted soil volume (94,500 cm^3) than non-MF-treated systems (6720 cm^3), alongside increased soil moisture retention, higher field capacity, reduced emitter clogging (12% to 5%), and improved application efficiency and emission uniformity [45]. Drip irrigation systems operating with brackish or fertilizer-enriched water are particularly prone to emitter clogging due to mineral precipitation and suspended solids, which reduces discharge uniformity and irrigation efficiency [88,89]. Field experiments further show that MF-treated irrigation water mitigates emitter clogging in drip fertigation systems under increasing fertilizer loads, increasing discharge variation rates by 4.1–29.0% (up to 64.4% across seasons) and reducing clogging mass by 14–75%, largely by limiting deposition of quartz, silicate, and carbonate-based precipitates [88]. However, the effectiveness of magnetic water treatment on dripline uniformity appears to be water quality dependent, with poor performance observed under certain saline water compositions but improved uniformity under intermediate salinity

conditions, supporting evidence that EMF treatment efficiency is strongly governed by irrigation water chemistry [60,89].

Several studies attribute these responses to changes in water-soil interactions following magnetic treatment. Laboratory and column investigations suggest that magnetic treatment can reduce surface tension and viscosity and promote partial degassing of irrigation water, leading to enhanced soil permeability and capillary-driven flow [36,50]. Under drip irrigation, MF-treated water altered wetted bulb geometry, increasing surface wetted radius by ~6% and reducing vertical wetted depth by ~6% in homogeneous soils rather than deep percolation. In layered-textural profiles, responses depended on stratification, with increases or decreases in wetted depth observed depending on soil layering, while changes in water content distribution were not statistically significant [82]. However, not all studies report significant changes in bulk soil water content, highlighting strong dependence on soil texture, structure, and wettability.

Quantitative increases in soil moisture content of approximately 7–8% relative to untreated irrigation have been reported in loam and sandy loam soils irrigated with EMF-treated water [83,90]. Field-scale experiments further indicate that prolonged irrigation with EMF-treated water can reduce evaporation and percolation losses, contributing to improved soil water availability under drip irrigation systems [81,84,87].

Recent column and field studies using MF-treated brackish water provide additional resolution of infiltration and salt transport processes. In one-dimensional soil column experiments using MF-treated water (0.2–5 g L^{-1}) at 0.3 T, infiltration time to a depth of 40 cm increased by 17.4–47.0%, while cumulative infiltration increased by 5.4–10.6%, indicating slower wetting-front advance combined with greater water retention within the soil profile [31]. These hydraulic changes were accompanied by pronounced vertical salinity redistribution, characterized by reduced salinity in upper soil layers and increased salt accumulation at depth. Niaz et al. [91] reported that MF-treated water treatments significantly increased leachate volume and salt leaching compared with the control.

Column studies further demonstrate sodium displacement depths of 15–40 cm, with increased salt accumulation at ~90 cm, confirming redistribution rather than removal of salts from the soil system [86]. Magnetic conditioning also altered salinity dynamics by reducing sodium and chloride accumulation in the root zone, lowering the Na/Cl ratio (1.07 to 0.98), decreasing soil electrical conductivity and soluble ion concentrations, and thereby facilitating salt leaching and reducing salinity stress in the root zone [45,92]. Across all salinity levels, reductions in soil salt content under MF-treated irrigation were negatively correlated with plant growth indicators, highlighting the importance of soil salinity redistribution in mediating downstream crop responses [87]. EMF-treated water was associated with notably lower soil salinity and sodicity indicators, electrical conductivity, and sodium adsorption ratio relative to non-EMF-treated irrigation [32,93]. Improved soil water retention and enhanced salt leaching are not necessarily contradictory, as these responses may occur under different soil hydraulic and drainage conditions. Although increased water retention may reduce deep percolation and associated salt leaching, downward salt transport can still occur during irrigation events. Therefore, these processes should be interpreted within the context of soil water and salt balances rather than as independent indicators of improved soil conditions.

Importantly, and consistent across studies, EMF treatment does not reduce total salt input to the soil. Reported reductions in surface or root-zone electrical conductivity instead reflect downward redistribution of salts following the advance of the wetting front, consistent with classical soil physics describing onion-shaped wetting and solute fronts under localized irrigation [94]. In well-drained soils, such redistribution can alleviate osmotic stress in the active rooting zone, whereas in poorly drained or shallow water-table systems,

salts may accumulate in subsurface horizons and return to the surface through capillary rise during drying cycles [95,96]. Consequently, agronomic benefits of EMF-treated irrigation water depend critically on soil drainage, leaching fraction, and long-term salt export rather than redistribution alone. Collectively, these findings indicate that EMF-treated irrigation water modifies soil moisture and salinity dynamics primarily by reshaping wetting-front geometry and solute transport pathways, with outcomes strongly conditioned by soil texture, drainage, and irrigation design. However, the magnitude of long-term subsoil salt accumulation under EMF-treated irrigation remains unquantified because available studies generally lack multi-season salt mass balances, deep percolation measurements, drainage water salinity, and groundwater monitoring. Consequently, whether downward redistribution ultimately results in effective salt export or progressive accumulation below the root zone remains unresolved. Long-term field studies should therefore quantify depth-resolved soil salt storage, leaching fraction, drainage water flux and salinity, and groundwater EC to establish system-level salt balances and evaluate environmental sustainability [97].

Interpretation of these findings should account for differences in experimental scale and boundary conditions. Column studies provide controlled evidence of infiltration and solute redistribution but vary in initial soil moisture, column dimensions, drainage configuration, and air displacement conditions, all of which can independently influence wetting-front and solute-transport behavior. Consequently, column-scale responses should not be directly extrapolated to field conditions. Field studies provide greater agronomic relevance but may also be constrained by treatment device replication. Future studies should therefore clearly report both experimental boundary conditions and treatment device replication.

