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Review

Potential of MgB_2 Superconductors for Magnetically Aided Wastewater Treatment: Feasibility and Future Prospects

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Abstract

This study reviews key aspects of utilizing superconductors in wastewater treatment. It analyzes the interplay between magnetic fields and treatment processes, with a particular focus on the application of superconductors. The potential of MgB_2 superconductors is evaluated based on their inherent properties, alongside an exploration of the challenges and future opportunities associated with their potential implementation. A comprehensive literature review demonstrates the efficacy of magnetic fields in eliminating or drastically removing heavy metals, especially from industrial wastewater streams, through magnetic separation techniques. This review compares the efficiency of magnetic separation to conventional treatment methods, highlighting its potentials. Critical factors such as magnetization in wastewater, magnetic gradients, and magnetic memory are identified and discussed as crucial elements in optimizing magnetic separation processes. Furthermore, the study draws upon extensive research to investigate the technical considerations associated with magnetic wastewater treatment, ultimately evaluating the role of superconductors, particularly MgB_2, in advancing this technology. The feasibility and future prospects of MgB_2 superconductors within the context of wastewater treatment are also explored.

Keywords: wastewater treatment; magnetic separation; superconductors; MgB_2

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1. Introduction

The proper treatment of municipal and industrial wastewater incurs significant costs to effectively remove pollutants to ensure the water is clean and reusable. However, common contaminants in wastewater effluents still include heavy metals, surfactants, residual organic compounds, salts, and soluble bases [1]. Current conventional treatment methods often fail to eliminate these pollutants, but may concentrate or convert them into different phases [2]. Nevertheless, ongoing progress is being made to develop new strategies for wastewater treatment (WWT) focused on a wider array of pollutants [3]. Numerous physicochemical techniques are utilized for wastewater treatment, with mass transfer serving as the basis for these pollutant removal methods, like aeration in flotation units, adsorption of dissolved organics and on activated carbon and other adsorbents, dissolved salts on ion exchange materials, and removal of gas and volatile organics from water by stripping. These techniques are preferred due to their simplicity, flexibility, high efficiency, and potentials for recovery of pollutant for resource recycling. Additionally, physicochemical treatment is often viewed as more reliable than other methods since it does not depend on living organisms [4–6].

Magnetic fields (MFs) are emerging as a promising technique in wastewater treatment (WWT), enhancing physicochemical processes by improving contaminant separation and removal. They promote flocculation and settling of particles and boost microbial activity for organic pollutant degradation by facilitating oxygen transfer [7,8], so MFs enhance both physical and biological treatment processes. Research indicates that MFs can reduce energy consumption and operational costs by altering water properties, aiding in adsorbent regeneration, and improving membrane efficiency. While not standalone solutions, they complement traditional methods like coagulation and adsorption, enhancing overall treatment efficiency [9,10]. A review by Zaidi et al. highlighted the benefits of magnetization in wastewater treatment, showing significant improvements in solid–liquid separation and bacterial activity [11]. However, further research is needed to optimize these systems for various contaminants [7,12]. While some research has examined the impact of MFs on WWT, both physical and biological systems, the results remain complex and not entirely understood. MFs have been studied for their role in the magnetic adsorptive separation of dyes and heavy metals, the treatment of domestic wastewater, and photo magnetic coupling. Their environmental sustainability and efficiency provide exciting opportunities for advancing WWT, contingent on a deeper understanding of its underlying mechanisms [13]. For instance, a study by Krzemieniewski et al. investigated the effects of a constant MF (0.4–0.6 T) on wastewater properties, using samples from two sources with different characteristics [14]. The findings showed a consistent reduction in chemical oxygen demand (COD) (25–55%), chlorides (25–40%), ammonium nitrogen (N-NH4) (50–66%), and orthophosphates, which decreased to 3.37–6.00 mg/dm^3. Iron concentration increased significantly, reaching 2.35–8.10 mg/dm^3. Both types of magnetically treated wastewater exhibited similar modification degrees and trends. While parameters such as reaction rate, total alkalinity, and color showed minor fluctuations, extending wastewater detention time improved pollutant removal efficiency [14].

Magnetic separation technology is considered a physical method that utilizes variations in magnetism to achieve materials separation based on their behavior in a non-uniform magnetic field. This approach is environmentally friendly, efficient, and has minimal impact on the physical and chemical properties of raw materials. It is primarily employed in the processing of magnetic ferrous minerals [15]. The application of MFs has the potential to enhance physical performance, particularly in solid liquid separation [11]. Moreover, in the context of wastewater treatment and magnetic materials, there is a wide range of nano-adsorption materials with high selectivity and with excellent adsorption capabilities that show significant potential for application in WWT [16,17]. Magnetic materials are low cost and can be easily recovered using MFs, making them valuable in microbiology, sensing, and magnetic medicine applications [18]. Agasti et al. suggest that magnetic nano materials with high saturation magnetization can effectively serve as carriers for pollutants in wastewaters [19]. The use of magnetic fields for water purification and contaminant separation are potentially more efficient and cost-effective than traditional methods like precipitation [15,19]. MFs can be categorized by magnetic field intensity (MFI) into four types: weak (<0.001 T), moderate (0.001–1 T), strong (1–5 T), and ultra-strong (>5 T) [20]. Furthermore, MFs can be classified as dynamic magnetic fields (DMFs) or static magnetic fields (SMFs), depending on whether the MFI varies over time [13].

In the first two decades of the 21st century, numerous publications have emerged, highlighting research that supports the use of superconductivity [21] in environmental protection techniques [22], while one of these techniques and applications is focusing on superconducting magnetic separation. Superconducting magnetic separation is increasingly recognized for its potential in wastewater treatment technology. Research began in 1987 at Osaka University, leading to the development of a prototype separator for paper factories and successful laboratory demonstrations [23–26]. However, many pollutants in wastewater from industries such as paper, chemicals, pharmaceuticals, and food are organic substances that are not ferromagnetic and cannot be removed by magnetic separation alone. To facilitate this process, magnetic seeds must be added to the wastewater, allowing superconducting magnetic separation to treat it effectively. Surface modifications of the seeds enhance their interaction with pollutants. This method offers advantages over traditional treatments, including lower costs, a smaller occupied area, and shorter operation times. The availability of commercial cryocoolers for superconducting magnets has further simplified and reduced the cost of establishing these systems [27]. Superconductors are categorized based on their transition temperatures into high temperature superconductors (HTS) and low temperature superconductors (LTS) [28].

Magnesium diboride (MgB_2), first synthesized by Bovenkerk et al. (1959), gained prominence in 2001 when Prof. Jun Akimitsu's research team discovered its superconducting properties [29]. This breakthrough was notable due to MgB_2's simple composition—magnesium and boron—which makes it cost-effective and easy to produce. As an intermetallic superconducting compound, MgB_2 exhibits a Tc of 39 K, surpassing conventional superconductors like Nb_3Ge, Nb_3Sn, and NbTi, though falling short of HTS. Its advantages include a high Jc, affordability, and flexibility, enabling efficient cooling via cryogenic systems (e.g., liquid neon at ~15 K or liquid hydrogen) rather than energy-intensive liquid helium (4.2 K). This positions MgB_2 as a promising material for digital cryo-electric technologies [28,30].

Researchers emphasize MgB_2's potential for applications like superconducting wires, films, and strong magnetic field generation, which can aid in wastewater treatment by removing heavy metals and dyes [13]. Its low electrical resistance [31] and thermal stability [32] enhance energy efficiency, particularly in large-scale operations [33].

Ongoing efforts aim to optimize MgB_2's performance as a viable alternative to conventional superconductors, leveraging its accessible raw materials and straightforward synthesis [34]. With its combination of high Tc, affordability, and abundance, MgB_2 holds significant promise for advancing technologies reliant on efficient, scalable superconducting solutions.

2. Heavy Metals

Heavy metals such as cadmium, arsenic, chromium, zinc, nickel, copper, mercury, and lead are major freshwater pollutants, posing serious health risks due to their toxicity and persistence [35]. Industrial activities release these metals, which are highly soluble and can accumulate in aquatic life and the human food chain [35]. Various treatment methods have been developed, including membrane filtration, adsorption, ion exchange, chemical precipitation, nanotechnology, and electrochemical processes. Access to clean water is increasingly critical as availability declines from pollution and population growth, even in resource-rich areas. While rainwater harvesting offers short-term relief, effective wastewater treatment and reuse are essential. Wastewaters contain toxic pollutants classified as organic, inorganic, and biological, with a focus on removing inorganic heavy metal ions to prevent environmental discharge. Excessive metal accumulation can cause serious health issues, such as skin irritations from zinc and cancers from nickel. Thus, effective treatment is crucial for reducing pollutants to safer levels. Heavy metals can persist in the body for long periods due to their non-biodegradable nature [36,37]. Azimi et al. examined methods like membrane filtration, ion exchange, chemical precipitation, and adsorption, while electrochemical methods include electrocoagulation and electrodeposition [38]. Photocatalysis and nanotechnology also play roles in treatment. Preferred methods are cost-effective and environmentally friendly, although biological processes mainly target biodegradable substances rather than heavy metals [38].

According to conventional methods for heavy metals wastewater treatments, researchers have explored various methods for removing heavy metals from wastewater. Traditional approaches include electrochemical treatments like electrocoagulation, electroflotation, and electrodeposition. Other techniques involve physicochemical processes such as chemical precipitation and ion exchange, along with adsorption using materials like activated carbon and wood sawdust. Newer methods include membrane filtration, photocatalysis, and nanotechnology. This section reviews these techniques, highlighting their pros and cons in industrial applications. Although electrochemical treatments have historically been overlooked due to high electricity costs, recent advancements have made them more efficient and cost-effective, especially for tackling stubborn pollutants. We will focus on three key electrochemical technologies: Electrocoagulation (EC), Electroflotation (EF), and Electrodeposition (ED), examining their principles and methodologies [38]. Figure 1 shows the conventional methods for heavy wastewater treatments and their classification accordingly.

