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Review

Thermal Desalination Technologies and Electromagnetic-Field-Assisted Approaches for Seawater Treatment: A Comprehensive Review

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Abstract

Seawater desalination has become a critical approach to mitigating the global scarcity of freshwater resources. This study aims to comprehensively review desalination methods based on thermal and electromagnetic methods, examining their processes, benefits, and limitations. Thermal methods include multi-stage flash distillation, multi-effect distillation, thermal vapor compression, and mechanical vapor compression. These techniques rely on evaporation and distillation to remove salts and are effective in treating highly saline water. However, they consume large amounts of energy and are prone to problems such as limescale and corrosion. In contrast, electromagnetic-based technologies represent a novel, promising approach for enhancing desalination performance. Electromagnetic fields contribute to improved membrane performance and equipment longevity by modulating ionic behavior and mitigating surface fouling. Empirical studies suggest that such interventions can lead to reduced energy usage and lower rates of mineral deposition. The findings reviewed here suggest that integrating thermal and electromagnetic techniques may offer a viable pathway toward more sustainable, efficient, and reduced environmental impacts.

Keywords: seawater desalination; thermal processes; electromagnetic fields; sustainable desalination

1. Introduction

The rising scarcity of fresh water is one of the major issues that have gained worldwide importance, primarily due to the rise in population, urbanization, climate-induced disruptions, and increased water requirements from the agricultural and industrial sectors [1]. Even though the Earth has an ample supply of water, only 2.5% of the total volume qualifies as freshwater, and an even smaller portion is directly usable for human needs [2]. The mismatch between water availability and consumption across time and regions has led to cyclical shortages in many areas, currently affecting around 71% of the global population with moderate-to-severe water stress levels [3,4]. It has been predicted that about 2.2 billion people in 50 countries (mainly located in low and middle-income areas) will be affected by physical water stress by 2050 if the current water consumption trend persists, as illustrated in Figure 1 [5]. In such a context, desalting seawater is increasingly considered an indispensable technical answer [6]. In the wide array of such technologies, thermal desalination and processes based on electromagnetic fields have garnering significant attention of scientists and policymakers due to their unique theoretical foundation and operational advantages. Thermal desalination falls into the first category, one of the most mature and

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widespread techniques, which is based on the phase-transformation phenomena (evaporation/condensation) for the separation of fresh water from saline solutions [7]. Systems such as multiple-effect distillation have seen widespread deployment [8], especially in arid zones such as the Middle East, where historically low energy prices due to ample fossil fuel supplies made these energy-intensive methods more economically viable [9]. The recent advancements in technology have been focused on improving the performance of the desalination plants, especially by increasing the stages of distillation in multi-stage flash systems with the objective of increasing production and minimizing consumption [10]. On the other hand, the use of electromagnetic fields in the purification and desalination of water has been identified as an innovative and promising technique that has been gaining much interest and attention in recent times [11]. By altering the physical and chemical characteristics of water, electromagnetic force has been found to possess considerable promise in descaling, increasing filtration efficiency, and minimizing total energy consumption [12,13]. These advantages make desalination by means of an electromagnetic field a prominent and innovative method for efficient desalination.

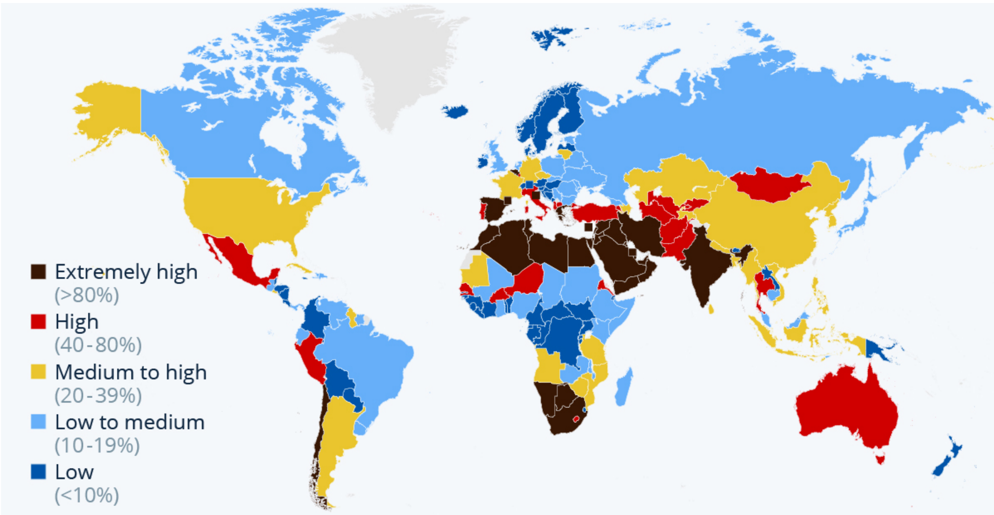

Figure 1. Projected global water stress levels by 2050 [14].

Figure 2 above illustrates the different desalination technologies categorized into four main categories: evaporation and condensation, filtration, crystallization, and electromagnetic processes [15]. Each category groups specific methods for separating fresh water from dissolved salts in salt or brackish water [16]. Here is a brief explanation of each category. Among technologies, evaporation and condensation systems constitute the established approaches for producing freshwater for domestic and municipal purposes. This category includes mechanical and thermal processes that exploit water's phase transition (evaporation and condensation) to produce fresh water [17,18]. Mechanical processes include mechanical vapor compression, which uses a heat pump to compress water vapor, increasing its energy efficiency [19]. In the thermal processes category, multiple-effect distillation is a widely used technique where heat is reused through multiple stages to reduce energy consumption [20]. Another example is multi-stage flash distillation (MSF), which uses variable pressures to induce water evaporation, often employed in large industrial facilities [21]. Solar distillation is an eco-friendly method that uses solar radiation for the evaporation and condensation of water, which makes it an appropriate method for small-scale setups in remote areas [22,23]. Humidification–dehumidification (HDH) techniques also involve the integration of the processes of humidification and dehumidification for the production of freshwater, often using renewable sources of energy [24]. A solar chimney uses solar energy to create an upward flow of air within the chimney, which is then used for the processes of evaporation and condensation within a closed loop [25,26]. Thermal vapor compression techniques improve the efficiency of evaporation by compressing the vapor, which helps to reduce the energy consumption [27]. Membrane distillation (MD) is a thermally driven separation process in which a porous hydrophobic membrane allows only water vapor to pass through its pores under a vapor pressure gradient induced by a temperature difference, while liquid water and non-volatile solutes are retained [28]. Filtration technologies use membranes or other filter materials to separate dissolved salts from water [29]. The above techniques show high effectiveness and are often employed [30]. Reverse osmosis (RO) is a pressure-driven membrane process that is often utilized for seawater treatment. During the process, seawater with high salinity is subjected to pressure and forced to pass through a semi-permeable membrane. The membrane is a selective barrier that allows water molecules to pass through while rejecting other impurities.