3.2. Nutrient Mobility, Rhizosphere Processes, and Implications for Unconventional Water Reuse

Several studies using EMF-treated water further report enhanced uptake of K and Ca alongside other macro- and micronutrients, suggesting a potential association between EMF treatment and improved nutrient assimilation and physiological activation, as reflected in improved K^+/Na^+ ratios [30,93,98–103]. These responses may be associated with altered ion transport, expanded wetted soil volume, and changes in rhizosphere chemistry; however, the relative contributions of these proposed mechanisms have not been consistently established through direct measurements. Enhanced availability of phosphorus and selected micronutrients has also been observed, potentially resulting from changes in nutrient transport, greater root accessibility, and potentially altered dissolution of sparingly soluble minerals. However, the relative contributions of these processes remain uncertain, and the available evidence does not establish a direct causal relationship between specific physicochemical changes in treated water and plant nutrient uptake. Therefore, reduced mineral scaling in engineered systems does not necessarily contradict the possibility of altered nutrient mineral dissolution in soils, although neither response should be assumed to occur universally.

Controlled field experiments further demonstrate that magnetically treated irrigation water enhances plant nutrient uptake in a depth-dependent manner. Under MF irrigation, leaf nitrogen concentrations were significantly higher than under conventional water. Phosphorus concentrations increased linearly with irrigation depth for both water types, but MF irrigation resulted in significantly greater P accumulation at moderate to full replacement levels [104]. Calcium and magnesium concentrations declined with increasing irrigation depth overall, yet MF-conditioned irrigation consistently maintained higher Ca and Mg levels at full irrigation. In addition, MF treatments increased shoot concentrations of micronutrients such as Cu and Mn, indicating enhanced nutrient availability and uptake under magnetically conditioned irrigation [103]. In poplar seedlings subjected to NaCl stress, MF treatment reduced root Na^+ concentrations by approximately 29% and prevented

salt-induced depletion of K^+ and Ca^{2+}, maintaining K^+/Na^+ and Ca^{2+}/Na^+ ratios near control levels and indicating enhanced ionic homeostasis under saline conditions [105]. Ion-specific responses have also been reported, with water MF-treated at 0.2 T increasing Ca^{2+} and Mg^{2+} concentrations by approximately 10% relative to non-MF-treated controls, while no significant effects were observed for P or Fe, indicating selective enhancement of divalent cation uptake rather than uniform increases across all nutrients [106]. Similarly, MF-treated irrigation has been shown to substantially increase K accumulation, in some cases approaching twofold higher K concentrations than non-MF-treated controls at advanced growth stages [100].

At the fertilizer management level, Zedan et al. [98] reported that irrigation with MF-treated water improved nitrogen use efficiency in cowpea, allowing reductions in applied nitrogen fertilizer of up to 25% without adverse effects on crop performance under tested experimental conditions. Rhizosphere-mediated nutrient mobilization has also been reported, where magnetically treated recycled and saline irrigation water (1500–3000 $mg \cdot L^{-1}$) increased available soil P and extractable K, coinciding with post-harvest soil pH reductions potentially attributed to enhanced organic acid release by roots, which may have contributed to desorption and availability of P and K [74]. However, root organic acid release was not directly measured in this study, and its contribution to nutrient mobilization remains hypothetical. Column experiments demonstrate that E-EMF-treated irrigation water alone can increase NO_3^- leaching (by ~19–37%, depending on water type), whereas the combination of E-EMF treatment with compost significantly reduced NO_3^- losses (up to ~25% under brackish water) relative to the untreated control, highlighting the potential combined effects between E-EMF conditioning and organic amendments in improving nitrate retention [32]. Because compost addition and EMF treatment can independently influence nutrient transport and retention, the observed combined-treatment benefits should not be attributed solely to EMF conditioning without appropriate factorial controls. This combined treatment response was accompanied by substantial increases in soil organic carbon, with EMF-treated irrigation water and soil composted columns exhibiting organic carbon gains exceeding those of compost alone, suggesting enhanced soil carbon content and nutrient availability under combined EMF and organic matter management. These findings suggest that EMF conditioning may have value when integrated with organic soil amendments, where altered water and solute transport may complement the nutrient-retention and soil-buffering functions of added organic matter. However, the available evidence is currently based on a limited number of studies, and it remains unclear whether the observed combined treatment responses reflect enhanced biological activity, physicochemical retention processes, or their combined effects. Nutrient retention and leaching are ion-specific processes influenced by soil chemistry, plant uptake, and amendment application; therefore, enhanced salt migration does not necessarily imply increased leaching of all nutrients. Further field-scale studies should therefore evaluate EMF–organic amendment interactions using measurements of soil organic carbon persistence, nitrogen transformation and loss pathways, microbial community responses, and crop nutrient-use efficiency. Recent field studies reported that MF-treated irrigation, particularly when combined with aeration, can substantially enhance soil nitrogen retention, with soil nitrate-N concentrations increasing by ~25–30% and soil available nitrogen and organic matter maintained at higher levels across seasons, indicating improved nitrogen transformation and stabilization rather than simple accumulation [107].

EMF-treated irrigation should be interpreted cautiously because existing agricultural studies do not clearly distinguish direct MF effects on microorganisms from indirect responses mediated through changes in the soil environment. Magnetized or EMF-treated irrigation has been associated with shifts in bacterial and fungal community composition,

including increases in beneficial taxa; however, recent evidence also shows strong relationships between these microbial shifts and concurrent changes in soil properties [108]. Salinity itself is a major regulator of microbial community structure, enzyme activity, and C and N cycling through osmotic and ionic stress, suggesting that reductions in root-zone salinity and improved soil moisture conditions could indirectly stimulate microbial activity and associated carbon and nutrient cycling [109]. Direct MF effects on microorganisms are biologically plausible, with laboratory studies reporting changes in microbial growth, metabolic and enzyme activity, and gene expression, but the mechanisms remain insufficiently resolved and have rarely been isolated under agricultural soil conditions [110–112]. Therefore, the available evidence currently supports an indirect soil-mediated pathway more strongly than a direct microbial response to EMF-treated irrigation. Controlled experiments that independently manipulate EMF exposure, soil moisture, and salinity while measuring microbial biomass, community composition, enzyme activities, and functional genes are needed to distinguish these pathways. Integration of EMF treatment with soil amendments, such as compost and organic fertilizer, has demonstrated combined benefits, including increased cation exchange capacity, improved aggregation, and enhanced microbial biomass, collectively supporting nutrient retention and availability in saline soils [32,63,75,78,98,113,114]. However, these findings span different experimental scales and treatment combinations, and the independent contribution of EMF treatment cannot always be isolated when aeration, fertilizers, compost, or seed treatments are applied concurrently.