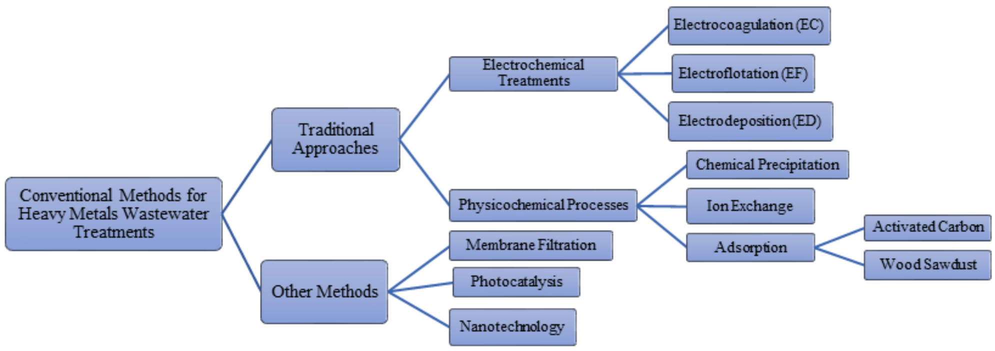

Figure 1. Conventional methods for heavy metals WWT diagram [38–42].

2.1. Electrocoagulation

Electrocoagulation (EC) has emerged as an effective technology for wastewater treatment, though challenges with reactor design and electrode reliability have limited its adoption. Recent advancements have made EC a viable option for small-scale applications. The process uses electrolysis to remove pollutants, with Al and Fe electrodes first patented in the U.S. in 1909. In a basic EC reactor, a low electric current is applied to wastewater using sacrificial electrodes. Initially, heavy metal ions are held in the water by electrical charges. When an electric field is introduced, these charges neutralize, leading to the coagulation of suspended pollutants. The resulting heavy metal particles agglomerate into larger, more stable sludge or flocs, which can be removed more easily, though this can be costlier. The EC process involves anode dissolution, generation of hydroxide and hydrogen at the cathode, electrolytic reactions, coagulant adsorption on pollutants, and removal of colloids through sedimentation or flotation [41,42].

The study by Vasudevan et al., presents scanning electron microscopy SEM images showing the condition of an Al alloy anode before and after the electrocoagulation (EC) process for chromium removal. The results indicate that using an Al alloy anode at a current density of 0.2 $A.dm^{-2}$ and a pH of 7.0 achieved an impressive removal efficiency of 98.2%. Additionally, the sludge generated during both batch and continuous EC processes was effective in removing zinc from rinse water. EC is an environmentally friendly method that uses electrons as reagents, eliminating the need for chemical additives and reducing the risk of forming new pollutants. While EC may struggle with highly soluble particles, it is particularly effective at removing small colloidal particles by inducing their motion through an electric field [40].

2.2. Electroflotation

Electroflotation (EF) has become an innovative method for removing heavy metal pollutants, especially in dilute solutions where traditional methods struggle, particularly fewer than 50 mg/m^3. EF is popular for its adaptability, simple design, environmental compatibility, cost-effectiveness, and compact size. It is used in various industries, including oil-water emulsions, groundwater disinfection, food processing, and sewage treatment, by floating pollutants to the surface. Researchers have combined electrocoagulation (EC) and EF into a single method called electrocoagulation-flotation (ECF), which yields better results than either method alone. For instance, Da Mota et al., showed that ECF could achieve up to 97% removal of lead (Pb) and zinc (Zn) from synthetic solutions under optimized conditions [39].

2.3. Electrodeposition

Electrodeposition (ED) is an effective electrochemical method for recovering heavy metals. It requires no additional reagents, avoids sludge formation, and offers high selectivity and cost-effectiveness. In ED, dissolved metal ions are reduced and deposited onto the cathode, preventing corrosion. This method can also handle non-aqueous solutions or those with chelating agents, improving pollutant removal over traditional aqueous methods. For example, Wulan and Hariyadi found that a partitioned reactor significantly enhanced nickel reduction efficiency [43]. Chemical precipitation is a widely used method for removing heavy metals from water due to its simplicity and automation potential. However, it often requires significant chemical inputs, which can lead to pollution. In this process, precipitant agents react with heavy metal ions to form insoluble particles that are removed through sedimentation or filtration. Electrocoagulation (EC) may be preferred for its higher efficiency, reduced sludge production, and broader pollutant removal capabilities. Ion exchange involves reversible ion swapping between solid and liquid phases, where heavy metal ions are absorbed onto a resin, which then releases similar ions. Factors like pH, temperature, and concentration greatly influence ion exchange efficiency. Resins made from styrene-divinylbenzene are particularly effective in treating wastewater and recovering valuable metals. For instance, Gode et al., found that certain resins achieved high ion-exchange capacities for various heavy metals under optimal conditions [44]. Table 1 outlines the advantages and disadvantages of conventional EC, EF, and ED methods in wastewater treatment, based on relevant studies. Table 2 presents numerous studies related to conventional wastewater treatments without utilize MF technology. These studies employed various methods and techniques to mitigate or dispose of hazardous contaminants in wastewater.

Profeta et al., explore the production of synthetic FAU-type zeolites impregnated with $CaCO_3$ from various silicon sources and their effectiveness in removing Cd^{2+} ions from aqueous solutions. The results indicate that dispersing $CaCO_3$ on the zeolite surface significantly enhances adsorption performance compared to pristine zeolites, while the commercial beta zeolite shows inferior Cd^{2+} uptake due to lower Al and Ca content. Adsorption tests reveal that ion exchange and monolayer formation are key mechanisms in the Cd^{2+} uptake process. The FAU-type zeolites exhibit varying structural and textural properties that influence $CaCO_3$ dispersion and Cd^{2+} adsorption capacity. Overall, the study highlights the synergistic benefits of combining low-cost materials like zeolites and $CaCO_3$, providing a promising approach for effective heavy metal removal in water treatment applications and contributing to environmental sustainability [R1] [45].

Moraes et al., investigated the synthesis of zeolitic materials with distinct structural properties to remove the pesticide myclobutanil, addressing the environmental risks posed by pesticides. They utilized the layered precursor PREFER and 3D-faujasite, treating PREFER with CTAB for external functionalization and delamination. The PREFER-CTAB-90 °C sample demonstrated superior pesticide removal due to higher CTAB availability on exposed lamellae. In contrast, double-layered CTAB arrangements showed better performance than single layers. DFT calculations revealed that the adsorption of myclobutanil by two CTAB molecules is nearly four times more efficient than by one. This study validates the potential of CTAB-functionalized zeolites for effective pesticide removal, emphasizing the importance of CTAB arrangement in enhancing adsorption. Further research will explore interactions with other pesticide molecules [R2] [46].

Table 1. The advantages and disadvantages of conventional EC, EF, and ED methods in WWT [41–44].

Method	Advantages	Disadvantages
Electrocoagulation (EC)	- Achieved an impressive removal efficiency of 98.2% for chromium at a current density of 0.2 A.dm−2 and pH 7.0. - Environmentally friendly; eliminates the need for chemical additives, reducing the risk of new pollutants. - Effective at removing small colloidal particles, especially through induced motion in an electric field. - Reduced sludge production compared to traditional chemical methods.	- Challenges with reactor design and electrode reliability limit broader adoption. - Higher operational costs due to energy requirements and maintenance of sacrificial electrodes. - May struggle with highly soluble particles, limiting its effectiveness in certain scenarios.
Electroflotation (EF)	- Effective in removing heavy metals, especially in dilute solutions (e.g., <50 mg/m^3) where traditional methods struggle. - Adaptable for various industries (e.g., oil-water emulsions, groundwater disinfection, food processing). - Cost-effective with simple design; compact size facilitates integration into existing systems. - Combined with EC (ECF method) achieved up to 97% removal of lead (Pb) and zinc (Zn) under optimized conditions.	- Efficiency can be limited in very low concentration scenarios, requiring specific conditions for optimal performance. - Needs careful optimization to maximize removal efficiencies, which may complicate implementation.
Electrodeposition (ED)	- No additional reagents required, avoiding sludge formation and reducing waste. - High selectivity for heavy metal recovery, proven effective in applications like nickel reduction, where partitioned reactors significantly enhance efficiency. - Can handle non-aqueous solutions and those with chelating agents, improving overall pollutant removal. - Cost-effective due to the lack of additional chemicals and high recovery rates.	- Limited mainly to specific metal recovery applications, which may restrict its utility in broader wastewater treatment contexts. - Requires stringent control of operating conditions (e.g., voltage, pH) to maintain optimal performance, adding complexity to the process.

Electrodeposition (ED) is an effective electrochemical method for recovering heavy metals. It requires Magnetic technology has been widely utilized across various fields for several decades, especially in the domain of water and wastewater treatment. The upcoming section will explore the specific applications of magnetic technology in this area, highlighting its effectiveness and advantages. Furthermore, we will present a thorough comparison between wastewater treatment processes that incorporate magnetic field technology and conventional methods that do not utilize this approach. This analysis will be supported by numerous studies from the extensive literature. By examining both methodologies, we aim to emphasize the benefits and potential improvements that magnetic technology can bring to wastewater management, particularly in enhancing efficiency in contaminant removal and overall treatment performance.

Table 2. Conventional WWT without using MFs technology.