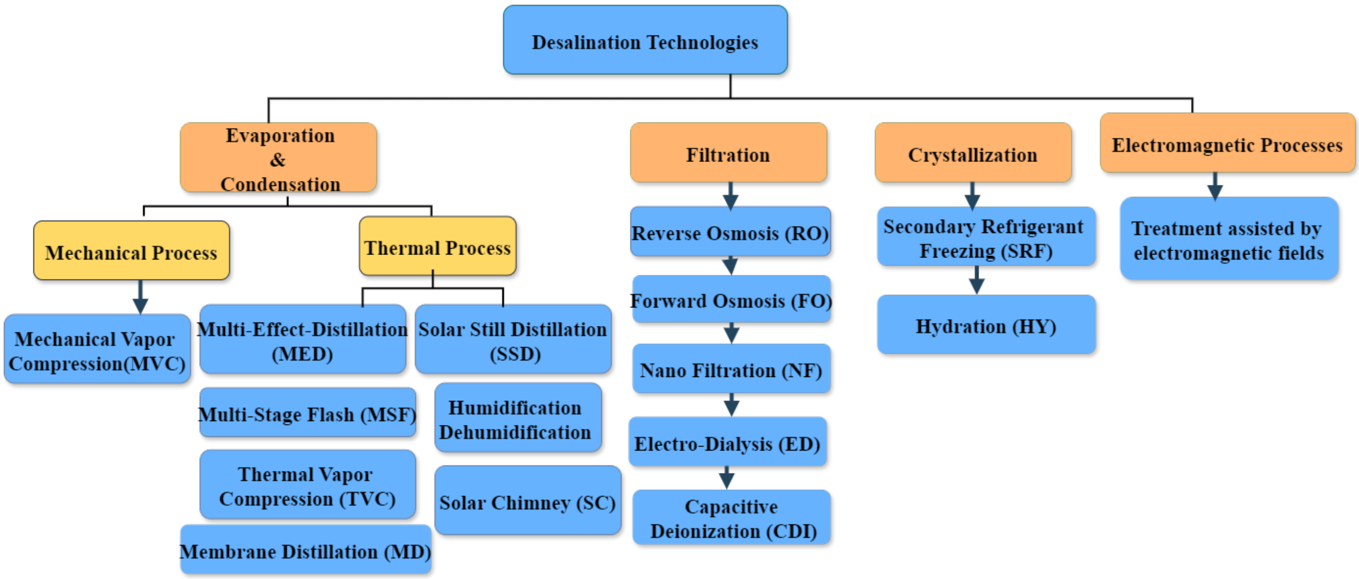

Figure 2. Fundamental methods of desalination [15].

For proper functionality and membrane integrity, RO systems require proper treatment of feedwater, which is often necessary to avoid fouling and scaling, as well as periodic replacement of the membranes. In addition, proper treatment of the brine solution generated during the process is also important, as improper handling can cause environmental problems [31]. Forward osmosis is an alternative form of reverse osmosis that is considered low-energy technology. It involves the use of an osmotic pressure gradient for the removal of water [32]. Nanofiltration is similar to reverse osmosis but with larger pores that are capable of passing ions but rejecting other larger molecules [33]. The use of an ion exchange resin involves the substitution of dissolved salts with other ions. It is mainly used as a pre- or post-treatment [34]. Crystallization involves the precipitation of salt crystals from the solution. The final product obtained is pure and clean water [35]. The secondary refrigerant freezing method involves the freezing of the solution and precipitation of salt crystals, this method is mainly used in special situations [36]. The electromagnetic method involves the use of electromagnetic fields that improve the efficiency of the separation of salt and water. It is also used for the prevention of scaling [37]. The goal of the process of desalination by an electromagnetic field is to change the behavior of water ions and molecules, thus improving the separation process efficiency and reducing the scaling phenomenon [38]. Although membrane-based processes, especially reverse osmosis, are dominant in contemporary commercial seawater desalination processes, this review deliberately limits its scope to thermal and electromagnetic field-based processes, which are still significantly underrepresented in the contemporary scientific literature [39]. The thermal methods of desalination have been well established and continue to benefit from the advancements of technology, but they have the disadvantage of being energy-intensive and susceptible to problems of sedimentation and contamination [40]. On the other hand, the electromagnetic field-enhanced method of desalination has not yet left the experimental stage, but the results of some pilot studies have been very promising. For example, some of the latest research has revealed the possibility of an increase of up to 10% in the rate of flux of the filtrate in electromagnetic-field-enhanced membrane distillation processes, along with an improvement of 13% in the recovery of water and a significant decrease in the rate of flow during the reverse osmosis pretreatment [41]. The main research gap addressed by this review is the lack of comprehensive analysis and comparison of the results of the conventional thermal methods of desalination and the new electromagnetic-field-enhanced methods of the process. For example, existing research has not often compared the energy consumption of the two methods, their scalability, or their technical and economic viability, or the possibility of the integration of electromagnetic fields into the conventional thermal processes of desalination, such as multi-effect distillation processes or multi-stage flash evaporation processes. By conducting a rigorous benchmarking assessment of electromagnetically assisted heat-based desalination across key performance indicators including energy efficiency, sludge reduction, water production cost, and applicability to highly saline seawater, this review aims to provide a current and future perspective to guide both academic research and industrial application towards more sustainable hybrid desalination systems.

2. Thermal Desalination Methods

2.1. Multi-Effect Distillation

Multi-effect distillation operates on the principle of successive water evaporation in several effects or chambers of decreasing pressure, each chamber reusing the heat of condensation from the previous one to evaporate more water [42]. This process reduces energy consumption compared with simple distillation while achieving high desalination rates [43,44]. The underlying principle of the multi-effect distillation process is illustrated in Figure 3, which shows the system's basic configuration and operational sequence [45].

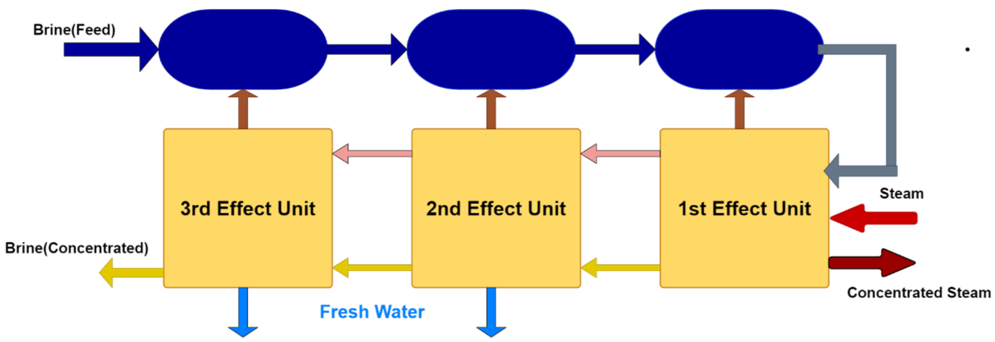

Figure 3. Typical schematic diagram of multi-effect distillation [46].