When applied to unconventional waters, including brackish groundwater and reclaimed wastewater, EMF conditioning may improve soil compatibility by modifying salt transport pathways and enhancing root-zone moisture retention. Reported benefits include reduced sodium accumulation in upper soil layers, improved plant ionic balance, and increased water productivity. However, EMF does not address trace contaminants or boron toxicity and should be viewed as complementary, rather than a substitute for, desalination or targeted treatment processes. The most promising applications lie within integrated reuse frameworks that combine partial desalination, EMF conditioning, and soil amendments, integrating desalination to reduce bulk salinity, EMF to influence transport behavior, and organic matter to enhance soil buffering capacity. Verification of these synergistic effects requires field-scale experiments with full soil–water–plant mass balance.

4. Crop Physiological Responses, Yield, and Water Productivity Under EMF-Treated Irrigation

Crop responses to EMF-treated irrigation water have been associated with integrated effects of modified soil moisture distribution, altered salt transport, and changes in nutrient availability. Reported outcomes include accelerated germination, enhanced vegetative growth, improved ionic balance, and increased yield or water productivity, particularly under saline or deficit irrigation. However, responses vary widely with crop species, soil texture, irrigation regime, and EMF exposure parameters as summarized in Tables 2 and 3. Studies combining EMF-treated irrigation water with seed pretreatment, fertilizer application, or organic amendments are included where relevant to integrated soil–water–plant management; however, their combined effects cannot be attributed solely to treated irrigation water unless independent treatment comparisons are available. Several studies report faster germination and improved seedling establishment when crops are irrigated with EMF-treated water, especially under moderate salinity or water limitation, potentially involving changes in proteins and enzyme activity [74,115–121]. Enhanced early vitality has been reported under several experimental conditions, although field-scale validation remains limited, and many studies confound seed magnetic exposure with irrigation water treatment. Where direct seed magnetic exposure and irrigation water treatment were

combined or not clearly separated, the reported germination response cannot be attributed specifically to EMF-treated irrigation water. Agronomically, establishment benefits appear most relevant where salinity or limited water availability delays emergence, while under optimal irrigation conditions EMF-related effects on germination are generally modest.

Table 2. Representative laboratory, pot, greenhouse, and soil column studies reporting plant physiological responses, yield, and yield components under EMF–treated irrigation water.

Crop	Experimental Scale	Water Type/Salinity	EMF Device & Exposure (Reported)	Major Soil/Plant Responses	Yield/Water Productivity Outcome	Methodological Reporting	Study
Tomato (Rocco and Monza varieties)	Pot	Fresh water	Static MF (4–6 mT) (seed & water) Q = 20 L/s	Accelerated phenology and enhanced early reproductive development	Early yield ↑ 28–51% in Monza, flowering advanced by 3–4 days, total yield ↑, no significant effect in Rocco variety. Independent effect of MF-treated water not established	n = 6; Stats: Yes; Control: Yes	[122]
Cereals, fodder crops, vegetables, melons	Field & Greenhouse (large-scale trials)	Fresh to alkaline irrigation water	Static MF (0.1 T) Magnetic treatment of irrigation water. Water velocity 1–2 m/s in pressurized systems and ~0.5 m/s in open systems	Improved root-zone moisture supplies due to high penetration of water and CO_2-mediated nutrient availability	Yield ↑ ~10–15% (greenhouse), improvement in water productivity, high salt leaching	n = NR; Stats: Yes; Control: Yes	[123]
Rice	Laboratory	Fresh water	Static MF (for 8 h) and dynamic MF (0.15–0.25 T; for 2 h) Magnetic treatment of irrigation water	Dynamic-flow MF-treated water significantly improved early germination; static treatments showed no significant improvement.	Germination increased from 72% (control) to 88% under dynamic-flow MF-treated water	n = 4; Stats: Yes; Control: Yes	[121]
Celery, Snow peas, Peas	Pot	Recycled & saline (1500–3000 mg·L^{-1})	Inline MF device (3.5–136 mT) Q = 10 mL/s; exposure ≈3 s; two passes)	Reduced Na^+ uptake, increased K^+ and Ca^{2+}, higher soil P and K	Celery: Yield maintained or ↑ under saline irrigation and 12% water productivity ↑; Snow peas: ↑ Pod yield. Pea yield—No benefits	n = 4; Stats: Yes; Control: Yes	[74]
Wheat and Flax	Pot	Fresh water	Inline MF (~30 mT)	Photosynthetic pigments ↑, endogenous total indole, total phenol and protein synthesis, nutrient uptake	Yield ↑ up to 33.3% for wheat and 10% for flax	n = 5; Stats: Yes; Control: Yes	[124]
Cucumber, Eggplant, Tomato, Squash	Greenhouse conditions	Brackish water	Static MF (20, 40, 60 mT) treatment intervals 0–300 min	Nutrient uptake ↑ and ↑ germination percentage, ↓ Na^+ in soil	Yield ↑, Plant height and fruits ↑ for cucumber	n = 3; Stats: Yes; Control: Yes	[73]
Lettuce	Pot	Fresh water	Static MF (36 mT) water velocity 0.15 m/min	Reduced root-zone EC, improved ionic balance	Yield ↑ (significant at 50% and 70% irrigation), total chlorophyll ↑ ~10–25% and concentrations of some macro and micro-nutrient ↑. Not significant at 100% irrigation	n = 10; Stats: Yes; Control: Yes	[21]