Method	Techniques Used	Investigation and Results	Reference
Adsorption on fly-ash-based substrates	Adsorption studies	Studied the adsorption of dyes and a hair conditioner to treat wastewater from a textile company; highlighted limitations of single-component studies for effective treatment.	[47]
Mesoporous alumina and calcium-doped alumina	Adsorption experiments	Investigated fluoride adsorption; found maximum removal capacities of 450 mg/g for fluoride and 200 L for arsenic at 100 ppb, treated effectively with just 1 g of mesoporous alumina.	[48]
Heat treatment of ordered mesoporous carbon	Surface modification	Modified surface chemistry via heat treatment in ammonia at 1173 K; significantly increased adsorption of three anionic dyes compared to commercial activated carbon.	[49]
Synthesis of magnetic iron oxide/silica	Characterization (SEM, TEM)	Developed a cost-effective method using vegetable oil; confirmed synthesis and characterization of nanocomposite particles through SEM and TEM.	[50]
N-butylimidazolium functionalized resin	Adsorption studies	Explored phenol adsorption; achieved maximum removal of 92.2 mg/g at pH 11.2, with effective regeneration using a 0.5 M NaOH and NaCl solution.	[51]
Humic acid-coated Fe_3O_4 nanoparticles	Adsorption experiments	Examined removal of methylene blue; achieved optimal removal efficiency at neutral pH, with easy regeneration of nanoparticles.	[52]
Untreated and modified Polyalthia longifolia	Comparative analysis	Evaluated Cr(VI) removal; found that acid-treated leaves performed best, enhancing removal efficiency significantly.	[53]
Green coconut shell powder	Adsorption modeling	Investigated trace metal removal; modeled adsorption characteristics with Langmuir and Freundlich isotherms, demonstrating effective metal uptake.	[54]
Diatomite modified with aluminum compounds	Sorbent development	Developed a fluoride-selective sorbent; achieved a 2.5-fold increase in specific surface area and enhanced fluoride removal capacity from 8.9 to 57.6 mg of F/g.	[55]
Comparison of sorbents	Performance evaluation	Studied removal of phenoxyalkanoic acid herbicides; identified a decreasing trend in herbicide uptake, with 2,4-DB being the most efficient sorbent.	[56]
Octadecyltrimethyl-ammonium micelle-montmorillonite	Comparative analysis	Focused on removing humic acid from water; found that composites outperformed activated carbon in HA removal, indicating higher efficacy.	[57]
Sorbent derived from coffee grounds	Adsorption studies	Evaluated fluoride removal; achieved the highest efficiency when calcined at 600 °C, indicating effective application for fluoride treatment.	[58]
UV irradiation with Fe(0)/air, ozone, and Fenton	Oxidation studies	Investigated humic acid oxidation; Fe(0)/air achieved over 99% oxidation of humic acid in 9 min, significantly reducing toxicity and THMFP.	[59]
Catalytic wet peroxide oxidation (CWPO)	Catalyst optimization	Stabilized landfill leachate with Al/Fe-pillared clay; achieved up to 50% removal of chemical oxygen demand (COD) and a biodegradability index of 0.3.	[60]
Hybrid process with beta-MnO_2 nanowires	Oxidative removal studies	Studied oxidative removal of bisphenol A; removal efficiency varied with pH and was influenced by the presence of humic acid and metals.	[61]
Kinetics and oxidation products analysis	Kinetic studies, LC-MS/MS analysis	Investigated trimethoprim oxidation using ferrate(VI); revealed second-order kinetics and identified primary oxidation products.	[62]
Electrochemical reduction using titanium species	Electrochemical analysis	Studied perchlorate reduction; found that a high pitting potential of 12.77 V (SHE) was necessary for effective removal, with minimal impact from pH and electrode surface area.	[63]
BDD-ZVI electrochemical treatment	Electrochemical oxidation	Employed boron-doped diamond electrodes with zero-valent iron; achieved enhanced removal of p-nitrophenol through combined electrochemical oxidation and coagulation processes.	[51]

3. Magnetic Field and Water Treatment

This study highlights the applications of MFs in calcium carbonate crystallization, water purification, coagulation and sedimentation of colloidal particles, and wastewater treatment, emphasizing their potential benefits and limitations while calling for further research in this area. MFs have shown effectiveness in separation processes by influencing the characteristics of contaminants, thereby enhancing purification efficiency when combined with other techniques [64]. Various magnetic technologies utilize permanent magnets or HGMS in methods like magnetic seeding, magnetic adsorption, and electromagnetic devices, each affecting system performance differently [12]. However, the mechanisms behind these applications are not fully understood, leading to conflicting theories in the literature. For example, while Kronenberg et al. proposed molecular nucleation as a key principle, it does not explain how this occurs or the varying effects of magnetism [65]. To address these gaps, the review highlights four critical factors in the use of magnetic fields: magnetization and magnetic field manifestation, the presence of a magnetic gradient, the influence of Lorentz force, and the phenomenon of magnetic memory [66] as specified in Figure 2 which presents the magnetic field and water treatment diagram.

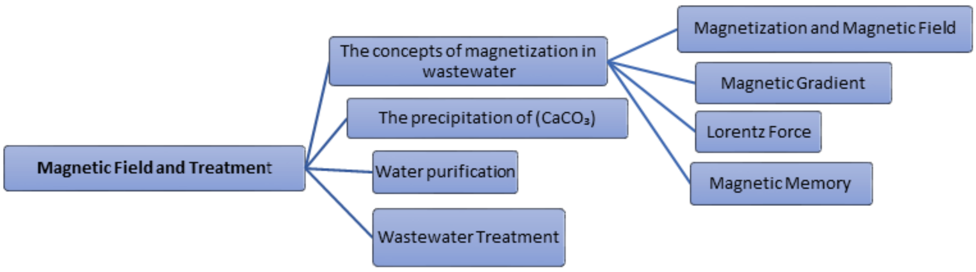

Figure 2. Magnetic field and water treatment diagram [11,12,64–68].

We follow Figure 2 to demonstrate the effects of magnetic fields and treatment based on numerous comprehensive studies related to MFs and water treatment. This includes: (i) the concepts of magnetization in wastewater, focusing on aspects of the magnetization and magnetic Field, the magnetic gradient, lorentz force, and magnetic memory; (ii) the effects of magnetic fields on the precipitation of calcium carbonate ($CaCO_3$); (iii) the process of magnetic purification of water; and (iv) a detailed examination of how magnetic treatment has influenced contaminated water and its subsequent processing:

3.1. The Concepts of Magnetization in Wastewater

Electrodeposition (ED) is an effective electrochemical method for recovering heavy metals. It requires no additional reagents, avoids sludge formation, and offers high selectivity and cost-effectiveness.

3.1.1. Magnetization and Magnetic Field

Molecules can be polar or non-polar. In non-polar molecules, positive and negative charges align, centering their gravity. In polar molecules, this alignment does not naturally occur, leading to a displacement between positive nuclei and negative electrons. Without a magnetic field, polar molecules have random orientations, preventing charge alignment. However, a strong magnetic field can align polar molecules by their charges. Non-polar molecules also move randomly without a magnetic field, as their charges overlap. A magnetic field separates these charges, causing them to align with the field [11].

3.1.2. Magnetic Gradient

The importance of magnetic applications goes beyond just the strength of the magnet itself. It is essential to consider the magnetic gradient or the concentration of magnetic flux, which can vary significantly across the magnetic device. The energy produced by magnetizing a material, along with the magnetic field within a specific volume, plays a vital role in this process. A strong magnetic gradient is particularly important for effective particle separation, especially when dealing with small volumes. Moreover, using a magnetic gradient in combination with an alternating field proves to be more effective than relying solely on a static field. This approach is especially beneficial for aggregating substances like $CaCO_3$, resulting in faster crystallization and improved descaling outcomes. These findings have been validated by researchers like Kronenberg [65], Iwasaka and Ueno [69], and Franzreb and Holl [70]. Magnetic filtration removes suspended solids and starch by creating a magnetic gradient as a solution flows through coils magnetized by external permanent magnets. These magnets, arranged with alternating poles, generate an oscillating magnetic field that enhances the gradient by concentrating flux lines. As the solution moves through the coils, charged particles are attracted and separated. The effectiveness of this process depends on the magnetic strength and the characteristics of the coil magnetization.

3.1.3. Lorentz Force

Lorentz Force is crucial in magnetic applications, acting on charged particles in a magnetic field. It depends on the particle's charge, velocity, and the magnetic field’s perpendicular component. When charged particles move perpendicularly to the field, the Lorentz force displaces charges, causing molecular instability and particle aggregation. Research shows this force enhances processes like dissolution, crystallization, and stabilization of coordinated water. An example is found in magnetic treatment devices (MTDs) that help prevent limescale deposition in pipes [12].

3.1.4. Magnetic Memory

Magnetic memory refers to the duration during which particles retain their magnetization properties following exposure to a magnetic field of specific intensity. Various instances of magnetic memory phenomena have been documented in the works of Srebrenik et al. [71], and Colic and Morse [72]. The effects of magnetic memory on particles have been studied over time periods ranging from 10 min [68] to 150 h [73]. Notably, Higashitani et al., observed magnetic memory in a $CaCO_3$ solution for up to six days following exposure to a magnetic field [74]. Magnetic memory suggests that when a magnetic field interacts with water molecules, it alters their kinetic energy, affecting dipole momentum and leading to stable particle aggregation. These aggregates can remain stable even after the magnets are removed, allowing magnetic memory to persist nearly indefinitely. However, the effects of magnetic memory on microorganisms differ from those on water molecules. While stronger magnetic memory can enhance particle aggregation, it does not have the same effect on bacteria. Instead, weak or strong magnetic memory may either promote or hinder bacterial growth, influencing the performance of systems like wastewater treatment. These effects arise from variations in magnetic susceptibility [12].

3.2. *$CaCO_3$*

The precipitation of calcium carbonate ($CaCO_3$) is important for its use as a pigment, filler, and adsorbent in various industries. Research shows that applying a magnetic field can change $CaCO_3$ clusters in supersaturated solutions, promoting the growth of aragonite while suppressing calcite formation. This magnetic treatment also aids in reducing scaling by encouraging homogeneous nucleation of $CaCO_3$. However, careful exposure to the magnetic field is vital when treating water with silica to ensure effective crystallization and minimize scaling. $CaCO_3$ scaling can cause operational issues like pipe blockages and reduced efficiency in heaters. Various methods have been used to combat scaling, including electrochemical processes and chemical inhibitors, but these can pose health risks in drinking water systems. Consequently, physical methods like magnetic treatment have emerged as effective strategies for preventing mineral salt encrustation [68].