2.2. Multi-Stage Flash

Multi-stage flash distillation is a thermal process in which heated seawater is introduced into a series of chambers at decreasing pressure, causing it to evaporate instantly (flash) and condense this vapor to obtain fresh water [47]. Each chamber uses the latent heat of condensation from the previous stage, improving energy efficiency [48]. Figure 4 provides a detailed representation of the configuration and operating principles of a multi-stage flash desalination unit, enhancing the understanding of the process.

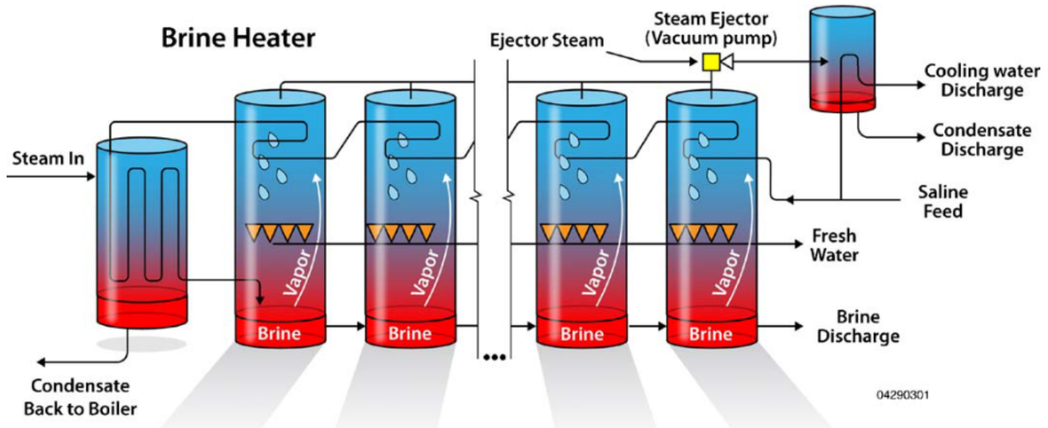

Figure 4. Typical schematic diagram of multi-stage flash distillation [49].

2.3. Vapor Compression

The vapor compression process is based on the principle that steam produced during evaporation can be mechanically compressed, raising its temperature and pressure [50,51]. The resulting high-energy vapor is then employed to transfer heat to the incoming saline feedwater through a heat exchanger, sustaining a continuous cycle of evaporation and condensation that leads to freshwater production [52]. In practical applications, vapor compression can be implemented through two main approaches, with some systems combining features of both. Figure 5 presents the first method, illustrating the configuration and functional operation of a desalination unit based on mechanical vapor compression.

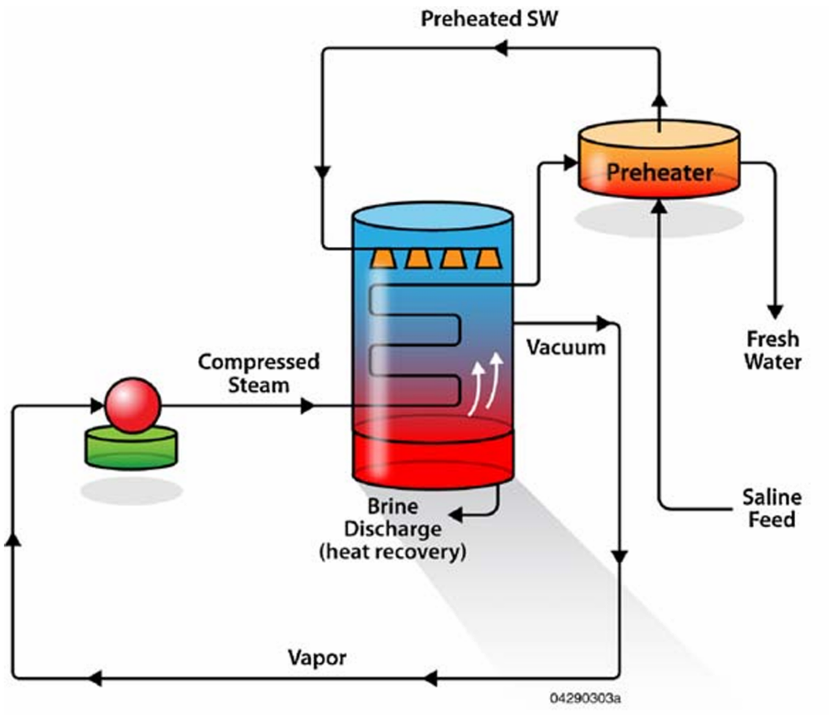

Figure 5. Mechanical vapor compression desalination [53].

Mechanical vapor compression (MVC) is a thermal desalination method based on the principle of liquid-vapor phase transition [54]. It functions through direct mechanical compression of vapor arising from the evaporation of seawater, thus increasing the pressure and temperature of the vapor [55]. The condensed vapor is used to preheat the incoming saline brine with a heat exchanger to produce further evaporation [56]. Such technology is widely used in stand-alone or hybrid systems for small-scale to medium-scale fresh water production. At the beginning of the MVC cycle, the saline feed water is pumped into the evaporation chamber, where it is partially vaporized [57]. The vapor produced is drawn off and transferred into a mechanically driven compressor, usually using electrical means, where it is compressed to an increased pressure and temperature [58]. This high-energy vapor is, in turn, recycled to heat the incoming saline water by means of a heat-exchanger, thus setting up a flow of evaporation and condensation [59]. Fresh water is obtained when the compressed vapor has given up its heat. A recovery heat exchanger is often added to increase the global efficiency of the systemeven further. The residual heat of the brine discharge and the distilled fresh water is conveyed by this part to preheat the saline inlet feed water [60]. The preheating requirement of external energy for vaporization may be minimized by this preheating, and is sometimes followed by contacting the feed with a recycle brine stream for enhanced heat exchange performance. The thermal vapor compression unit uses the same strategy reported in Figure 6.