Table 2. *Cont.*

Crop	Experimental Scale	Water Type/Salinity	EMF Device & Exposure (Reported)	Major Soil/Plant Responses	Yield/Water Productivity Outcome	Methodological Reporting	Study
Poplar	Pot	Saline nutrient solution	MF-treated irrigation (0.03 T device-rated capacity 4–6 m^3/h)	Photosynthesis and nutrient uptake ↑, root development ↑, C/N ratio in leaves ↑, Na^+ toxicity ↓	Biomass ↑, water use efficiency ↑	n = 3; Stats: Yes; Control: Yes	[35]
Grapevine	Pot	Saline water	MF-treated irrigation (0.03 T device-rated capacity 4–6 m^3/h)	Chlorophyll ↑, photosynthetic rate ↑, stomatal conductance and transpiration date	Growth ↑, Photosynthetic performance 18–56%↑ stress tolerance and water use efficiency ↑	n = 3; Stats: Yes; Control: Yes	[34]
Salvia	Pot	Saline water	Static MF (0.3 T–0.6 T for single pass to 30 min)	↑ chlorophyll, ↑ phenolic compounds and stimulated the activity of peroxidase and polyphenol oxidase, ↑ salt tolerance	Water use efficiency↑, Plant growth↑	n = 3; Stats: Yes; Control: Yes	[125]
Dundale pea	Soil columns, greenhouse study	Fresh & brackish water	E-EMF treatment (150 kHz electric field) Q = 33.33 mL/s for 5 min (recirculation)	Downward salt redistribution; improved NO_3^- retention with compost	Yield and growth ↑, Organic carbon 7% ↑	n = 3; Stats: Yes; Control: Yes	[32]

Note(s): ↑ indicates an increase, and ↓ indicates a decrease. Reported yield and water productivity responses are relative to non-EMF controls within each study and are not directly comparable across experiments due to differences in experimental scale, crop, salinity, irrigation regime, and EMF exposure. Q = water flow rate; n = number of experimental units per treatment; NR = not reported. Statistical analysis and control conditions are indicated where available but do not imply that all treatment comparisons were statistically significant. Water productivity values based only on applied irrigation should be interpreted as irrigation water productivity rather than evapotranspiration-based crop water productivity. Selected representative studies are presented to illustrate the development and variability of MF/EMF irrigation research; the table is not an exhaustive compilation of published studies.

Table 3. Representative field-scale studies reporting plant physiological responses, yield, and yield components under EMF–treated irrigation water.

Crop	Study Scale	Water type/Salinity	EMF Device & Exposure (Reported)	Major Soil/Plant Responses	Yield/Water Productivity Outcome	Methodological Reporting	Study
Cereals, fodder crops, vegetables, melons	Field & Greenhouse (large-scale trials)	Fresh to alkaline irrigation water	Static MF (0.1 T) Magnetic treatment of irrigation water. Water velocity 1–2 m/s in pressurized systems and ~0.5 m/s in open systems	Improved root-zone moisture supplies due to high penetration of water and CO_2-mediated nutrient availability	5–20% yield ↑ in ~75% of field cases, improvement in water productivity, high salt leaching	n = NR; Stats: Yes; Control: Yes	[123]
Brinjal	Field	Normal and saline water	Static MF (18–20 mT) Q = 2 L/s for 10 min (recirculation)	Improved soil moisture, reduced salinity stress	Yield ↑ ~15–20%, ↑ plant height	n = NR; Stats: Yes; Control: Yes	[84]

Table 3. *Cont.*

Crop	Study Scale	Water type/Salinity	EMF Device & Exposure (Reported)	Major Soil/Plant Responses	Yield/Water Productivity Outcome	Methodological Reporting	Study
Potato and corn	Field	Saline water	E-EMF treatment, 15-min treatment	Na^+ accumulation ↓, nutrient (N, P, K) uptake ↑	Early establishment benefit, Yield ↑ ~10% in spring; autumn ground yield ↑ ~11% but not significant	n = 3–5; Stats: Yes; Control: Yes	[92]
Cotton	Field	Fresh water and saline soil	MF-treated irrigation 0.1–0.5 T (optimum ≈0.3 T)	Soil water content 33–56%↑, ↑ salt leaching	Yield ↑ 28–32%, water use efficiency ↑ 27–43%	n = 3; Stats: Yes; Control: Yes	[87]
Cowpea	Field	Fresh–moderate salinity	MF-treated irrigation inline passage during irrigation (1.45 T)	N uptake efficiency ↑ and 25% ↓ rate of nitrogen fertilizer	Yield ↑, vegetative growth↑, water use efficiency ↑	n = 3; Stats: Yes; Control: Yes	[98]
Jujube	Field	Brackish water	MF-treated irrigation water (0.1–0.5 T)	↓ salt content 15–34%, ↑ downward salt transport, ↑ total carbon 13–63% and nitrogen (12–148%)	Yield ↑ ~12–22%	n = 3; Stats: Yes; Control: Yes	[30]
Cotton	Field (2 years)	Brackish water	E-EMF treatment with water velocity of 0.5 m/s	↑ chlorophyll, ↑ antioxidants, ↓ lipid peroxidation	Yield ↑ 2–13%, Water use efficiency ↑	n = 3; Stats: Yes; Control: Yes	[126]
Jujube	Field (3 years)	Fresh water	MF treatment (Q = 1666.67 mL/s, 1–2 passes) + Microbial organic fertilizer	Bulk density ↓ 3.07–11.04%, porosity ↑ 1.97–14.75%, water-holding capacity, enzyme activity, and aggregate stability improved	Yield ↑ 3.66–21.38%; fruit quality improved	n = 3; Stats: Yes; Control: Yes	[63]
Cotton	Field	Brackish water	Magnetized-ionized brackish water + organic/inorganic fertilizer.	Water retention and salt leaching improved; soil physicochemical properties and microbial diversity improved	Cotton growth and yield improved	n = 3; Stats: Yes; Control: Yes	[75]
Wheat	Field (2 seasons)	Saline-soil conditions	MF-treated irrigation water and seeds + compost/urea	Soil pH and EC ↓, nutrient uptake and grain quality improved	Grain and straw productivity improved. MW alone: grain yield ↑ 65–82% relative to respective untreated controls.	n = 4; Stats: Yes; Control: Yes	[78]

Note(s): ↑ indicates an increase, and ↓ indicates a decrease. Reported yield and water productivity responses are relative to non-EMF controls within each study and are not directly comparable across experiments due to differences in study scale, crop, salinity, irrigation regime, and EMF exposure. Q = water flow rate; n = number of experimental units per treatment; NR = not reported. Statistical analysis and control conditions are indicated where available but do not imply that all treatment comparisons were statistically significant. Water productivity values based only on applied irrigation should be interpreted as irrigation water productivity rather than evapotranspiration-based crop water productivity. Selected representative studies are presented to illustrate the development and variability of MF/EMF irrigation research; the table is not an exhaustive compilation of published studies.

