**Al-Rafidain Journal of Engineering Sciences**

**Journal homepage https://rjes.iq/index.php/rjes**

**ISSN 3005-3153 (Online)**

# Review of Wastewater Treatment Techniques Using Magnetic Fields

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**ARTICLE INFO**

***Article history:***
Received 20 June 2025
Revised 20 June 2025
Accepted 30 June 2025
Available online 02 July 2025

***Keywords:***
Magnetic field ,
wastewater,
Pollutant removal,
Advanced oxidation processes (AOPs)

**ABSTRACT**

This review describes the new methods of wastewater treatment based on magnetic forces, showing their efficiency and effectiveness of pollutants removal. Different approaches are discussed such as magnetic separation, magnetically responsive materials, and magnetic field-assisted processes. It reviews their governing principles, functionality against various pollutants, and the benefits over conventional wastewater treatment processes. It also combines some of the problems and limitations hindering the implementation of the magnetic field technologies in practical applications. In addition, by merging the present research results and case studies, this review seeks to deliver aspects of how magnetic field-based approaches could be applied to improve wastewater treatment processes and also assist sustainable environmental management.

## 1. Introduction

Only 2.5% of the water found on Earth is classified as freshwater, but four billion people experience water scarcity, a number that will continue to increase by 2050, mostly in developing regions[1]. The implementation of magnetic fields in the field of wastewater treatment has been recognized as a potential approach to improving the efficiency of conventional methods and achieving an effective treatment of contaminants to the next generation of innovative wastewater treatment technology [2] . Magnetic techniques utilize the special characteristics of magnetic fields in the transport and removal of contaminants, helping to enhance sedimentation and the agglomeration of pollutants for easier removal [3] . Magneto-induced technologies have been shown in recent studies to allow for dramatically shorter treatment times and lower energy consumption levels, thus presenting a desirable option both for larger wastewater facilities as well a smaller decentralized systems[4] . Until then, investigating the mechanisms of magnetic fields affecting wastewater treatment will be essential to improving these methods and extending their use to other environmental conditions, as research continues to develop[5] . Such knowledge may trump developing strategies to optimize performance with minimum cost which can finally lead to a higher potential of sustainability in global water utilization[6].

### *1.1.Background on Wastewater Treatment by magnetic methods*

Water is a diamagnetic material. The water molecule ($H_2O$) molecule is made up of one oxygen atom and two hydrogen atoms, held in an isosceles arrangement by two

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https://doi.org/10.61268/74pn6f46

covalent bonds or shared pair of elections, forming an angle of 104.45° at the apex, (Figure1) due to two pair of unshared electrons associated with the oxygen, (and these give the oxygen a slight negative charge, and a slight positive charge on the other hand hydrogen. And thus this arrangement of water molecule will behave as a magnetic dipole. As a result, the water molecules tend to arrange themselves in the direction of a hydrogen bond, and this hydrogen bond tends to make water molecules aggregate, as you can see in figure 2. Water has four of its properties due to hydrogen bonds: (1) water is more dense in its liquid state than solid state, (2) water has cohesion and high boiling point, (3) water has an extremely high solvent power [7].