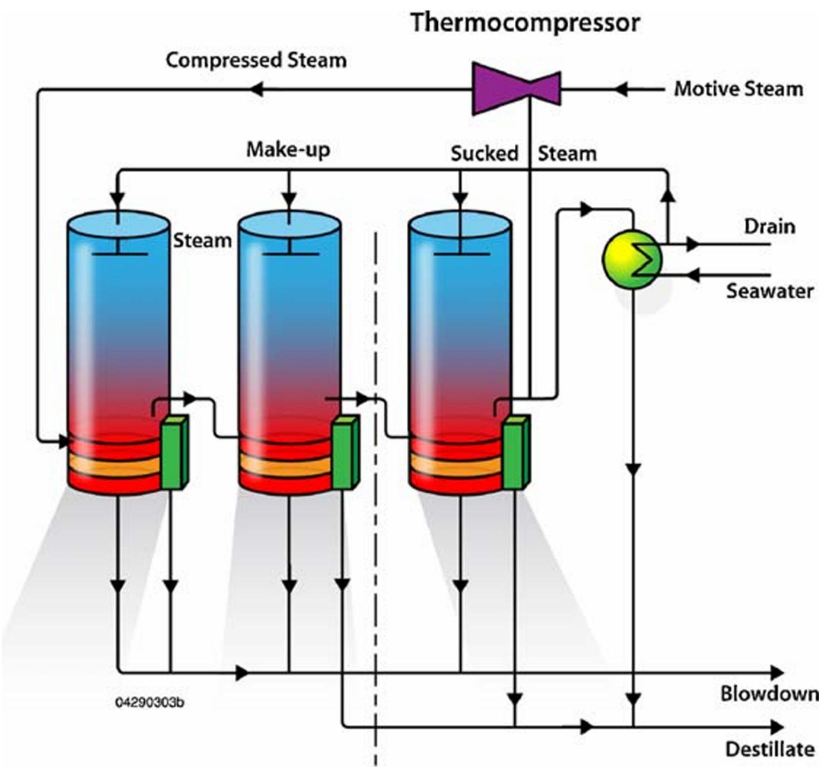

Figure 6. A conceptual schematic of a thermal vapor compression desalination unit [61].

The primary distinction in the process of increasing vapor pressure lies in the methods employed. The thermal vapor compression process utilizes a thermal compressor, typically powered by high-pressure steam that is often reclaimed as waste from power generation facilities. Thermal vapor compression (TVC) systems rely on the integration of both thermal and electrical energy sources. The thermal energy powers the compression process, while electrical energy runs auxiliary components such as circulation pumps. In practical applications, TVC is often combined with multi-effect distillation systems, creating a hybrid setup known as a MED-TVC desalination plant, as shown in Figure 7.

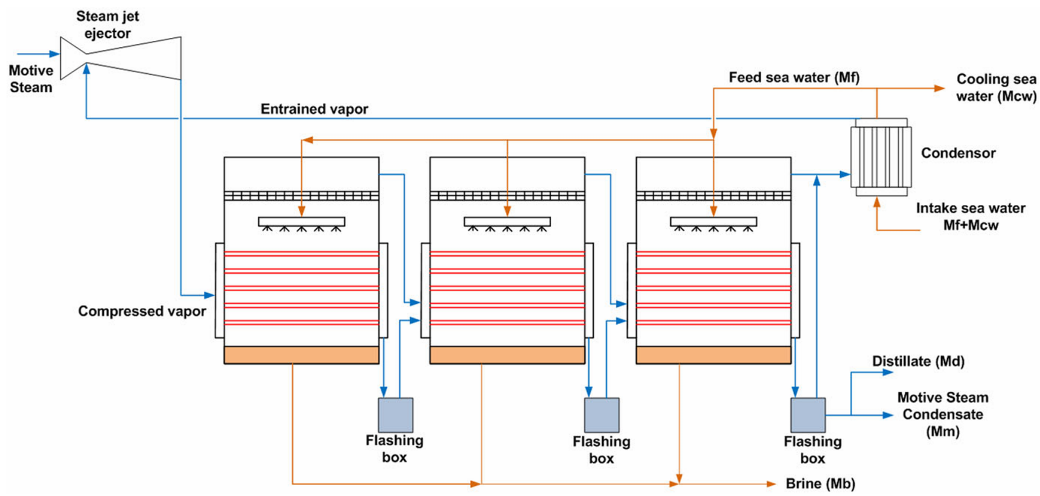

Figure 7. A simplified schematic illustrating the configuration of a MED-TVC unit [62].

3. Advantages and Limitations of Selected Desalination Methods

Table 1 provides a comparative overview of various thermal desalination technologies, including MED, MSF, TVC, MVC, and MED-TVC hybrid systems [63].

Table 1. Advantages and limitations of thermal desalination technologies.

Technology	Advantages	Limits	Ref.
Multi-Stage Flash (MED)	– High operational stability – Significant industrial capacity – Adaptation to very salty waters – Long life and low maintenance	– High thermal consumption – High initial investment – Sensitive to mineral deposits – Environmental impact	[64,65]
Multi-Stage Flash (MSF)	– Integrates heat recovery and heat rejection units, enabling latent heat reuse and improved efficiency – Minimal tendency for plugging and scaling – Suitable for high-salinity feed water	– Requires significant thermal energy input – More susceptible to scaling/corrosion than MED – High operational costs (expensive water production)	[66,67]
Thermal Vapor Compression (TVC)	– Efficient use of thermal energy via high-pressure steam – Suitable for large-scale industrial projects – Can be coupled with waste heat sources (e.g., power plants)	– Requires reliable high-pressure steam supply – More complex maintenance for hybrid configurations – High initial capital cost	[68]
Mechanical Vapor Compression (MVC)	– Compact stand-alone systems (100–3000 m^3/day) – Reduced energy use via heat exchangers – Produces high-purity water	– Fully dependent on electricity – Scaling and corrosion due to saline-water contact – Limited capacity for very large projects	[69–71]
MED–TVC	– Optimizes energy use by combining MED and TVC – Freshwater recovery efficiencies up to 85% – Treats seawater and brackish water	– High capital cost due to integration – Higher technical complexity (advanced control needed) – Still energy-intensive despite improved efficiency	[72–74]

The comparison presented in Table 1 highlights the inherent compromises of each of these thermal desalination processes, especially in terms of energy efficiency, capital costs, and process complexity. For instance, the multi-effect desalination process is associated with high reliability in operation and maintenance requirements, making the process an ideal candidate in an industrial environment. However, the multi-stage process, applicable in the desalination of highly saline water, still retains the disadvantage of high energy requirements. Similarly, the vapor compression process possesses desirable overall performance; however, the process is restricted by the availability of energy resources coupled with processing capacity. Moreover, the hybrid processes, such as the combination of MED and TVC, possess enhanced efficiency; however, the process is restricted by increased capital costs coupled with technological complexity, making the process require expert skills in operation.

4. Magnetization Method in Water Desalination

The desalination technique using electromagnetic fields involves the application of electromagnetic waves for an alteration in the physicochemical properties of saline water. The application of electromagnetic fields affects the hydrogen bonds between water molecules, reducing the size of the clusters and the surface tension and viscosity of the water [75,76]. The application of electromagnetic fields enhances the evaporation and permeation of water through the membranes [77]. In addition, the electromagnetic fields polarize the dissolved ions, thus optimizing the separation of the ions during the desalination process using electrodialysis or reverse osmosis techniques. Moreover, the application of electromagnetic fields inhibits the crystallization of salts, including calcium carbonate, thus reducing the scaling and fouling of the desalination equipment and thus extending the lifespan of the equipment. Recent studies have shown that the application of electromagnetic fields can reduce the energy consumption in the desalination process by 15–20% compared with the conventional thermal desalination process [78]. Furthermore, electromagnetic fields treatment eliminates the need for chemical antiscalants, contributing to a lower environmental footprint. Despite its promise, this method faces challenges related to high initial costs and the need for parameter optimization tailored to specific aspects.