3.3. Water Purification

Water management practices vary by source, including natural, domestic, and industrial wastewater management, each requiring specific strategies for reuse or disposal, often through purification. Purification methods include adsorption, biotechnology, catalytic processes, membrane processes, ionizing radiation, and magnetically assisted techniques [67,75,76]. Despite extensive research, there is a gap in reviews on magnetization's role, leading this review to explore magnetic technology in water accordingly. Water, the most common solvent, is highly susceptible to magnetization. MFs significantly affect its self-diffusion coefficient, evaporation rate, and cluster size. These changes relate to alterations in molecular structure, such as particle polarization and electrokinetic potential [77–81]. Table 3 presents various studies examining the effects of MFs on water, while Figure 3 visually depicts the hydrogen bonds of water molecules with and without SMFs.

Table 3. The magnetic field influences on water.

The Impact of Magnetic Fields on Water Purification	References
Exposure to a SMF of 0.4–0.6 T accelerated precipitation and improved sludge coagulation by reducing electrokinetic potential.	[14]
SMF of 0.0025 T lowered the conductivity of deionized water, attributed to changes in the ionic hydration shell.	[82,83]
Water's structural stability and viscosity are closely tied to its hydrogen bonding.	[84]
SMF exposure from 0 to 10 T increased hydrogen bonds by up to 0.34%, decreasing the self-diffusion coefficient while enhancing viscosity and stability.	[81]
A 6 T magnetic field strengthened hydrogen bonds in H_2O and D_2O by inhibiting thermal motion through the Lorentz force, termed "enhanced-dynamic magnetic susceptibility."	[80]
Moderate MFs (less than 1 T) can also promote hydrogen bond synthesis.	[79]
MFs may weaken hydrogen bonds between water clusters but enhance bonding within the clusters.	[85]
Magnetized water has a lower friction coefficient than unmagnetized water, indicating reduced hydrogen bond strength.	[78]
MFs alter hydrogen bonding dynamics in water, enhancing reactions like improved adsorption.	[77]

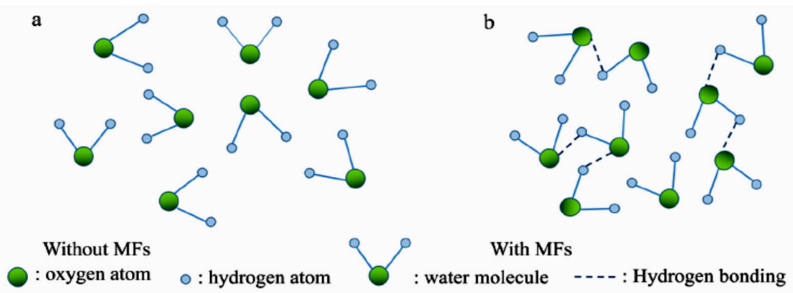

Figure 3. Magnetic fields enhance the H_2 bonds between water molecules. (**a**): H_2 bonds of water molecules without static MFs, and (**b**): H_2 bonds of water molecules in the presence of static MFs [13].

As a compression, Table 4 presents the effects of SMFs on WWT containing heavy metals, based on various relevant studies. It specifies the removed species, the magnetic field intensity, and the observed effects.

Table 4. Effects of SMFs on the heavy metal removal.

Removed Species	Adsorbents	MFI (T)	Observed Effects	References
Cu^{2+}	Zerovalent iron	<0.001	Removal efficiency increased by 88%	[86]
Cd^{2+}, Zn^{2+}	Zeolite and carbon modified with calcium and iron	0.086	Total molar removal increased by 10%–20%	[87]
Cu^{2+}, Pb^{2+}, Cd^{2+}	Granular activated alumina	0.118	Removal efficiency increased by 1.9%–8.2%	[88]
Zn^{2+}	Na-rectorite	0.32	Adsorption capacity increased by 10%	[89]
Cu^{2+}	Ca-rectorite	0.34	Adsorption capacity increased by 12%	[90]
As^{5+}	Ferric chloride	0.35	Removal efficiency increased by 6%–50% at different coagulant levels	[91]
Cu^{2+}, Ni^{2+}, Cd^{2+}	Activated carbon	0.517	Total molar removal increased by 11%	[92]
Cu^{2+}, Ni^{2+}	Vermiculite and halloysite	0.518	Removal efficiency decreased by 5.2% and 20.5%, respectively	[92]
Cd^{2+}, Zn^{2+}	Activated carbon	1	Adsorption capacity increased by 63% and 15%, respectively	[93]

3.4. Wastewater Treatment

Rapid population growth has significantly increased water consumption, worsening water pollution. Researchers have explored various physical, chemical, and biological methods, including magnetic fields, to address these challenges. While studies show that higher MFs intensities improve the removal of organic compounds such as a 30% increase in phenol removal at 450 mT, as noted in a study by Jung et al. [94], mixed effects on bacterial biodegradation are noted. Sakai et al. explored a submerged filter system using magnetically anisotropic tubular media with a high magnetization of 2100 Oe for sewage treatment through magnetic seeding. This system effectively treated sewage with a COD concentration of 200 mg/L, achieving up to 94% removal within 8 h. The results indicate that magnetic field intensity has a mixed effect on the biodegradation of pollutants, as different bacteria exhibit varying magnetic susceptibilities, leading to either inhibition or enhancement of activity. However, the optimal magnetic field intensity to enhance bacterial activity and biodegradation remains unclear, necessitating further research [95]. While implementing MFs in water treatment has potential, it has limitations. A key factor is exposure intensity, which typically ranges from 1 mT to 1 T. Higher intensity may hinder bacterial activity, impacting treatment performance. Each bacterium responds differently to magnetic fields, with some thriving under high intensities and others preferring lower levels. Thus, understanding these dynamics is crucial, as specific bacteria can either obstruct or aid treatment processes [96,97].

Additionally, the influent flow mode; single pass versus recirculation, affects coagulation and contaminant removal efficiency. Studies indicate that recirculation leads to better removal performance due to the magnetic memory effect, which enhances particle interactions and solid–liquid separation. For biological wastewater treatment, a single pass flow configuration is generally more effective [9,79,96,98–101].

4. Magnetic Water

Magnetic water treatment (MWT) modifies the physical and chemical properties of water through magnetic field exposure, offering benefits such as scale prevention, improved soil quality, enhanced plant growth, increased crop yields, water conservation, and wastewater treatment. This process restructures water molecules into small hexagonal clusters, facilitating their movement through microorganisms' cell membranes while blocking toxins, making magnetized water biologically advantageous [102]. The use of electromagnetic fields (EMFs) has expanded in various sectors, including environmental management and industry, with MWT recognized for its potential benefits amid rising water demands and droughts. Research shows that MWT improves irrigation water quality, enhances crop yields, prevents scale formation, and treats wastewater, while also exhibiting antimicrobial properties beneficial for food processing [103]. Magnetic wastewater treatment (MWWT) uses EMFs to enhance treatment processes, offering safety, environmental benefits, low costs, and no known harmful effects. EMFs modify water properties, promote sludge precipitation, and improve the removal of phosphorus and organic compounds. Integrating cleaning agents with MWT boosts the agents' effectiveness, allowing for a reduction in cleaner consumption by one-third to one-fourth [104].

Research includes magnetite slurry, magnetic particles, and pulsed electric fields. Most MWWT systems employ magnets or electromagnets to remove pollutants like phosphates and heavy metals, while SMFs are gaining interest, though more studies are needed on their effects on organic substrate biodegradation, especially nitrogen compounds [105,106]. However, the effects of MFs on the biodegradation of organic substrates are not well understood and the optimal MF strength for enhancing biological processes remains unclear. For instance, Jung et al., observed positive effects at an induction of 490 mT. They demonstrated that the impact of magnetic poles on phenol biodegradation. The magnetic north pole slowed phenol reduction and decreased oxygen consumption, inhibiting microorganisms. In contrast, the magnetic south pole accelerated phenol degradation, increased oxygen consumption, and led to excessive extracellular protein build-up, enhancing microbial activity. The findings suggest that the south pole promotes bio-oxidation of phenol, while the north pole inhibits it, with extracellular protein secretion as a positive indicator of biodegradation [94].

Magnetic particle technology is essential in MWWT for its absorption and coagulation capabilities, effectively recovering metals from electroplating rinse water, sewage sludge, and hydrometallurgical effluents. This process attaches pollutants to a magnetic carrier, usually magnetite, enabling efficient separation and reuse. A study by Sakai investigated a submerged filter system with magnetically anisotropic tubular media for sewage treatment. By adding ferromagnetic powder of iron oxide to activated sludge, biofilm formation was enhanced through magnetic attraction, achieving 72% to 94% COD removal from sewage at a concentration of 0.2 g/L over 8 h, with biofilm formation occurring in just 15 min [95].

5. Superconductor and High Magnetic Field

In this section, we discuss the superconductor and high magnetic field in terms of applications and wastewater treatment, magnetic separation of industrial waste waters, and high gradient magnetic separator and wastewater treatment as shown in Figure 4.

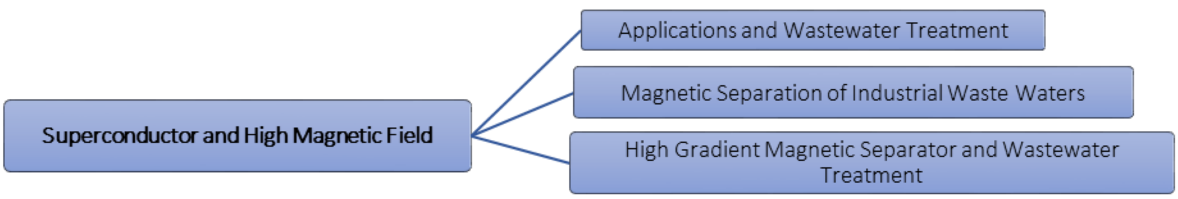

Figure 4. Superconductor and high magnetic field diagram [9,107–113].