EMF-treated irrigation water has been associated with increased plant height, leaf area, chlorophyll content, and stomatal conductance across cereals, vegetables, and fruit crops [20,30,35,73,78,115,116,127]. Elevated chlorophyll and carotenoid concentrations suggest improved photosynthetic capacity and stress tolerance, commonly linked to improved root-zone moisture availability and enhanced uptake of potassium, calcium, and magnesium [20,21,34,99,117,124,128–130]. Under saline conditions, EMF-treated systems frequently exhibit reduced sodium accumulation in shoots and improved nutrient uptake, mitigating ion toxicity and supporting metabolic function [74,92,114,131]. Several investigations also report increased antioxidant enzyme activity and phenolic compound production in plants irrigated with EMF-treated water under osmotic or abiotic stress, indicating modulation of plant defense pathways (e.g., elevated peroxidase and polyphenol oxidase activity and greater total phenolic content relative to untreated irrigation) [101,125,128,132,133]. Evidence from a pulsed magnetic field pretreatment study further indicates that magnetic exposure can selectively modulate enzyme activities, enhancing antioxidant and stress-related enzymes while downregulating specific hydrolytic enzymes during early development, consistent with metabolic reprogramming rather than uniform stimulation [101]. These physiological responses may arise partly from changes in soil moisture, salinity, and rhizosphere conditions; however, current evidence is insufficient to establish a direct causal effect of MF-treated irrigation water on plant physiology. Across field and controlled studies, EMF-treated irrigation water has been associated with improved vegetative growth, higher nutrient uptake, and reduced sodium accumulation in plant tissues under saline or unconventional water conditions, contributing to yield stabilization and stress mitigation [21,74]. Reported yield increases, with the largest benefits observed for salt-sensitive crops and under moderate salinity where root-zone electrical conductivity is effectively reduced [87].

Recent two-year field experiments using magnetoelectric brackish water further demonstrate that E-EMF conditioning enhances crop physiological performance and water productivity under arid, saline conditions. Compared with untreated brackish water, magnetoelectric treatment increased chlorophyll content by ~1.4–8.5%, enhanced photosynthetic efficiency, reduced lipid peroxidation (malondialdehyde ↓ by ~2–10%), and increased antioxidant enzyme activities (peroxidase, catalase, and superoxide dismutase ↑ by ~2–17%). These physiological improvements translated into greater dry matter accumulation (↑ ~3–22%), higher yields (↑ ~2–13%), and improved water use efficiency, with optimal irrigation quotas under E-EMF-treated brackish water lower than those required for yield maximization under untreated brackish irrigation [126].

Yield increases ranging from approximately 10% to over 40% have been reported in selected studies investigating MF- and E-EMF-treated irrigation water, with the largest gains reported in certain studies under saline or unconventional water conditions [30,74,84,87,98,130]. Improved biomass accumulation and fruit yield are generally associated with reduced root-zone salinity, enhanced nutrient availability, and improved soil moisture distribution. Under moderately saline irrigation, MF-treated systems often maintain yields comparable to freshwater controls by alleviating osmotic stress and improving ionic balance [74]. In contrast, when salinity exceeds crop tolerance thresholds, EMF treatment alone is insufficient to prevent yield decline, underscoring the continued need for partial desalination or blending strategies. Yield responses are crop-specific and strongly influenced by soil texture and drainage, with salt-sensitive crops benefiting most when EMF-induced redistribution effectively lowers electrical conductivity in the rooting zone. Salt-sensitive crops (e.g., vegetables and fruit trees) generally exhibit stronger relative responses to EMF-treated irrigation water than salt-tolerant cereals and forage crops, reflecting greater benefits from reductions in root-zone EC and improved nutrient balance. In contrast, halophytic or moderately salt-tolerant species tend to show smaller proportional gains, suggesting that EMF

conditioning primarily mitigates osmotic and ionic stress rather than enhancing intrinsic salt tolerance.

Beyond growth and yield, horticultural applications require evaluation of marketable produce quality. Putti et al. [134] reported approximately 35% lower blossom-end rot incidence in greenhouse tomatoes irrigated with E-EMF treated water, whereas increased fruit soluble solids were associated with fertigation dose rather than water treatment alone. Mohamed et al. [135] reported an 80.9% increase in strawberry yield under MF treatment (0.63 T) in tower aeroponics compared with untreated water in the same system. The treatment also produced the highest soluble solids (10.20 °Brix) and lowest titratable acidity (0.74%) in the second season. However, fruit firmness varied across cultivation systems and treatments, with the highest value (0.89 kg cm^{-2}) observed under untreated water in the nutrient film technique hydroponic system. Under saline irrigation, El Omari et al. [136] observed differences in tomato fruit weight, firmness, and juice content following MF treatment, although the approximately 10% increase in yield was not statistically significant. Beyond fruit-producing crops, MF- and E-EMF-treated nutrient solutions have also been investigated in soilless leafy vegetable production. In hydroponic arugula, Téllez et al. [137] reported increases of 36% and 25% in shoot fresh and dry mass, respectively, under MF treatment, whereas E-EMF treatment increased tissue Mg, Mn, and Fe concentrations without comparable biomass improvements. Root-associated algae incidence decreased from 56% in the control to 34% and 22% under MF and E-EMF treatments, respectively. Similarly, Téllez et al. [138] reported increases of 26% and 30% in lettuce shoot fresh and dry mass under MF treatment, compared with 18% and 24% under E-EMF treatment, although tissue nutrient concentrations did not differ significantly from the control. These findings suggest potential benefits for horticultural crop productivity and selected quality attributes, although responses vary across treatments and cultivation systems, while evidence on nutrient-solution chemistry, postharvest shelf life, and commercial-scale performance remains limited.