Each technology is evaluated based on its advantages, such as operational efficiency or adaptability to saline conditions, and limitations, such as high energy consumption or operational costs. The references indicate academic sources that support the described features and challenges of each method. This comparison aids in selecting the appropriate desalination technique depending on factors like scale, energy source, and water salinity [79]. Water compositions and uncertainties are related to long-term performance. The scalability of electromagnetically facilitated (EMF) systems is hindered by the high installation costs and the varying conditions of operation. The benefits of electromagnetic field treatment may also be reduced with long-term use due to various factors. More research is needed to overcome the technical and economic challenges. Figure 8 is a combined conceptual diagram of the desalination system based on the detailed descriptions of the patent submissions by the research team of Khalifa University. The diagram represents the liquid desalination system with a focus on the processes involved in the application of magnetic and electric fields.

Figure 8 shows an example of the liquid desalination system 100, which matches the various embodiments of the invention described above. As can be noted, the system has an inlet 114 for the introduction of saline water 102 into the system 100, which is located along supply line 110. Additionally, the system has an outlet 116 for the discharge of desalinated water 104.

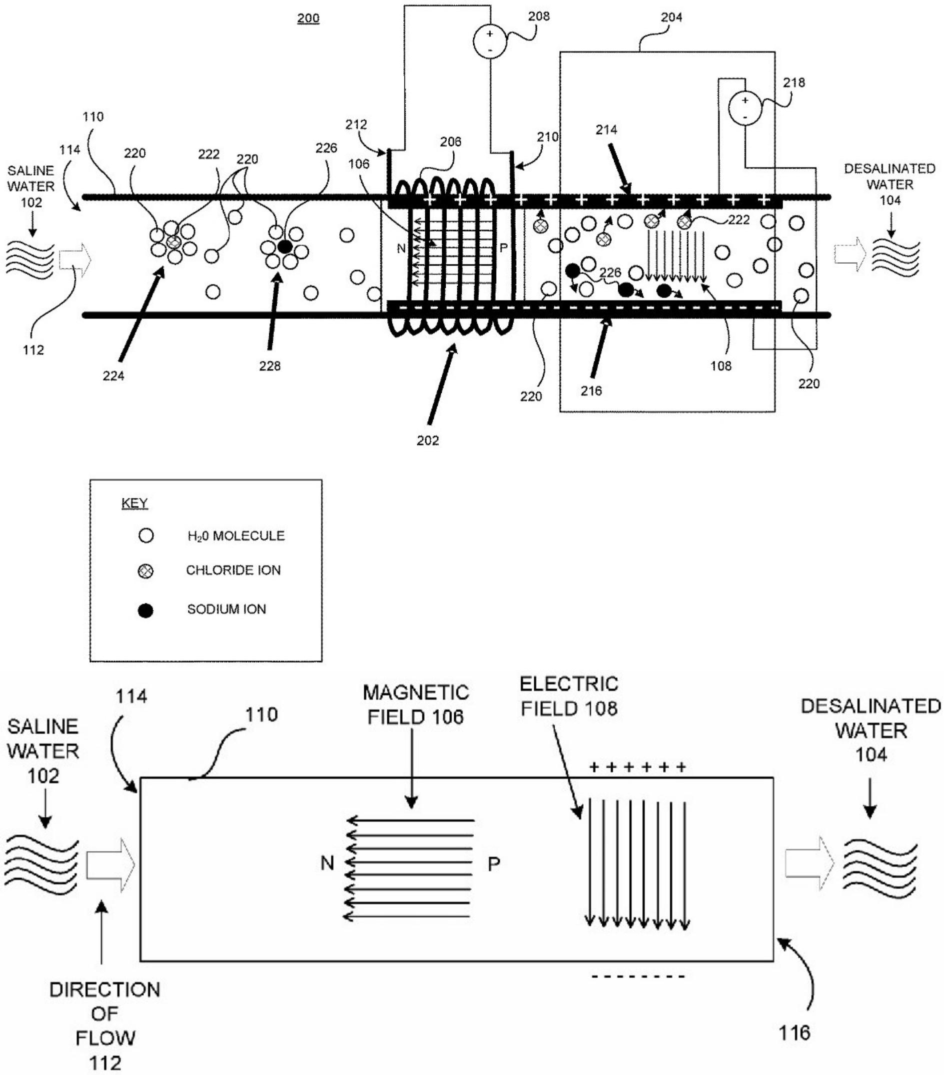

Figure 8. Desalination setup with electrical and magnetic fields [80].

Saline water 102 is subjected to oscillating magnetic field 106, which is applied in the direction opposite to the direction of the flow of the water 102. This helps to separate the ions. The magnetic field weakens the associational bonds between the sodium ions (Na^+) and the water molecules, as well as the associational bonds between the chloride ions (Cl^-) and the water molecules. Next, electric field 108 is applied to the feed line after the saline water has passed the magnetic field. In the electric field, the sodium ions (Na^+) and the chloride ions (Cl^-) are drawn towards the electrodes of the electric field [80]. This is an efficient method for the desalination of water since the outgoing water is free of impurities without the need for any additional components or agents. The presence of the two fields simultaneously is crucial for the optimization of the process for the desalination of water. Figure 9 presents the physical configurations for generating the fields necessary for this process [81]. More precisely, these EMF devices ensure the application of a magnetic field to the saltwater flow, facilitating ionic separation under the effect of Lorentz-type forces. There are typically applied using permanent-magnet arrangement (Figure 9) or solenoid-based configurations Figure 9, each with its own technical specificities and impacts on the efficiency of the process [82].

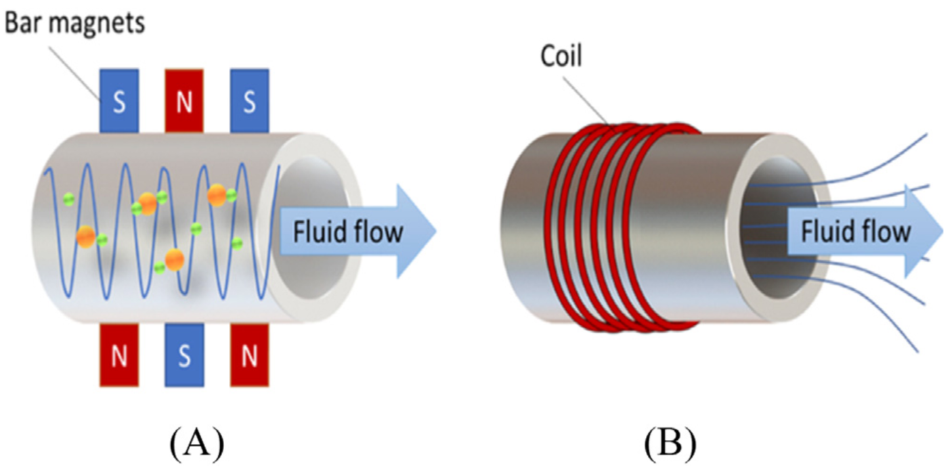

Figure 9. Representative electromagnetic field device configurations commonly used in water treatment. (**A**) Permanent magnet; (**B**) solenoid coil [83].