5.1. Applications and Wastewater Treatment

Superconducting magnetic separation systems are becoming vital for wastewater treatment. A newly developed large bore conduction-cooled magnet improves these capabilities, building on techniques used since the 1970s for heavy metal ion removal. With only 2.5% of Earth's water being fresh and climate change threatening availability, compact systems for sewage and groundwater treatment are essential [110]. These superconducting systems offer advantages over conventional activated sludge treatment, such as higher efficiency, faster processing, and reduced costs. Conduction-cooled magnets are more convenient and cost-effective than liquid helium-cooled options [109]. Following K. Watanabe's introduction of the first conduction-cooled magnet in 1992, advancements have resulted in commercially available cryogen-free systems that generate high magnetic fields. Optimal performance requires a magnetic field above 0.7 T. While large bore magnets typically rely on liquid helium, conduction-cooled designs face challenges that require further research. The manufacturing process utilizes dry winding technology for insulation and stability, ensuring secure conductor placement [108].

Liu et al. developed a superconducting magnet with NbTi solenoid coils, featuring a 400 mm horizontal warm bore and a maximum central field strength of 2.56 T. Its two-stage 1.5 W 4 K GM cryocooler cools the system to 4.8 K in about 65 h. Testing confirmed it met design specifications. The magnet has a 460 mm inner bore solenoid made from insulated multi-filamentary NbTi/Cu wires, each 0.55 mm in diameter. Operating at 65 A, it generates a central field of 2.56 T, with simulations suggesting a peak of 3.4 T. A 20% safety margin is included for stability. The coil is wound on an aluminum former designed to minimize eddy current heat and simplify assembly. A copper braided layer enhances conductance, and a fiberglass binding layer manages hoop stress from the Lorentz force. The magnet is protected with diodes, and after multiple cycles, three quench incidents were recorded at 55 A, 62 A, and 69 A. It operated successfully at 65 A, maintaining a maximum temperature rise below 70 K during the 69 A quench [113].

In 2023, Nicola Di Costanzo et al. studied the rising global production of sewage sludge and evaluated anaerobic digestion as a sustainable management strategy. This process creates methane-rich biogas and nutrient-rich digestate. They investigated the effects of a 1.5 T static magnetic field (SMF) on sewage sludge's chemical composition and methane production, focusing on flow rate, mixing ratios, and total solid content. Results showed that the SMF decreased methane production by 24% and reduced concentrations of ionic species (NH^{4+}, NO^{-3} $PO_4{}^{-3}$, $SO_4{}^{-2}$, and Mg^{+2}) in the sludge's liquid phase. However, it also facilitated the precipitation of valuable compounds like struvite. While the high-intensity SMF negatively impacted methane generation, it supported nutrient recovery and circular economy principles. Further research is needed to understand these effects and optimize sludge management [114].

5.2. Magnetic Separation of Industrial Waste Waters

Magnetic separation techniques have been used since the 1840s in mining to concentrate magnetic ore and remove magnetizable particles from slurries. The introduction of high-field superconducting magnets in the 1960s led to superconducting separators, initially for refining kaolin clay. Recently, interest has shifted to environmental applications, resulting in superconducting separators for water purification and sulfur removal from coal. The effectiveness of these processes relies on optimizing factors like particle size, magnetic susceptibility, magnetic force density, and flow velocity. Gillet et al. [115] conducted research that supports the use of cryomagnetic separation for nonferrous waste. They describe a separator featuring an integrated liquefaction unit and a powerful 5 T magnetic field. The study emphasizes the system's automated operation and its potential environmental benefits, particularly for extracting metals from industrial effluents. Additionally, it explores how high-temperature superconductors could improve magnetic separation technology in the future.

Hartikainen et al., studied open gradient magnetic separation as a continuous method without matrix elements. They developed a separator using a liquid helium cryostat and interchangeable NbTi and Nb_3Sn coils to purify synthetic and real steel mill wastewater. This process involved chemical treatment to prepare dissolved metals like chromium, iron, nickel, and molybdenum for magnetic separation using ferromagnetic magnetite. The separator achieved 82% separation efficiency for chromium in synthetic wastewater and a 55% reduction in molybdenum concentrations in genuine wastewater as magnetic flux density increased, demonstrating its potential for effective wastewater purification. The flow velocity of the wastewater through the separation zone was maintained at 7 L/min. Chromium concentrations in the purified samples were determined using AAS spectroscopy, with each sample undergoing three analyses, and mean values reported in Table 4. The maximum magnetic flux density achieved with NbTi coils was 3 T, at which only 18% of the original chromium concentration remained. A gradual decrease in concentration with increasing magnetic flux density suggests that higher fields could enhance separation efficiency. However, the results from genuine wastewater were unsatisfactory due to pH stabilization challenges. Molybdenum (Mo) ions behaved as expected, remaining bound to the ferrugo and not desorbing with reduced pH. Table 5 also presents the concentrations of molybdenum after separation, with a flow velocity of 4.5 L/min [116].

Table 5. Heavy metals concentrations in wastewater before separation and the concentrations of Cr and Mo after separation [116].

Heavy Metals Concentrations in Wastewater Before Separation	**Concentration (mg/L)**
Solid matter	8.8
Dissolved Cr	0.13
Dissolved Ni	<0.01
Dissolved Fe	0.05
Dissolved Mo	9.8
Total Cr	0.25
Total Ni	0.34
Total Fe	0.39
Total Mo	9.8
Magnetic Flux Density (T)	Cr Concentration After Separation
0.7	6 mg/L
1.3	6 mg/L
1.8	5.5 mg/L
2.4	5.5 mg/L
3.0	5.5 mg/L
Magnetic Flux Density (T)	Mo Concentration After Separation
1.0	6.2 mg/L
1.5	6.0 mg/L
2.0	5.9 mg/L
2.5	5.6 mg/L
3.0	5.5 mg/L

On the other hand, He et al. [117] studied an innovative up-concentration process for carbon-neutral wastewater treatment using an enhanced magnetic separation (EMS) system. This pilot-scale system maximizes energy recovery from municipal wastewater through magnetic-driven separation and adsorption. After one year of operating a 300 m^3/d EMS system, it removed over 80% of particulate organics and 60% of soluble organics in just 10 min, using only 0.036 kWh/m^3. The EMS system offers significant advantages in efficiency, space utilization, and cost-effectiveness, making it promising for organic recovery. Baek et al. [118] explored a wastewater treatment method using magnetic microbeads and a magnetic field. Their tests showed that contaminants attach to microbeads during stirring, forming magnetic flocs that can be easily separated. The method requires only a compact precipitation tank and reduces processing time due to strong magnetic attraction. Experimental results confirmed that flocs can be manipulated with a standard electromagnet, validating the method's feasibility for optimal wastewater treatment systems.

5.3. High Gradient Magnetic Separator and Wastewater Treatment

One prominent technique is High Gradient Magnetic Separation (HGMS), which uses a magnetically susceptible wire bed within an electromagnet. When a magnetic field is applied, it creates non-uniformities that generate significant field gradients, attracting and capturing magnetic particles. The effectiveness of HGMS relies on the strength of these gradients, as well as factors like particle size and magnetic properties [76]. Ha et al. [75] highlight that superconducting HGMS systems are particularly effective in removing pollutants and paramagnetic substances due to their ability to generate higher magnetic field strengths. For instance, cryocooled Nb-Ti superconducting magnets can achieve field strengths up to 6 Tesla. The efficiency of HGMS has been demonstrated in steam condensers of thermal power stations, where contaminants like α-Fe_2O_3 (hematite) and γ-Fe_2O_3 (maghemite) were effectively removed, reducing water turbidity. Additionally, decreasing the wire diameter of the magnetic filter and increasing the mesh size improved turbidity removal, as these changes affect the magnetic gradient and enhance purification efficiency. Tuutijärvi et al. [67] also demonstrated the successful adsorption of arsenic pollutants (As(V)) using a combination of magnetic separation and γ-Fe_2O_3 nanoparticles.

Some elements, like copper, are essential for human health but can also be toxic, often appearing as heavy metal contaminants in the environment. The release of industrial effluents containing heavy metals into water systems is a significant environmental challenge. Traditional wastewater treatment methods such as ion exchange, electro-refining, coagulation, reverse osmosis, and chemical treatments have limitations in cost, energy use, and sludge production. High Gradient Magnetic Separation (HGMS) presents an effective and eco-friendly alternative for recovering metals from wastewater, using magnetic force to separate pure metals without coagulants. The effectiveness of HGMS depends on the geometric properties and saturation of the matrix, as noted by Vincent-Viry et al. [119]. HGMS has proven effective for small, weakly magnetic particles. To increase the magnetic field gradient, ferromagnetic wires can be incorporated, enhancing the force on particles. HGMS has been successfully applied in various industries. For example, Newns and Pascoe [120] demonstrated the removal of iron from kaolin. Additionally, metal ions can be removed from wastewater using magnetic hydroxide flocs, which can be separated effectively. Arsenic removal was improved by 15% with the addition of cationic polyacrylamide during HGMS such as Okada et al. [112] successfully removed arsenic from geothermal water using iron (III) sulfate and HGMS. Oka et al. [111] achieved over 85% removal efficiency for ferrite precipitates in laboratory wastewater with HGMS. S.K. Baik et al. [107] studied a High Gradient Magnetic Separator (HGMS) that uses a matrix to create a high magnetic field gradient, attracting ferro- or paramagnetic particles with forces thousands of times stronger than those from magnetic flux density alone. This makes HGMS more effective than other magnetic separators. The matrices, typically made of stainless steel wires, are used in a superconducting HGMS designed for wastewater purification, generating a magnetic field of up to 6 T. The researchers analyzed the magnetic field and its gradient to calculate the forces on particles in wastewater. Using the Finite Element Method (FEM), they conducted both 2D and 3D analyses, finding that the magnetic force on a particle is, on average, 160 times greater with the matrix. The 3D analysis confirmed a slightly higher peak flux density, while the overall field distribution remained similar to the 2D results.