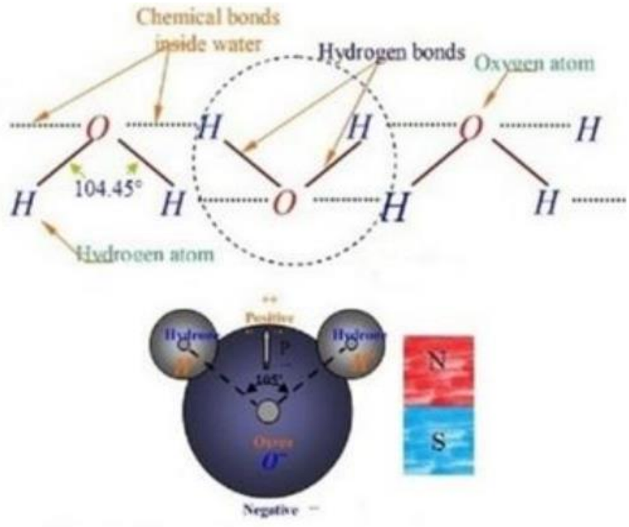


**Figure1** Normal Water molecule[7]

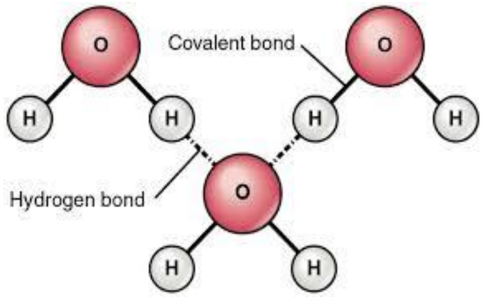


**Figure 2** Normal Water molecule

The chemical hydrogen break hydrogen bonds between water clusters, and the water molecules will arrange in one direction as shown in (figure 3), and this Magnetization can influence on the two forces that controlling the water structure Then Reducing the bond angle, From 104.45° to 103° [8]. Therefore, to lessen the assembly stage among the water molecules, also to lessening the clusters sizes rearranging into single species or little species, So the viscosity of the magnetic water is lower than the viscosity of the ordinary water. The alterations in the composition of water molecules may alter the physical and chemical properties [9].

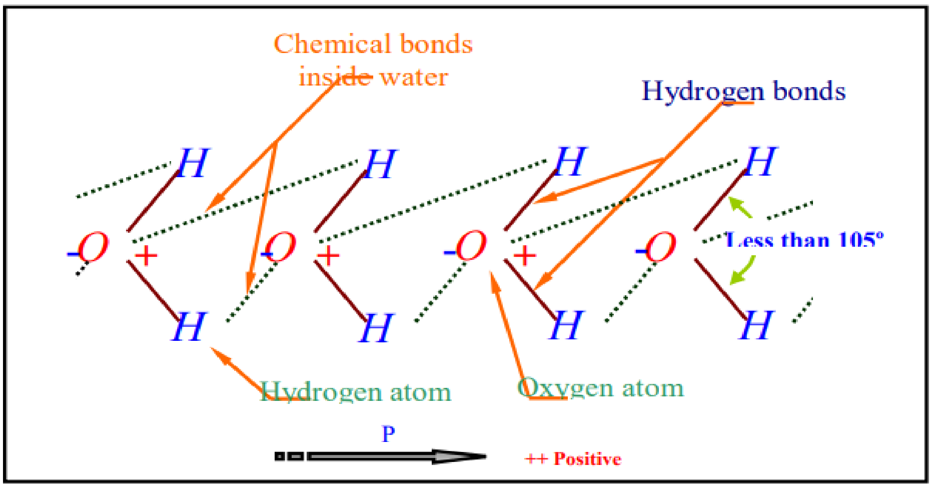


**Figure 3** Water molecules under effect of MF

*1.2.Importance of Magnetic Field in Treatment Processes*

In order to modify the behavior of particles and microorganisms for the purpose of accelerating the reaction rates and/or enhance the efficiency of separation processes [10]. Researchers are working to utilize the unique elements of magnetic fields to maximize current treatment solutions and create new methods that replicate treatment practices that could change the wastewater management paradigm [11]. Such methods not only intend to improve the efficiency of treatment, but also to decrease energy consumption and mitigate adverse effects on the environment, thus contributing to more sustainable solutions in the field [12] . These should reduce operational costs while meeting ever-tighter regulatory requirements, which would be a win-win for the industry and public health. But beyond how well they do the job, these are some of my favorite applications because of how much they offer in terms of sustainable water management. Applications of magnetic fields seek to promote environmental sustainability across various industries by minimizing the reliance on chemical-based approaches and increasing the efficiency and efficacy of overall treatments [13] . Such an innovative approach is going to help in improving the wastewater treatment technologies with an urgency to address the environmental challenges emerging out of water pollution [14].

## 2. Principles Behind Magnetic Field Techniques

*2.1.Fundamentals of Magnetic Forces and Fields*

These are some of the most basic forces and fields in nature that arise from the movement of electric charges. The orbits of electrons around atomic nuclei generate a magnetic moment, which contributes to the properties seen in materials. The position of the permanent magnets or electromagnets creates the magnetic fields, which can be configured and tuned in real time to maximum and minimum intensity and given trajectories (e.g., Helmholtz and Maxwell coils) [15]. Water changes when putting in a magnetic field. One important effect is that water molecules may reorganize through modified hydrogen bonding, which can affect the behavior of contaminants in solutions and their removal [16]. It is fundamentally based on the Lorentz force; charged particles passing through a magnetic field experience this force, altering their trajectories, which is an important factor that can enhance the electrochemical reactions in subordinated wastewater treatment. Furthermore, MHD effects can be stimulated by an imposing external magnetic field, which contributes to the improvement of ion convection and mass transfer rates via agitation of the electrolyte in electrochemical processes [17]. Knowledge of these forces assists in effective pollutant removal in the wastewater treatment process. The Inhomogeneous magnetic field is also important–together these two parameters may be strong predictors of performance rather than just the strength of the applied magnetic field alone constituting a determinant factor for sugar separation effectiveness [16] , thus the importance of magnetic technology can also promote sustainable use of environmental interaction.