5. Configurations and Conditions in Electromagnetic Field Desalination

Electromagnetic field devices employed in water treatment systems typically fall into two main categories permanent magnets and solenoid coils [84]. Permanent magnets are generally produced from ferromagnetic alloys containing elements such as iron, nickel, cobalt, or rare-earth metals. The electromagnetic field strength produced by these magnets varies according to their spatial configuration and the total number of magnetic components used. In some configurations, magnets are aligned with alternating poles, while in others, the arrangement is uniform. Alternatively, solenoids consisted of coils of electrically conductive wire that generate magnetic fields within their cavities when an electric current passes through them. Various solenoid configurations, such as linear, annular, and other geometric designs, have been developed to meet different application requirements. The resulting magnetic field strength is determined by parameters such as the number of coil turns and the wire thickness [85]. Figure 9 presents a schematic illustrating the electromagnetic-field-assisted desalination process.

The induced electromagnetic field increases the deviation of ions, which occurs in accordance with the Lorentz force acting as the ions travel within the field. The relationship between the magnetic force magnitude and the electromagnetic field is expressed in Equation (1) [86].

$$|\mathbf{F}| = q\,|\mathbf{v} \times \mathbf{B}| = q\,v\,B\,\sin\theta \tag{1}$$

where **v** is the particle velocityt, q is the electric charge, θ is the angle formed by the velocity vector **v** and the magnetic flux density vector **B**, and **B** is related to the induced magnetic field [87,88]. To ensure a thorough understanding of the performance and scientific significance of magnetic water treatment, it is important to discuss its main advantages and disadvantages.

Laboratory-Scale Electromagnetic-Field-Assisted Desalination: Experimental Installations and Performance

Moreover, the technique of electromagnetic-field-assisted desalination has been identified as an emerging concept for water desalination. Most research has been carried out at the laboratory level to assess the feasibility and performance of the technique for water desalination. An example illustrating the generation of the electromagnetic field and the application of the technique for water treatment is presented in Figure 10. In this example, the Aqua-4D electromagnetic device was used to circulate saline water inside a cylindrical pipe exposed to an external electromagnetic field. This setup enabled controlled, repeatable, and cyclic electromagnetic exposure, providing a clear visualization of how electromagnetic fields are physically implemented in experimental water treatment studies and allowing for systematic investigation of EMF–water interactions under well-defined operating conditions.

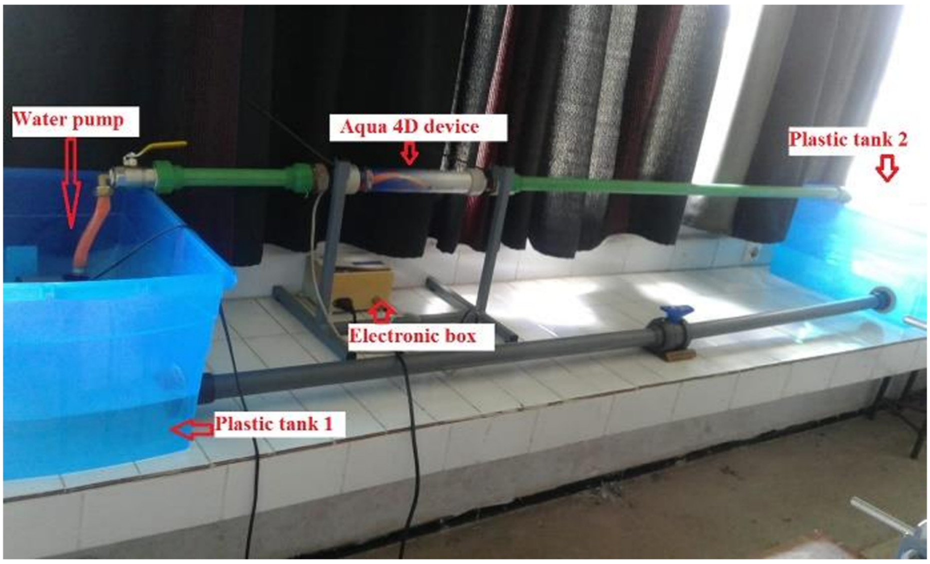

Figure 10. Equipment of electromagnetic field generator (Aqua-4D device) used for laboratory-scale water treatment experiments [89].

Building on this general electromagnetic treatment concept, a more application-oriented laboratory implementation is illustrated in Figure 11, which presents an electromagnetic treatment (EMT) setup that is specifically designed for desalination experiments. In this setup, saline water is transported via an iron pipe and covered by a solenoid coil that is supplied with low direct current voltages, ranging from 2 to 10 V. This setup is a direct and efficient method of exposing saline water to an electromagnetic field for desalination. By using this setup, considerable desalination efficiency has been achieved, ranging from 15.37% to 54.6% for chloride ion removal and reaching 13.35% for sodium ion removal, depending on the voltage and dilution ratio. Figure 11's closeness to the above discussion establishes a direct connection between the experiment and desalination.

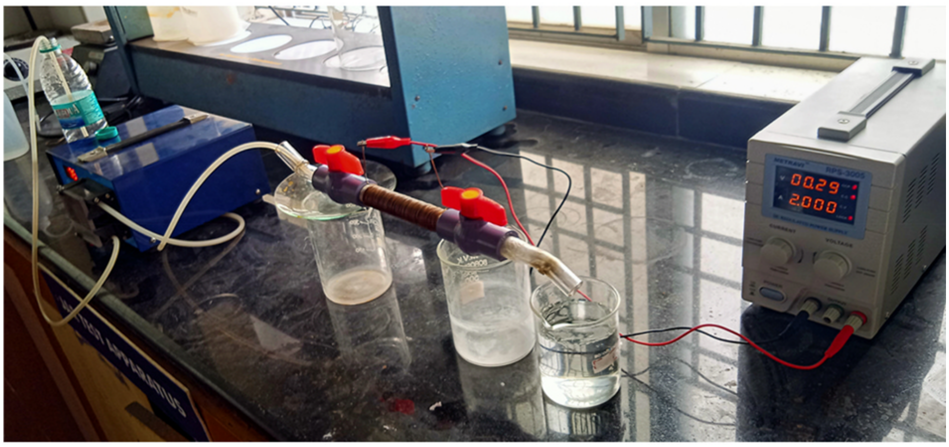

Figure 11. Laboratory setup of electromagnetic treatment [90].