Improved water productivity defined as yield per unit of applied water is among the most practically relevant outcomes of EMF-treated irrigation. Several field studies report maintenance or enhancement of yield under reduced irrigation volumes, indicating more efficient utilization of soil moisture [20,34,74,87,98]. These gains are attributed to expanded wetted soil volume, improved lateral water movement, and enhanced root access to available moisture, particularly under drip irrigation where MF conditioning may reduce localized drying and salt accumulation near emitters. However, many studies estimate water productivity based solely on applied irrigation and yield, without accounting for evapotranspiration or drainage losses [139]. Such estimates should be interpreted as irrigation water productivity rather than direct evidence of improved crop water use efficiency, because changes in soil-water storage and deep percolation may contribute to the apparent gains. Future studies should distinguish irrigation water productivity (yield per unit of applied irrigation) from evapotranspiration-based crop water productivity (yield per unit of actual crop evapotranspiration) and, where feasible, quantify irrigation, precipitation, evapotranspiration, soil-water storage changes, runoff, and deep percolation through a complete field water balance. Irrigation water productivity responses to MF conditioning vary across crops and experimental conditions, with improvements of approximately 27.4–42.8% reported for cotton under specific magnetic irrigation conditions in Xinjiang [87]. Favorable soil and crop responses were observed at an MF strength of approximately 0.3 T in certain studies [30,87], although the optimal intensity varies with crop type, soil conditions, water quality, and exposure duration. Nevertheless, MF treatment does not eliminate salinity stress under severe conditions and cannot substitute for desalination or adequate drainage; rather, it functions as a complementary management strategy that enhances water produc-

tivity and yield stability when integrated with appropriate irrigation design and salinity control practices [87].

Functionally, crop responses to EMF-treated irrigation water can be interpreted as enhanced establishment, physiological stress mitigation through improved ionic balance, yield stabilization under moderate salinity, and increased water productivity under deficit irrigation. Importantly, EMF treatment does not eliminate salinity stress but alters its spatial expression within the soil profile, making crop benefits contingent on adequate drainage, appropriate leaching fractions, and integration with complementary management practices.

Despite numerous positive reports, crop responses remain inconsistent. Variability arises from differences in EMF exposure dose, irrigation water chemistry, soil texture, crop species, and experimental scale, with many studies relying on short-term pot or greenhouse experiments that may overestimate field performance. Few investigations quantify long-term impacts on soil salinity or groundwater quality, raising concerns that EMF-induced redistribution may delay rather than resolve salinization when salt export through drainage is insufficient.

5. EMF Treatment in Agricultural Water Reuse Systems: Complementarity with Desalination and Soil Amendments

The distinct mode of action proposed for EMF treatment, together with reported soil and crop responses under selected conditions, raises the possibility that EMF could be evaluated as complementary treatment within integrated water management strategies. The increasing reliance on unconventional water sources for irrigation has intensified interest in treatment strategies that balance water quality improvement, energy consumption, and soil sustainability. Desalination technologies, particularly RO, are widely used for removing dissolved salts from brackish and saline waters, providing reliable control of electrical conductivity and ionic composition [13,140–142]. However, agricultural utilization is constrained by energy demand, membrane fouling and scaling, concentrate disposal, and capital cost, particularly in inland regions lacking brine management infrastructure [14,143–146]. Even when RO permeate is blended with untreated water to achieve crop-appropriate salinity, residual sodicity and trace constituents may continue to affect soil structure and plant performance, highlighting that RO alone may not resolve all constraints associated with unconventional water irrigation [147]. EMF treatment operates fundamentally differently from desalination. EMF does not remove salts or contaminants; instead, it is proposed to influence transport behavior and crystallization kinetics, influencing how water and solutes interact with soils and plant roots [18,25,26]. Consequently, E-EMF should be viewed not as an alternative to desalination but as a complementary conditioning step that may enhance downstream soil performance and irrigation efficiency when partial desalination or blending strategies are employed [32].

Within this context, EMF treatment may provide value by conditioning irrigation water after partial desalination. When applied to blended RO permeate or moderately saline irrigation water, EMF conditioning has been associated with improved wetting behavior, enhanced downward salt transport, and reduced lower surface soil salinity under selected experimental conditions. Reduced surface salt crystallization has also been proposed as a possible consequence of altered precipitation kinetics; however, this mechanism remains unverified in agricultural soils. The observed reduction in surface salinity is more directly consistent with enhanced downward salt redistribution rather than changes in crystallization alone. Importantly, downward salt redistribution does not necessarily indicate net salt removal from the soil profile unless sufficient drainage and leaching occur. EMF has also been proposed as a pre-conditioning step to influence scaling propensity upstream of RO or during concentrate handling by altering crystallization pathways and particle morphology,

potentially reducing mineral attachment to membrane surfaces [27,40,58,148]. While such effects are primarily demonstrated in engineered systems, extension to agricultural RO applications requires validation through controlled fouling experiments and long-term performance monitoring.

Importantly, EMF conditioning may improve the soil compatibility of partially desalinated waters. Blended irrigation waters often retain elevated sodium adsorption ratios even when total salinity is reduced [3]. EMF-treated irrigation water has been reported to facilitate downward migration of sodium and improve ion balance in plant tissues, suggesting potential benefits for sodicity management when combined with adequate calcium supply and drainage [30,32,74]. The most promising role of EMF-treated irrigation water is within integrated water reuse frameworks that combine engineered treatment with soil rehabilitation practices. In such systems, partial desalination or blending reduces bulk salinity to crop-tolerable levels, EMF conditioning may influence transport behavior and surface salt accumulation, and soil amendments, particularly compost or organic matter, enhance aggregation, cation exchange capacity, and microbial activity. Together, these components act synergistically to improve root-zone conditions, nutrient availability, and water productivity [32,75,113,114].

Implementation of EMF within agricultural reuse systems requires careful consideration of exposure configuration, flow rate, and water chemistry. Treatment effectiveness depends on cumulative EMF dose, defined by field strength, residence time, and hydraulic conditions, while placement upstream of irrigation emitters enables continuous conditioning in drip or micro-irrigation systems. However, variability in device design and inconsistent reporting of operational parameters complicate comparison across studies, underscoring the need for standardized exposure metrics. EMF-induced salt redistribution must also be evaluated alongside drainage capacity and leaching fraction to avoid unintended accumulation in subsoil horizons or groundwater [3,18,26].