6. MgB_2 Superconductors Challenges

MgB_2 presents a compelling avenue for advanced applications due to its unique combination of superconducting properties, cost-effectiveness, and operational flexibility [121,122]. Characterized by a simple binary composition and a critically high Tc ≈ 39 K, MgB_2 surpasses conventional LTS [123,124]. This elevated Tc enables operation within the 10–20 K range, allowing the use of energy-efficient cryocoolers rather than complex liquid helium systems- significantly reducing cooling costs and infrastructure demands [125]. Furthermore, MgB_2 exhibits a high Jc and demonstrates mechanical adaptability in wire and tape configurations, making it a versatile candidate for applications spanning MRI, particle accelerator magnets, and next-generation power grids [126–128]. While challenges in scalability and mechanical brittleness persist, advances in composite engineering and doping strategies (e.g., carbon nanotube integration) are rapidly enhancing its durability and high-field performance.

MgB_2 is a simple metallic binary compound that exhibits the highest T_c among all known superconductors to binary alloys. With a $T_c \approx 39$ K, MgB_2 surpassed the T_c of inter-metallic superconductors that were prevalent during that time. This groundbreaking announcement sparked widespread enthusiasm within the global scientific community, igniting a surge of research interest ranging from investigations into fundamental physics properties to practical applications. The exceptional characteristics of MgB_2 superconductor make it an attractive material for a diverse range of applications, including large-scale systems and electronic devices. Key attributes that contribute to its appeal include its high T_c, large coherence lengths (ξ), J_c, simple crystal structure, and high upper critical fields (H_{c2}). Additionally, MgB_2 exhibits transparency of its grain boundaries to current flow [129]. Researchers have successfully fabricated MgB_2 into various shapes, such as bulks [130,131], single crystals [132,133], thin films [134,135], wires [136,137], and tapes [138,139].

In comparison to traditional metallic low-temperature superconductors (LTS) and copper oxide high-temperature superconductors (HTS), MgB_2 stands out due to its distinctive characteristics. Notably, MgB_2 exhibits a significantly higher T_c than LTS, while also experiencing fewer challenges associated with anisotropy and weak links at grain boundaries, which are inherent in HTS [140]).

The crystal structure of MgB_2 is depicted in Figure 5, revealing its simple binary compound nature and a hexagonal AlB_2 type structure resembling other borides. The unit structure comprises alternating hexagonal layers of magnesium atoms and graphite-like honeycomb layers of boron atoms. The magnesium layers separate the boron planes, with each magnesium atom positioned between the centers of the hexagons forming the boron lattice planes. Within each boron layer, a hexagon consists of six boron atoms, resulting in an overall 1:2 Mg-B ratio within the unit cell. The entire material structure of MgB_2 exhibits anisotropy [140,141], with the B-B distance within the plane being significantly shorter than the distance between layers.

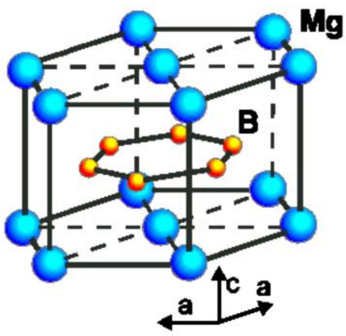

Figure 5. Hexagonal crystal structure of MgB_2 [142].

Table 6 provides a comprehensive overview of the typical parameters of MgB_2 in comparison to other practical superconductors. Numerous magnetization and transport measurements have been conducted to investigate the behavior of MgB_2, and the results consistently indicate the absence of weak-link electromagnetic effects at grain boundaries [129] and fast flux creep [143]. Transport measurements carried out under high MFs using dense bulk samples have yielded J_c values that align closely with those obtained from magnetization measurements [144]. This correspondence lends support to the notion that the inductive current flows coherently throughout the entirety of the sample, unaffected by the presence of grain boundaries. Consequently, the motion of flux lines within the material will play a decisive role in determining the dependence of J_c on both MF and temperature. The absence of weak-link behavior at grain boundaries in MgB_2 is a significant advantage, as it enhances the overall electrical transport properties and ensures the coherence of the superconducting current across the material. These findings contribute to a more comprehensive understanding of the underlying mechanisms governing the superconducting properties of MgB_2, paving the way for further exploration and optimization of its flux pinning and current-carrying capabilities.

Table 6. Basic properties of the practical superconductors [145].

Parameter	NbTi	Nb_3Sn	MgB_2	YBCO	Bi-2223
T_c (K)	9	18	39	92	110
Anisotropy	Negligible	Negligible	1.5~5	5~7	50~200
J_c at 4.2 K (A/cm^2)	~10^6	~10^6	~10^6	~10^6	~10^7
H_{c2} at 4.2 K (T)	11–12	25–29	15–20	>100	>100
H_{irr} at 4.2 K (T)	10~11	21~24	6~12	5~7 (77 K)	0.2 (77 K)
Coherence length ξ(0) (nm)	4~5	3	4~5	1.5	1.5
Penetration depth λ(0) (nm)	240	65	100~140	150	150
Resistivity $\rho(T_c)$ (μΩcm)	60	5	0.4	150~800	40~60

For the production of superconducting magnets, the essential material forms are long-length, flexible conductors capable of being wound into coils. In the context of magnesium diboride (MgB_2), these conductors are fabricated as wires and tapes. The dominant industrial-scale approach for their manufacture is the Powder-in-Tube (PIT) method, which is broadly categorized into two principal variants: the in situ and ex situ routes. The selection between these routes represents a critical engineering trade-off between final superconducting performance and manufacturing considerations (Table 7) [146,147].

Table 7. Comparison of PIT fabrication routes for MgB_2 wires and tapes [122,124,128].

Fabrication Route	Description	Key Process Parameters	Advantages	Disadvantages
In Situ PIT	Precursor powders (Mg + B) are packed, cold-worked, and then reacted within a metallic sheath to form the MgB_2 conductor.	• Reaction Temperature: 600–900 °C • Sheath Material: Fe, Ni, Monel • Precursors: Mg, amorphous/crystalline B	• Forms clean, reactive grain boundaries, leading to high Jc. • Generally superior in-field performance.	• Significant volume contraction (~25%) during reaction can introduce porosity. • Potential for unreacted Mg to remain.
Ex Situ PIT	Pre-reacted MgB_2 powder is packed, cold-worked, and then sintered within a metallic sheath to form the final conductor.	• Sintering Temperature: 800–1000 °C • Starting Material: High-purity MgB_2 powder	• Excellent control of initial stoichiometry and purity. • Greater dimensional stability during heat treatment.	• Powder is susceptible to oxidation/contamination. • Potentially weaker inter-grain links, leading to reduced Jc.

6.1. Challenges and Opportunities in WWT Applications

Despite its inherent advantages, the application of MgB_2 in WWT systems faces hurdles that underscore untapped potential rather than insurmountable limitations:

1. Cryogenic Operational Efficiency:

MgB_2's 10–20 K operational window offers a practical advantage over traditional LTS, as cryocoolers for this range are increasingly efficient and modular. Optimizing thermal budgets and parasitic heat loads could further enhance energy efficiency, positioning MgB_2 as a cost-competitive solution for specialized applications.

2. Material Innovation:

While MgB_2's brittleness complicates large-scale deployment, its simple composition and low raw material costs enable rapid prototyping of composite architectures (e.g., SiC-doped wires) to improve mechanical resilience. Advances in grain boundary engineering are also poised to boost flux pinning, enhancing Jc at higher MFs.

3. Magnetic Separation Superiority:

MgB_2-based HGMS systems hold unique promise for removing paramagnetic contaminants (e.g., heavy metals, microplastics) with precision. Its Tc advantage over LTS allows stronger MFs at lower cooling costs, enabling targeted pollutant removal in industrial effluents where regulatory compliance justifies investment.

4. Economic and Hybrid Potential:

MgB_2's low production costs and compatibility with hybrid systems (e.g., integration with electrochemical reactors or membrane filtration) could offset cryogenic expenses. Pilot-scale trials focusing on lifecycle cost analyses are critical to demonstrating its long-term viability for niche WW applications.

The main hurdle for MgB_2 is its cryogenic cooling which demands cryogenic equipment. Cryogenic equipment are expensive to buy and costly to run. Additionally, MgB_2 research has prioritized magnets and energy over water purification, leaving its wastewater applications underexplored. Existing magnetic separation methods (e.g., electromagnets) remain more economical, and scaling MgB_2 for large treatment plants needs more research.

MgB_2 could find use in specialized applications, such as ultra-high-field magnetic nanoparticle recovery in high-value industrial wastewater. Advances in cryogen-free cooling and hybrid systems (combining MgB_2 with conventional methods) may improve feasibility. While still early, further research into scalable fabrication, stability, and cost–benefit analysis is crucial to unlocking MgB_2's potential in environmental remediation.

Main point is permanent magnets can apply weak Magnetic field. Superconducting magnets with room temperature bores can apply moderate of high Magnetic fields. This is not well investigated yet. MgB_2 has advantages over other superconductors as it does not require liquid helium and can be cooled by conduction cryogenic cooling.

6.2. Pathways for Accelerated Adoption

To advance the integration of MgB_2 into WWT systems, the following strategic priorities are proposed:

1. Material Optimization

Refinement of doping strategies—such as the incorporation of TiB_2 nanoparticles or graphene—is critical to enhance the Jc and mechanical stability of MgB_2. These dopants improve flux-pinning mechanisms and grain boundary cohesion, enabling higher magnetic field tolerance and durability in harsh operational environments.