Although the full-scale design of magnetic desalination plants has yet to be achieved, the laboratory setup presented in Figures 10 and 11 and the performance metrics quantified in the figures serve to reinforce the technical feasibility of the electromagnetic field-based desalination process. This addresses the existing link between the physicochemical mechanisms and the empirical verification of the desalination process. Table 2 is a synthesized representation of the various aspects of magnetic desalination, including the recent scientific research and empirical verification of the desalination process.

Table 2. Advantages and limitations of magnetic water treatment [91,92].

Advantages	Limitations
Scale Prevention	**Inconsistent Effectiveness**
Alters the crystallization behavior of minerals such as calcium carbonate, reducing scale buildup on pipes and equipment.	Efficacy can vary depending on water composition, flow rate, and magnetic field strength, leading to inconsistent results.
Chemical-Free Process	**Limited Scientific Consensus**
Eliminates the need for chemical additives, making it environmentally friendly and reducing chemical residues in treated water.	Some studies report benefits, while others find negligible effects; the scientific community has not reached a consensus on Magnetic Water Treatment effectiveness.
Low Energy Consumption	**Not a True Softening Method**
Operates with minimal energy, especially when using permanent magnets, contributing to cost savings and sustainability.	Does not remove hardness minerals but alters their physical properties, which may not suffice for applications requiring soft water.
Easy Installation and Maintenance	**Reduced Performance in Extremely Hard Water**
Generally easy to install without major modifications to existing plumbing and requires low maintenance.	May not effectively prevent scale formation in areas with very hard water, necessitating additional treatment methods.
Extended Equipment Lifespan	**Reduced Performance in Extremely Hard Water**
Minimizes scale and corrosion, prolonging the life of water-using appliances and industrial equipment.	May not effectively prevent scale formation in areas with very hard water, necessitating additional treatment methods.
Environmental Sustainability	**No Filtration Capability**
Reduces reliance on disposable filters and chemical treatments, leading to less environmental waste and a smaller ecological footprint.	Does not remove contaminants like bacteria, viruses, or chemical pollutants; often used with filtration systems for comprehensive treatment.

Table 2 summarizes the benefits and drawbacks of using magnetic water treatment as a method for managing scale formation in water systems, particularly in desalination contexts. Magnetic water treatment (MWT) is promoted for being a chemical-free, low-energy, and eco-friendly option that can help extend equipment lifespan and reduce scale buildup. However, its effectiveness can be inconsistent.

6. Discussion: Critical Analysis, Economic Perspective, and Research Outlook

6.1. Critical Analysis of Thermal Desalination Technologies Based on Quantitative and Operational Constraints

Table 3 presents a quantitative comparison of the main operational, energy, environmental, and economic parameters of conventional thermal desalination technologies. This comparative analysis forms the basis for the critical assessment developed in this section.

The quantitative comparison presented in Table 3 provides a basis for a critical assessment of traditional thermal desalination technologies, depending on clearly defined operational limits. Generally, these technologies are optimized for desalination plants that operate with a high-salinity feed typical of seawater. Moreover, these technologies consistently produce a high-quality distillate with total dissolved solids (TDS) less than 10 ppm. Such operational conditions, in principle, affect energy consumption, and this should be considered in any assessment. From this perspective, multi-stage flash desalination plants require the highest total electric equivalent, ranging from 13.5 to 25.5 kWh/m^3. Such a requirement is a result of a large amount of thermal energy required in this process, supplied in the form of steam. Despite its reliability and applicability in large-scale desalination plants, this process is now heavily constrained by energy and climate considerations, mainly owing to its high thermal energy requirement and, consequently, its greenhouse gas emissions, calculated to be 24 kg CO_2/m^3. In contrast, multi-effect distillation plants show a better energy efficiency, with a lower total electric equivalent, ranging from 6.5 to 11 kWh/m^3 and lower greenhouse gas emissions, calculated to be 19.2 kg CO_2/m^3. Vapor compression desalination plants, including MVC and TVC, show a complex relationship in this context. On one hand, MVC plants do not require any additional energy input, as this energy is provided by a compressor. On the other hand, this energy is supplied in a large amount, with a total electric equivalent ranging from 7 to 12 kWh/m^3. This analysis shows that there are higher unit prices for water with alternative technologies, while TVC technologies are found to have intermediate performance with a dependency on steam availability. Also, it is noted that thermal-based desalination technologies are mainly dependent on thermal energy, as opposed to electric-based technologies that are dependent on electrical energy, whose cost and quality are different. Therefore, it is noted that thermal energy is converted to its equivalent value of electrical energy. However, it is noted that the comparison provided in Table 3 is relative in nature, and it is clear that no technology is best in terms of energy and environmental considerations. and economic performance, and that technology selection must ultimately be guided by site-specific conditions such as plant capacity, energy availability, and sustainability objectives.

Table 3. Comparison of desalination techniques [93–97].

Parameter	MSF	MED	MVC	TVC
Water type	Seawater, Brackish	Seawater, Brackish	Seawater, Brackish	Seawater, Brackish
Operation temperature (°C)	90–110	70	70–100	63–70
Typical unit size (m^3/day)	50,000–70,000	5000–15,000	100–3000	10,000–30,000
Electrical energy consumption (kWh/m^3)	4–6	1.5–2.5	7–12	1.8–6
Thermal energy consumption (kJ/kg)	190–390	230–390	none	145–390
Electrical equivalent of thermal energy (kWh/m^3)	9.5–19.5	5–8.5	none	9.5–25.5
Total electric equivalent (kWh/m^3)	13.5–25.5	6.5–11	7–12	11–28
CO_2 emissions (kg CO_2/m^3)	24	19.2	11.5	21
Distillate quality (TDS, ppm)	∼10	∼10	∼10	∼10
Unit product cost (USD/m^3)	0.52–1.75	0.52–1.01	2–2.6	0.827

6.2. Positioning of Electromagnetic-Field-Assisted Desalination Relative to Thermal Technologies

To position electromagnetic-field-assisted desalination relative to conventional thermal technologies, a comparative analysis based on key operational, energetic, environmental, and techno-economic criteria is required. Table 4 summarizes the fundamental differences between these approaches in terms of working principles, salinity suitability, energy consumption, cost, and technological maturity. This comparison provides a structured framework to assess the complementary roles of electromagnetic-field-assisted treatments and established thermal desalination processes, rather than to imply direct equivalence between technologies operating under fundamentally different physical mechanisms.