EMF devices are generally low energy, non-chemical conditioning technologies whose primary value lies in enhancing the performance of existing water treatment and irrigation infrastructure rather than replacing conventional treatments such as RO [14,26]. However, direct engineering-economic comparisons among standalone desalination, desalination coupled with EMF, and integrated desalination–EMF–soil amendment systems remain limited. While standalone RO involves substantial capital and energy requirements associated with pressurization, membrane replacement, fouling control, and concentrate management, hybrid systems introduce additional EMF and soil-amendment costs that may potentially be offset by reduced scaling, improved soil compatibility, enhanced crop productivity, or lower irrigation demand. These potential benefits have not yet been evaluated consistently within a common economic framework. Accordingly, future techno-economic and life cycle assessments should compare capital and operating costs, specific energy consumption, concentrate management requirements, amendment costs, crop productivity and water use benefits, greenhouse gas emissions, and long-term soil rehabilitation needs across desalination–only, desalination–EMF, and integrated desalination–EMF–soil amendment systems.

Beyond engineered desalination, soil-based interventions remain critical to the long-term success of agricultural water reuse. Within this context, EMF-treated irrigation water may offer practical value as a low energy conditioning approach integrated with partial desalination, soil amendments, and precision irrigation, rather than as a standalone treatment. By potentially influencing transport processes that influence salinity expression and nutrient availability, EMF can improve the soil compatibility of unconventional waters and support resilient crop production, while desalination remains essential where salinity exceeds crop tolerance thresholds. Further research should evaluate the effects of MF/E-EMF conditioning on fertigation chemistry, nutrient precipitation, and nutrient use

efficiency in recirculating systems, alongside long-term fruit quality and salinity responses in perennial crops.

The performance of EMF treatment depends strongly on salinity level, soil drainage, crop sensitivity, and irrigation design; implementation requires site-specific evaluation rather than universal application [30–32]. In particular, EMF treatment may provide greater benefit under selected salinity and soil conditions where salt redistribution and improved wetting behavior may alleviate root-zone stress, whereas severe salinity conditions may still require desalination or blending strategies. Figure 2 presents a conceptual decision-support framework illustrating conditions under which EMF treatment may function as a potential complementary conditioning approach or as part of integrated salinity management strategies. The salinity risk categories are informed by FAO irrigation water quality guidelines [3], while management decisions should additionally consider crop-specific salinity tolerance, initial soil salinity, soil texture, and drainage conditions. Importantly, irrigation water electrical conductivity (ECw) and soil saturated-paste extract electrical conductivity (ECe) represent distinct measurements and should not be directly interchanged when evaluating salinity risks.

The most promising future application of EMF technologies lies within integrated agricultural water reuse systems that combine partial desalination, physical water conditioning, soil amendments, and precision irrigation strategies. In such systems, desalination or blending reduces bulk salinity, EMF treatment may influence transport and crystallization behavior, and soil amendments improve buffering capacity, aggregation, and nutrient retention. Potential soil amendments include compost or other organic matter, gypsum for managing sodicity-related soil constraints, and biochar for improving selected soil physical and chemical properties [149–154]. Although these amendments have established applications in soil management, their combined performance with MF/E-EMF-treated irrigation water remains insufficiently evaluated. Therefore, their inclusion in Figure 3 represents proposed integrated management strategies rather than experimentally validated synergistic treatments. Figure 3 illustrates a conceptual framework integrating these complementary approaches to enhance the sustainability and soil compatibility of unconventional irrigation water reuse. Evaluation of this concept requires replicated, multi-season field studies comparing integrated and individual treatments while quantifying water quality, soil salinity and sodicity, crop response, water balance, energy requirements, operational costs, and economic feasibility. Such evaluations should also distinguish root-zone salt redistribution from actual salt export by quantifying subsurface salt accumulation, drainage-water flux and salinity, and potential groundwater impacts.

6. Research Gaps, Priorities, and Future Directions

Despite numerous laboratory and greenhouse studies reporting positive effects of EMF-treated irrigation water, translation to field-scale agricultural systems remains limited and inconsistent. Reported outcomes vary widely, reflecting strong dependence on EMF exposure parameters, irrigation water chemistry, soil properties, crop species, and experimental scale. This variability represents a primary barrier to broader adoption and scientific acceptance [82,84,155]. A fundamental limitation is the inconsistent reporting of EMF treatment conditions, which severely constrains reproducibility and meaningful cross-study comparison [25]. Addressing this limitation requires standardized reporting of treatment and experimental conditions, as discussed below.

Soil texture, mineralogy, and irrigation water chemistry strongly mediate EMF responses [33]. Enhanced wettability and lateral water redistribution observed in sandy loam and loam soils may not translate to coarse sands dominated by gravitational drainage or to fine-textured clays prone to dispersion [31,82,83,90]. Similarly, ionic strength, alkalinity,

calcium concentration, and sodium adsorption ratio (SAR) govern both salinity expression and soil structural stability, leading to context-dependent EMF effects [33,60,89]. Studies that do not characterize baseline soil and water properties risk attributing observed responses to EMF when they may reflect inherent physicochemical variability.

Long-term sustainability remains insufficiently addressed. EMF-treated irrigation water commonly promotes downward redistribution of salts, reducing root-zone electrical conductivity in the short term. Without adequate drainage, however, salts may accumulate in subsurface horizons or groundwater [3,156,157]. Few investigations quantify salt mass balance or groundwater quality over multiple seasons, leaving cumulative impacts unresolved. Without sufficient drainage and salt export, EMF-induced redistribution may delay rather than prevent soil salinization, potentially shifting salinity risk from the surface to subsoil or groundwater compartments.

Economic considerations are also underexplored. Although EMF devices are generally low-cost and energy-efficient, their agronomic value depends on consistent field performance [26]. Comprehensive techno-economic analyses comparing desalination-only systems with integrated desalination-EMF-soil amendment frameworks are largely absent, limiting assessment of cost-effectiveness and scalability.

Publication bias toward positive outcomes complicates objective evaluation of EMF efficacy. Negative or null-result studies are rarely reported, skewing perception of effectiveness. Coordinated multi-site trials with standardized protocols and transparent reporting, including unsuccessful cases, are required to establish evidence-based guidance. Collectively, these limitations indicate that future progress requires hypothesis-driven, field-validated research integrating soil, plant, and water system processes.