2. Cryogenic System Innovation

Development of compact, high-efficiency cryocoolers with improved coefficients of performance is essential to minimize energy demands. Modular designs tailored for WWT infrastructure could reduce cooling costs while enabling scalable deployment in industrial or decentralized settings.

3. Interdisciplinary Synergy

Collaborative frameworks between materials scientists, cryogenic engineers, and environmental researchers are necessary to design MgB_2-enhanced hybrid reactors. Such systems could integrate superconducting magnetic separation with electrochemical oxidation processes, targeting recalcitrant organic pollutants (e.g., pharmaceuticals, dyes) with unprecedented energy efficiency.

6.3. Limitations and Controversies in Applying MgB_2 Superconductors to WWT

While MgB_2 superconductors offer promising properties for magnetic water and wastewater treatment, like for instance, relatively high critical temperature (Tc $\approx$ 39 K), and strong magnetic field generation [28,130,147], the practical application of superconductors in water and wastewater treatment is still controversial.

The main challenge lies in the uncertain mechanisms of magnetic field interaction with water and contaminants. The effects on hydrogen bonding, electrokinetic properties, and microbial activity vary widely among studies, as experimental results in magnetic water treatment are often inconsistent. Moreover, many studies report negligible or contradictory effects, while others indicate neutral or even inhibitory effects [12,65,78–81,94–97]. This inconsistency and lack of reproducibility hinders the development of unified design of magnetic field-enhanced systems.

Furthermore, MgB_2 fabrication includes a harsh cryogenic process and exhibits mechanical fragility, which complicates system integration and increases energy and infrastructure costs—especially in municipal or decentralized settings [125,127]. Therefore, its application may be more feasible in specialized industrial scenarios, particularly for the recovery of high-value pollutants.

In addition, most target contaminants (e.g., organic matter and nutrients) are non-magnetic, requiring the use of magnetic seed materials for their effective separation, further complicating the process [15,27]. Without comprehensive pilot-scale validation and cost–benefit analysis, the widespread use of MgB_2 in wastewater treatment remains premature.

7. General Discussion

Heavy metals are major freshwater and industrial activities pollutants, posing serious health risks due to their toxicity and persistence. According to conventional methods for heavy metals removal/reduce in WWT, researchers have explored various methods for removing heavy metals from WW. Traditional approaches include electrochemical treatments like EC, EF, and ED. Other techniques involve physicochemical processes such as chemical precipitation and ion exchange, along with adsorption using materials like activated carbon and wood sawdust. Although electrochemical treatments have historically been overlooked due to high electricity costs. Numerous studies examined traditional methods like membrane filtration, ion exchange, chemical precipitation, and adsorption. While EC, EF, and ED offer promising solutions for WWT, each method has inherent disadvantages that can impact their effectiveness and adoption. EC faces significant challenges related to reactor design and electrode reliability. These issues can hinder the process's efficiency and scalability, making it less attractive for widespread use. Additionally, the operational costs associated with EC can be high due to energy consumption and the need for regular maintenance of sacrificial electrodes. Furthermore, although EC is effective in removing small colloidal particles, it may struggle with highly soluble pollutants, limiting its applicability in certain WW scenarios. EF, while adaptable and effective for removing heavy metals, also has its limitations. Its efficiency can diminish in very low concentration scenarios, requiring specific conditions to achieve optimal performance. This need for careful optimization can complicate the implementation of EF in practical applications. Moreover, the integration of EF into existing systems may necessitate additional infrastructure, which can be a barrier for some facilities. ED, although cost-effective and selective for heavy metal recovery, is primarily limited to specific applications. This restriction could reduce its utility in broader WWT contexts. Additionally, ED requires stringent control of operating conditions, such as voltage and pH, to maintain optimal performance. This complexity can pose operational challenges and necessitate advanced monitoring and control systems, making it less accessible for some treatment facilities [35–38].

The applications of MFs in water purification, coagulation and sedimentation of colloidal particles, and WWT, emphasizing their potential benefits and limitations while calling for further research in this area. MFs have shown effectiveness in separation processes by influencing the characteristics of contaminants, thereby enhancing purification efficiency when combined with other techniques. Various magnetic technologies utilize permanent magnets or high-gradient magnetic separation (HGMS) in methods, each affecting system performance differently. However, the mechanisms behind these applications are not fully understood, leading to conflicting theories in the literature [12,64,65].

A strong magnetic gradient is particularly important for effective particle separation, especially when dealing with small volumes. Moreover, using a magnetic gradient in combination with an alternating field proves to be more effective than relying solely on a static field resulting in faster crystallization and improved descaling outcomes. Magnetic filtration removes suspended solids and starch by creating a magnetic gradient as a solution flows through coils magnetized by external permanent magnets. These magnets, arranged with alternating poles, generate an oscillating MF that enhances the gradient by concentrating flux lines. As the solution moves through the coils, charged particles are attracted and separated. The effectiveness of this process depends on the magnetic strength and the characteristics of the coil magnetization [65,69,70].

Magnetic memory suggests that when a MF interacts with water molecules, it alters their kinetic energy, affecting dipole momentum and leading to stable particle aggregation. These aggregates can remain stable even after the magnets are removed, allowing magnetic memory to persist nearly indefinitely. However, the effects of magnetic memory on microorganisms differ from those on water molecules. While stronger magnetic memory can enhance particle aggregation, it does not have the same effect on bacteria. Instead, weak or strong magnetic memory may either promote or hinder bacterial growth, influencing the performance of systems like WWT. These effects arise from variations in magnetic susceptibility [12]. Moreover, magnetic treatment also aids in reducing scaling by encouraging homogeneous nucleation such as in $CaCO_3$. However, careful exposure to the MF is vital when treating water with silica to ensure effective crystallization and minimize scaling. Various methods have been used to combat scaling, including electrochemical processes and chemical inhibitors, but these can pose health risks in drinking water systems [68].

The effects of MFs on water purification processes that the exposure to a SMF of 0.4–0.6 T enhanced precipitation and improved sludge coagulation by reducing electrokinetic potential. This suggests that MFs can facilitate the aggregation of particles, potentially increasing the efficiency of WWT and observed that a much lower SMF of 0.0025 T decreased the conductivity of deionized water, indicating that MFs can affect ionic interactions within water. While studies highlighted the significance of hydrogen bonding in water, stating that its structural stability and viscosity are closely linked to these interactions, by demonstrating that exposure to SMFs ranging from 0 to 10 T could increase hydrogen bonds by up to 0.34%, which resulted in decreased self-diffusion coefficients and enhanced viscosity and stability of water. This finding suggests that MFs can promote water's structural integrity, potentially leading to improved purification outcomes. Furthermore, a 6 T MF can strengthen hydrogen bonds in both H_2O and D_2O, inhibiting thermal motion through the Lorentz force. This phenomenon, termed "enhanced-dynamic magnetic susceptibility," indicates that strong MFs may significantly influence molecular interactions in water while MFs may weaken hydrogen bonds between water clusters, they can enhance bonding within the clusters, as indicated by a lower friction coefficient in magnetized water. MFs alter hydrogen bonding dynamics, thereby enhancing reactions such as improved adsorption. Collectively, these findings suggest that MFs can play a crucial role in optimizing water purification processes by modifying the molecular interactions and structural properties of water [14,77–85].

The impact of SMFs on the removal of heavy metals from WW, illustrating variations in removal efficiency based on the type of adsorbent and MF intensity. Notably, the use of zerovalent iron for copper ion (Cu^{2+}) removal demonstrated a remarkable 88% increase in efficiency with an SMF intensity of less than 0.001 T. This suggests that even minimal MF exposure can significantly enhance the removal of specific heavy metal ions, making it an effective strategy for WWT. The application of zeolite and carbon modified with calcium and iron at an SMF of 0.086 T resulted in a total molar removal increase of only 10% to 20% for cadmium (Cd^{2+}) and zinc (Zn^{2+}). This indicates that while SMFs can improve adsorption, the extent of enhancement may vary significantly depending on the materials used. Granular activated alumina showed a modest increase in removal efficiency for multiple heavy metals (Cu^{2+}, Pb^{2+}, Cd^{2+}) at an intensity of 0.118 T, with improvements ranging from 1.9% to 8.2%. This variability highlights the need for tailored approaches when selecting adsorbents and MF strengths. Na-rectorite and Ca-rectorite exhibited increases in adsorption capacity for zinc (Zn^{2+}) and copper (Cu^{2+}) at 0.32 T and 0.34 T, respectively, with increases of 10% and 12%. Conversely, vermiculite and halloysite, under similar conditions (0.518 T), showed a decrease in removal efficiency for copper and nickel (Cu^{2+}, Ni^{2+}), indicating that the effects of SMFs can be highly dependent on the specific adsorbents used. Ferric chloride demonstrated a notable improvement in the removal of arsenic (As^{5+}) with a removal efficiency increase ranging from 6% to 50% at an intensity of 0.35 T, suggesting that SMFs can enhance coagulation processes in certain contexts. Activated carbon displayed significant improvements in adsorption capacity for cadmium (Cd^{2+}) and zinc (Zn^{2+}) at 1 T, with increases of 63% and 15%, respectively, underscoring the potential of MFs in optimizing heavy metal removal [86–93].