The comparative framework presented in Table 4 allows the positioning of electromagnetic field (EMF)-assisted desalination relative to conventional thermal technologies to be clarified in terms of operating principles, application scope, and technological maturity. Thermal desalination methods rely on phase-change mechanisms driven by evaporation and condensation, which makes them highly effective for high-salinity seawater treatment but intrinsically energy-intensive and environmentally demanding. In contrast, EMF-assisted treatments operate through non-thermal mechanisms involving modifications in ion mobility, hydration structures, and interfacial phenomena, resulting in substantially lower reported energy consumption under experimental conditions. However, these approaches are currently more suitable for brackish water applications and decentralized systems, rather than for large-scale seawater desalination.

Table 4. Comparison of thermal and electromagnetic desalination technologies [90,98,99].

Criterion	Thermal Methods	EMF-Assisted Treatment
Working Principle	Water is evaporated and condensed to separate salts	Application of electromagnetic fields to modify ion mobility, hydration structure, and interfacial phenomena.
Salinity Suitability	Highly effective for seawater (TDS > 35,000 mg/L)	More suitable for brackish water
Energy Consumption	High thermal and electrical demand (process-dependent)	0.856–4.28 kWh/m^3 (experimental range; 2–10 V, 2 A; artificial seawater)
Cost	Moderate to high (technology- and scale-dependent)	0.3–0.7 USD/m^3
Environmental Impact	High: brine discharge and high energy demand	Lower environmental impact; easily integrated with renewable energy
Typical Applications	Municipal supply, coastal industry, and arid regions	Agriculture, inland industries, and decentralized units
Technology Maturity	Well-established, widely deployed since the 1970s	Emerging and growing, mainly applied to brackish water treatment

From an economic and environmental perspective, it is clear that there are potential benefits of using electromagnetic field (EMF)-assisted desalination, as it presents a reduced energy demand, a minimized unit cost of water, and a high potential for using alternative energy sources. However, as it is still a relatively new technology with limited technological maturity, it is difficult to compare it with well-established thermal technologies that have had decades of industrial development. Therefore, it is not suggested that EMF-assisted desalination is a replacement technology, but rather a complementary one, particularly with hybrid technologies that can address issues of scaling, energy, and efficiency in conventional desalination systems.

6.3. Economic Perspective and Cost-Related Trade-Offs

However, an objective comparison between different desalination technologies should also consider an economic factor because the energy efficiency criterion cannot be used alone to assess the feasibility of different technologies. As indicated by the data presented in Table 3, conventional thermal technologies such as MSF, MED, MVC, and TVC have different unit water production costs. For example, large-scale thermal technologies such as MSF and MED have relatively moderate unit water production costs compared to other conventional technologies. These costs are usually between 0.52 and 1.75 USD/m^3. On the other hand, electrically intensive technologies such as MVC have relatively higher thermodynamic efficiencies but also have higher unit water production costs, reaching 2–2.6 USD/m^3. Moreover, the comparison between different technologies based on the data presented in Table 4 indicates that emerging technologies such as EMF-assisted technologies have relatively low unit water production costs compared to conventional technologies. For example, the unit water production costs for EMF-assisted technologies are between 0.3 and 0.7 USD/m^3. However, this data is based on experimental results and does not consider other factors such as the capital costs required to implement EMF technology. Thus, based on the data presented above, no direct economic equivalence between conventional and emerging technologies such as EMF-assisted technologies can be established. It should be noted that EMF-assisted technologies are economically viable technologies for brackish water treatment or can be used as tools to reduce the overall unit water production costs for hybrid technologies.

6.4. Remaining Challenges and Research Gaps in EMF-Assisted Desalination

In spite of the promising results obtained in various experiments and studies, electromagnetic-field-assisted desalination techniques are still characterized by several fundamental research gaps that impede their way towards practical application [85]. The most important gap lies in the insufficient and imprecise knowledge of the physicochemical mechanisms that are affected by electromagnetic fields with respect to the issue of heterogeneous deposits. Furthermore, the quantification of the relationship between the parameters of the electromagnetic field (field strength, frequency, voltage, and geometry of the electrodes/coils) and the performance indicators (calcification reduction, enhancement of mass transfer, etc.) has not yet been achieved with respect to different types of saline water [100]. Moreover, the problem of long-term operational stability and the effect of continuous exposure to the electromagnetic field on the properties of materials and membranes has not yet been adequately documented. Finally, the absence of integrated economic–environmental analyses, which take into account the costs of investment and operation compared with traditional anti-scaling technologies, represents an important limitation in the objective evaluation of the viability of these technologies [83].

6.5. Challenges and Future Directions

The synthesis of Tables 3 and 4 suggests that the most plausible and potentially influential trajectory appears to be hybrid desalination approaches. Instead of replacing conventional thermal-based desalination plants, EMF-based treatment processes could act as efficiency enhancers, for example, as an anti-scaling pretreatment step for multiple-effect distillation (MED) plants. This could have potential for countering heat exchanger fouling, thermal efficiency, and cost savings.

Future research should prioritize long-term pilot demonstrations using actual seawater, coupled with rigorous techno-economic analysis and life cycle assessment. Optimizing EMF operating parameters and system integration strategies will be key to unlocking synergistic benefits and advancing EMF-assisted desalination to higher technology readiness levels.

7. Conclusions

The race for desalination technology is shifting more and more towards the goal of accomplishing more with less: less energy, less environmental impact, and more convenient system integration. The conventional thermal-based methods, including multi-effect distillation, multi-stage flash distillation, thermal vapor compression, and mechanical vapor compression, remain the leaders for large-scale seawater desalination plants. While these methods are reliable and well understood, they are energy-intensive and prone to fouling, and have environmental consequences that encourage the search for alternative methods.

This is where the electromagnetic-field-assisted methods become prominent. If not seen as a replacement for the conventional methods, these methods are seen as an enhancement or an addition that could potentially help solve the problem of scaling, surface tension, and efficiency in some configurations, especially for brackish water and small-scale plants. While these methods have shown promise in the laboratory, their exact physicochemical mechanisms are not yet fully understood.

The more promising and realistic route for the future is the integration of EMF-assisted methods with conventional methods using the more established thermal-based methods.

Future studies should aim to lift the veil on the exact mechanisms, conduct thorough technical, economic, and environmental studies, and test the long-term viability of the methods under real-world conditions. With continued and careful progress, EMF-assisted methods could help create more dynamic and sustainable approaches for desalination without overextending the current industrial maturity of the methods.

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Abbreviations

MSF	Multi-Stage Flash
MVC	Mechanical Vapor Compression
MED	Multi-Effect Distillation
RO	Reverse Osmosis
FO	Forward Osmosis
NF	Nano-Filtration
IXR	Ion-Exchange Resin
SRF	Secondary Refrigerant Freezing
EMF	Electromagnetic Field
TVC	Thermal Vapor Compression
SC	Solar Chimney
MD	Membrane Distillation
HDH	Humidification–Dehumidification
ED	Electrodialysis
MW	Magnetic Water
TDS	Total Dissolved Solids
SSD	Solar Still Distillation
CDI	Capacitive Deionization

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