*2.2. How Pollutants Interact with Magnetic Fields*

Mechanisms involved in pollutant and magnetic field interactions during wastewater treatment that enhance removal efficiency Central to this interaction are the Lorentz forces that operate on charged particles in a magnetic field, which affections on their trajectory and the positioning in the solution. This force alters the trajectory of such particles, resulting in an increase in the frequency of collisions between contaminants and treatment agents, and subsequently enables effective separation processes[18].Magnetic separation methods utilize this concept successfully by attracting and separating ferromagnetic or magnetically susceptible pollutants from water. Water molecules can change structure, arrangement and behavior with the application of magnetic fields because iron will affect the way hydrogen is bonded with water. It has also been proved by studies that those modifications lead to the enhancement of the solubility and mobilization of substances to be removed [3].

Indeed, MHD effects are very useful as they create convection currents in the fluid that has been treated. Such currents reduce the thickness of the diffusion layer around electrode surfaces, thus increasing the acceleration of mass transport rates for ions and reaction kinetics during electrochemical processes[19]. Accordingly, it provides a more facilitated ion transportation to catalytic sites, which favors a higher removal rate of different pollutants.Moreover, the incorporation of magnetic-responsive materials reveals a new way of pollutant adsorption. The employment of such materials enables dynamic interactions with magnetic fields, thereby amplifying adsorption capacities and recovery processes post-treatment (as highlighted in. The synergy among these mechanisms—Lorentz force-driven particle dynamics, MHD-induced convection currents, and enhanced ion transfer—illustrates a comprehensive strategy for efficiently tackling a range of wastewater contaminations[18] .

## 3. Type of magnetic field

Static vs Electromagnetic Magnetic Field — Which Magnetic Field Is More Efficient in Magnetic-Based Wastewater Treatment The magnetic field type has a crucial impact on the behavior and efficiency of magnetic-based wastewater treatment. Laboratory and pilot-scale studies often employ static magnetic fields (SMFs), which are constant in magnitude and direction. They generally further the process of flocculation and sedimentation by imposing effects on ion mobility, lowering zeta potential, and forcing together colloids and suspended solids [21]. For example, SMFs have been reported to reducing turbidity, increasing total suspended solids and some heavy metals removal. On the other hand, EMFs evoke extra forces, especially in alternating (AC) electromagnetic fields, which can differ ionic bonds and modify microbial metabolic activity leading to better biodegradation mechanisms. Research works have also shown that passive electric electricfields (PEFs) can enhance bio-treatment via activation of microbial enzymes and faster nutrient removal in biological treatment processes, especially in activated sludge system[22]. However, in the case of biological degradation pathways, EMFs are expected to perform better, whereas SMFs are more efficient in physicochemical enrichment (e.g. flocculation, crystallization).

*3.1. Static magnetic field:* This type is based on a permanent magnet made from hard magnetic ferrites instilled on the pipe. This type helps reduce operational costs compared to other types of magnets, since no electricity would be required to generate a magnetic field. Figure 4 shows the set-up of the permanent magnets for magnetic water treatment[23].