Studies indicate that higher MF intensities can significantly improve the removal of organic compounds. For instance, a 30% increase in phenol removal at a MF intensity of 450 mT, a submerged filter system employing magnetically anisotropic tubular media with a high magnetization of 2100 Oe. This effectively treated sewage with a COD concentration of 200 mg/L, achieving an impressive removal efficiency of up to 94% within just 8 h. The mixed effects of MFs on bacterial biodegradation are particularly noteworthy; different bacterial strains exhibit varying magnetic susceptibilities, which can lead to either enhancement or inhibition of their metabolic activities. The optimal MF intensity for promoting bacterial activity and biodegradation remains ambiguous. While some studies suggest that intensities ranging from 1 mT to 1 T can be beneficial, higher MF strengths may inhibit bacterial function, thus impacting overall treatment performance. This variability indicates that specific bacteria may thrive under different magnetic conditions, complicating the establishment of a one-size-fits-all approach. Research indicates that recirculation enhances removal performance due to the magnetic memory effect, which improves particle interactions and solid–liquid separation. Conversely, biological WWT tends to be more effective with a single pass flow configuration. This suggests that the design and operational parameters of treatment systems must be carefully considered to optimize the benefits of MFs in conjunction with flow dynamics [94–97].

MWWT leverages EMFs to enhance various treatment processes, presenting numerous advantages such as safety, environmental benefits, low costs, and a lack of known harmful effects. The ability of EMFs to modify water properties significantly contributes to sludge precipitation and enhances the removal of phosphorus and organic compounds. Notably, integrating cleaning agents with MWWT can reduce their usage by up to 75%, showcasing the potential for significant cost savings and reduced chemical reliance. By incorporating ferromagnetic powder into activated sludge, achieved 72% to 94% COD removal within just 8 h, with biofilm formation occurring rapidly. This highlights the effectiveness of magnetic attraction in facilitating biofilm development, which is essential for efficient WWT [94,95,105,106].

Superconducting systems offer several advantages over conventional activated sludge treatment, notably higher efficiency and reduced processing times. For optimal performance, a MF intensity greater than 0.7 T is essential, with recent developments demonstrating the capability to generate fields as high as 2.56 T using NbTi solenoid coils. One such design operates at 65 A, achieving a central field strength of 2.56 T. This system features a unique construction with multi-filamentary NbTi/Cu wires, which ensures stability and effective heat management. Additionally, a safety margin of 20% signifies a robust design that can withstand operational stresses. The successful operation at high currents, with a maximum temperature rise maintained below 70 K during quench incidents, further confirms the reliability and effectiveness of these superconducting systems. In the realm of sewage sludge management, a separate study investigated the effects of a 1.5 T SMF on methane production during anaerobic digestion. The findings indicated a 24% reduction in methane production, along with decreased concentrations of several ionic species, including NH^{4+} and NO^{-3}. However, the application of the SMF also facilitated the precipitation of valuable nutrients such as struvite, suggesting a potential trade-off between methane yield and nutrient recovery. Moreover, the effectiveness of cryomagnetic separation for nonferrous waste has been demonstrated, utilizing a powerful 5 T MF to enhance metal extraction from industrial effluents. The automation of these systems offers significant environmental benefits, particularly in recovering valuable metals from WW streams. In a complementary approach, a separation efficiency of 82% for Cr was achieved in synthetic WW, along with a 55% reduction in molybdenum concentrations in real WW. Effective magnetic separation was maintained with a flow velocity of 7 L/min, although challenges related to pH stabilization in genuine WW were also noted [108–114].

The concentrations of heavy metals in WW after magnetic separation highlight the effectiveness of MFs separation via superconductors in reducing pollutant levels. Initially, the WW contained significant concentrations of several heavy metals, including dissolved Cr at 0.13 mg/L and Mo at 9.8 mg/L. The total concentrations of Cr and molybdenum were reported as 0.25 mg/L and 9.8 mg/L, respectively. The presence of solid matter at 8.8 mg/L further indicates a complex mixture requiring effective treatment solutions. The results indicated varying concentrations of Cr and molybdenum based on the applied magnetic flux density. For Cr, concentrations remained consistent at 6 mg/L across magnetic flux densities of 0.7 T and 1.3 T, and decreased slightly to 5.5 mg/L at higher densities of 1.8 T, 2.4 T, and 3.0 T. This suggests that while the initial removal was effective, increasing the magnetic flux density did not lead to further significant reductions in Cr concentrations. In contrast, the concentrations of molybdenum after separation exhibited a more gradual decline with increasing magnetic flux density. At 1.0 T, the molybdenum concentration was recorded at 6.2 mg/L, decreasing to 5.5 mg/L at higher densities of 2.5 T and 3.0 T. This trend indicates that magnetic separation is effective for molybdenum removal, albeit with diminishing returns at higher flux densities [115,116].

Over a year of operating a 300 m^3/d EMS system, the process removed more than 80% of particulate organics and 60% of soluble organics in just 10 min, utilizing only 0.036 kWh/m^3. This highlights the system's exceptional efficiency and cost-effectiveness in organic recovery, making it a promising solution for municipal WWT. the use of magnetic microbeads in WWT demonstrated that contaminants could effectively attach to microbeads during agitation, forming magnetic flocs that are easily separated. This method simplifies the treatment process, requiring only a compact precipitation tank and significantly reducing processing time due to the strong magnetic attraction of the flocs. The successful manipulation of these flocs with a standard electromagnet confirms the feasibility of this approach for optimizing WWT systems [117,118].

HGMS is another prominent technique, utilizing a magnetically susceptible wire bed within an electromagnet to create significant MF gradients. The effectiveness of HGMS is influenced by factors such as particle size and magnetic properties. superconducting HGMS systems can achieve field strengths up to 6 T, making them particularly effective for removing pollutants like iron oxides. For instance, the removal of α-Fe_2O_3 and γ-Fe_2O_3 from steam condensers significantly reduced water turbidity. Additionally, adjustments in wire diameter and mesh size can enhance purification efficiency by optimizing the magnetic gradient. HGMS also presents a viable solution for recovering heavy metals, which, while essential for human health, can become toxic in high concentrations. Traditional WWT methods often face limitations related to cost and efficiency. In contrast, HGMS utilizes magnetic forces to separate metals without the need for coagulants, offering an eco-friendly alternative. Studies indicate that the effectiveness of HGMS increases with the incorporation of ferromagnetic wires, enhancing the force exerted on particles achieved over 85% removal efficiency for ferrite precipitates in laboratory WW using HGMS, and the addition of cationic polyacrylamide improved arsenic removal by 15% during HGMS applications [67,75,76,111,119,120,124].

MgB_2 presents a promising alternative for superconducting applications due to its low production costs and the abundance of inexpensive raw materials. This versatility positions MgB_2 as a potential candidate for various applications, including in superconducting wires and tapes. However, its application in WWT remains largely unexplored, with several significant challenges hindering large-scale implementation. One major consideration is the limited research focused on the use of MgB_2 in WWT. While its superconducting properties are well understood, practical applications in this field are scarce. The predominant superconducting materials currently used in scientific and medical applications are NbTi and Nb_3Sn, which have proven track records. Consequently, the technology surrounding MgB_2 requires further validation before it can be effectively implemented in WWT processes. Operationally, MgB_2 superconductors must function at very low temperatures, around 39 K, necessitating complex cryogenic systems that consume substantial energy. This requirement poses significant challenges for large-scale WWT, which typically involves chemical and biological processes that may not align with the operational needs of superconductors. Additionally, the mechanical strength and stability of MgB_2 under the harsh conditions commonly found in WW environments could further limit its applicability. Despite its potential advantages, the economic feasibility of using MgB_2 in WWT is also a critical concern. Although MgB_2 is relatively cost-effective compared to other superconductors, the overall production costs can still be higher than conventional treatment methods. Therefore, the widespread adoption of MgB_2 in WW applications may be restricted to specific scenarios, such as the removal of heavy metals from hazardous industrial WW, which would require thorough research to establish its effectiveness. To make MgB_2 a viable option for

WWT several steps must be taken. Targeted studies are needed to identify the specific heavy metals present in hazardous and industrial WW. Additionally, enhancing MgB_2's properties through methods such as doping or composite creation will be crucial. Moreover, improving cooling systems and exploring hybrid approaches can help mitigate the energy demands of maintaining superconducting conditions. By integrating MgB_2 into a hybrid system with existing WWT facilities, it may be possible to leverage its superconducting properties to target specific pollutants effectively while minimizing disruption to other water constituents [121–128,146,147].

8. Conclusions

Conventional methods such as EC, EF, and ED offer viable solutions for WWT, yet each method has inherent disadvantages that can limit their effectiveness and widespread adoption. While these electrochemical techniques present innovative approaches, challenges related to reactor design, operational costs, and inefficiencies in removing hazardous pollutants from industrial WW must be addressed to enhance their efficiency and promote their use in various industries. This is particularly critical as rapid population growth intensifies water consumption and increases pollution levels, driving the need for diverse treatment methods, including the application of MF technology.

Despite extensive research, there remains a notable gap in reviews that focus on the role of magnetization and the potential of magnetic technology in water treatment. Physical methods, such as magnetic treatment, have shown effectiveness and demonstrate high performance in high WWT quality. Studies underscore the complex impact of MFs on water purification, with MWWT emerging as a promising approach to enhance WWT processes. The ability to modify water properties, enhance sludge precipitation, and improve pollutant heavy metals removal efficiency presents significant advantages, including cost savings and environmental benefits.

The continued advancement of superconductors and their integration with biological processes will be crucial to fully realize the potential of MWWT in addressing water pollution. Furthermore, the integration of superconducting magnetic separation systems marks a significant step forward in tackling water pollution and resource scarcity. High MF strengths have been shown to enhance pollutant removal and resource recovery, yielding promising results in sewage sludge management and industrial WW purification. However, challenges remain in optimizing conditions for maximum efficiency.

While the MgB_2 superconductor shows great potential due to its unique superconducting properties and cost-effectiveness, its application in WWT faces considerable barriers, including limited research and the need for low operational temperatures. Future efforts should focus on targeted studies to better understand the types of pollutants in WW and enhance MgB_2's properties. Additionally, improvements in cryogenic systems and the exploration of hybrid treatment approaches could facilitate the integration of MgB_2 into WWT processes. By overcoming these challenges, MgB_2 could become a valuable and promising tool for achieving efficient and effective WW management, particularly in the removal of hazardous heavy metals.

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