The lack of standardized reporting represents a primary barrier to translating EMF treatment from experimental studies into a reliable and reproducible agricultural practice. Establishing minimum reporting standards for EMF-treated irrigation studies is therefore a critical priority. At a minimum, publications should document field strength, device geometry, exposure length, flow rate, residence time, and whether treatment is continuous or intermittent, as these parameters collectively define EMF exposure dose. Without consistent reporting of these parameters, treatment conditions cannot be reliably reproduced or compared across studies, limiting quantitative assessment of dose–response relationships and the development of evidence-based operating guidelines. Comprehensive characterization of irrigation water chemistry (EC, pH, alkalinity, major ions, SAR, boron, and dissolved oxygen) and soil properties (texture, bulk density, initial EC and SAR, organic matter content, carbonate presence, and drainage class) is equally essential to enable interpretation and reproducibility. Treatment-to-application time should also be reported, particularly when evaluating the persistence of post-treatment effects.

Across the reviewed studies, changes in soil wetting and solute redistribution are more frequently reported, whereas improvements in nutrient availability and crop water productivity remain context-dependent and are supported by more limited evidence. Proposed molecular-scale mechanisms remain insufficiently verified, and long-term field-scale monitoring is limited. Targeted mechanistic experiments are needed to directly test hypothesized pathways. Controlled soil column studies should quantify ion breakthrough behavior, wetting front geometry, and mineral precipitation patterns to clarify whether EMF primarily affects infiltration, solute mobility, or crystallization kinetics. Particular attention should be given to determining whether persistent soil responses are associated with altered mineral nucleation, crystallization, or precipitation kinetics rather than transient changes in bulk water properties. At the plant scale, measurements of root hydraulic conductivity and ion transport under controlled salinity can help distinguish soil-mediated effects from potential direct influences on water uptake.

To address the experimental-scale and replication limitations identified above, robust evaluation requires replicated, multi-season field trials across diverse soil textures, salinity levels, and climatic regimes. These trials should include monitoring of soil electrical conductivity and ion profiles with depth, crop yield components, and water balance metrics, with particular attention to sodicity indicators, aggregate stability, and infiltration. Integration with drainage assessment and groundwater monitoring is necessary to evaluate the sustainability of EMF-induced salt redistribution.

Given the prospective role of EMF within integrated agricultural water management systems discussed in Section 5, future studies should evaluate whether EMF provides measurable complementary benefits when combined with established treatment and management approaches. Comparative evaluation of desalination-only, EMF-only, and combined blended water from desalination-EMF configurations can quantify effects on soil salinity dynamics and crop performance, while RO-based configurations can additionally be evaluated for membrane fouling. Coupling these approaches with compost or organic amendments offers additional opportunity to enhance cation exchange capacity, microbial activity, and soil buffering. Lifecycle and techno-economic assessments are needed to compare energy use, greenhouse gas emissions, operational costs, and agronomic benefits across standalone and hybrid treatment strategies.

Finally, emerging precision irrigation technologies provide powerful tools for evaluating EMF-treated systems. High-resolution soil moisture and electrical conductivity sensors, combined with remote sensing and automated irrigation control, enable real-time tracking of wetting fronts and salinity redistribution, moving evaluation beyond endpoint measurements such as yield alone. Future research could also explore multi-objective decision-making approaches to evaluate trade-offs among irrigation efficiency, drainage and salt management, nutrient retention, energy consumption, and economic feasibility in integrated EMF-based agricultural water management systems.

7. Conclusions

EMF-treated irrigation water has been reported to influence soil–plant systems primarily by modifying transport processes rather than altering bulk water chemistry. Reported responses include improved soil moisture distribution, salt redistribution below the root zone, potential improvements in nutrient availability, and crop water productivity gains under selected experimental conditions, although evidence for these agronomic benefits remains limited and context dependent. Overall, the available evidence is stronger for macroscopic responses, such as altered wetting and solute redistribution, than for proposed molecular-scale mechanisms involving persistent changes in water structure or ion hydration. Importantly, these macroscopic responses cannot necessarily be attributed exclusively to EMF treatment. Established soil processes, including infiltration and capillary flow, soil texture and mineralogy, ion exchange, carbonate and mineral precipitation, drainage, and conventional solute transport, may provide alternative or complementary explanations for some of the reported observations.

Accordingly, EMF should be considered a complementary low energy conditioning approach rather than a replacement for desalination when irrigation water salinity exceeds crop tolerance thresholds, with its potential to improve the soil compatibility of partially desalinated or blended waters by influencing wetting behavior, ion mobility, and crystallization pathways. When integrated with partial desalination and soil amendments, EMF-treated irrigation water may provide a prospective systems-level approach that warrants further evaluation for improving salinity management in agricultural irrigation.

Despite encouraging laboratory and greenhouse results, field-scale evidence remains limited. Variability in EMF exposure parameters, soil properties, water chemistry, and ex-

perimental design, combined with limited long-term monitoring, constrains reproducibility and deployment. Moreover, root-zone salinity reductions associated with downward salt redistribution under EMF-treated irrigation raise sustainability concerns under inadequate drainage, underscoring the need for salt mass balance assessment. Nonsignificant or negligible treatment responses have also been reported under certain experimental conditions, highlighting the context-dependent nature of EMF efficacy.

Advancing EMF-treated irrigation water toward reliable application will require standardized reporting of EMF exposure (including field strength, flow rate, and exposure duration where applicable), transparent documentation of experimental controls and replication, mechanistic experiments linking treatment to soil transport processes, and replicated multi-season field trials across diverse agroecological contexts. Together, these priorities directly address the key limitations identified in this review by resolving uncertainties in MF/E-EMF mechanisms, improving experimental reproducibility and comparability, and strengthening field-scale validation. Integrated evaluation of EMF, desalination, and soil rehabilitation strategies supported by precision irrigation and digital monitoring will be essential to quantify agronomic benefits, environmental trade-offs, and economic feasibility. Within appropriately designed reuse frameworks, EMF-treated irrigation water may contribute to more efficient unconventional water use; however, its long-term agronomic benefits and practical significance require further field-scale validation.

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