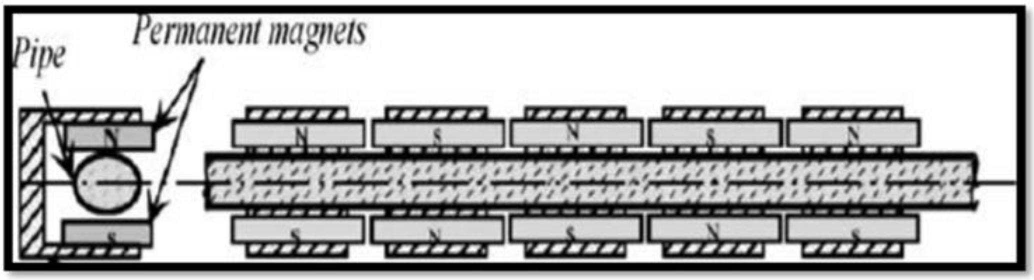


**Figure 4** Sketch of the set-up of the permanent magnets for the magnetic water treatment [23]

*3.2. Electromagnetic field:* This type is based on AC solenoid electromagnets (solenoids with ferromagnets) that generate an alternating magnetic field. In the case of electromagnets, the solenoid is instilled from electrical conducting wires, which generate a magnetic field within its cavity upon the passage of electric current on the pipe. The solenoid space for linear, annular, and various shape designs have been developed depending on the application as in figure 5 [24],[25].

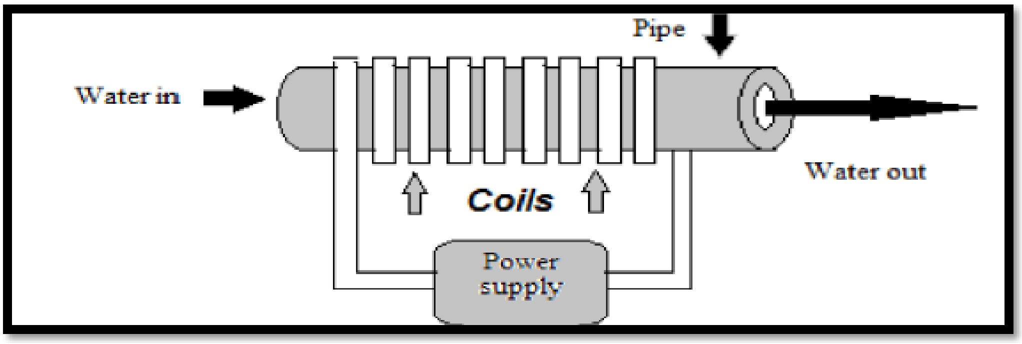


**Figure 5** Sketch of electromagnet for the magnetic water treatment [26]

## 4. Overview of Magnetic Fields in Treatment Processes

The applicability of magnetic fields as a mean to improve different treatment processes is a well-recognized phenomenon with proven potential in the efficiency and effectiveness of wastewater management [27] . This enhancement is accomplished through processes like enhanced solid-liquid separation and enhanced biologic activity resulting in an improved treatment of wastewater systems[28]. It is through higher solid-liquid separation and superior microbial activity that this improvement translates into a more effective treatment, especially in wastewater systems. Moreover, the application of magnetic fields can considerably save time in operation and improve treatment process performance, rendering it distinctively beneficial in management of wastewater[29]. Not only does the application of magnetic field in wastewater treatment provide a cost-effective solution but is also sustainable because of the low maintenance characteristics of permanent magnets over time. And, the application of magnetic field enables easily regeneration of the adsorbents, thus contributing to the treatment efficiency [30]. by allowing for several uses without significant loss of performance. This prompt recovery after magnetic induction highlights the feasibility of utilizing magnetic fields to prolong sustainability in the operation of wastewater treatment [31] . Magnetic field integration inside the treatment systems improve its performance and motivates environmental sustainability by minimizing the chemicals and energy consumption in a long-time period[32].

## 5. Types of Wastewater Treatment Techniques

### *5.1.Conventional Methods*

Traditional approaches to the treatment of wastewater, including the activated sludge process and trickling filters, have long been the mainstay of municipal and industrial wastewater treatment. These approaches are based mainly on biological degradation of organic matter with aerobic microorganisms. In particular, the activated sludge system is widely used owing to its effectiveness in the reduction of biochemical oxygen demand (BOD) and suspended solids. Nevertheless, conventional systems are usually very reliable and have been proven on a large scale, but these systems are energy- and chemical-intensive for aeration and sludge handling [33] and make them less sustainable in the long term.

### *5.2.Advanced Oxidation Advanced Oxidation*

Advanced oxidation processes (AOPs) are increased profile processes owing to their effectiveness at mineralising persistent organic pollutants that are resistant to traditional biological treatment. Advanced oxidation processes (AOPs) work based on the creation of hydroxyl radicals (•OH) which can unspecifically oxidize a great variety of contaminants including pharmaceuticals, dyes and industrial solvents (Glaze et al., 1987). Some popular AOPs are ozonation, UV/$H_2O_2$ and Fenton reactions.And this processes provide a very effective mechanism for the mineralization of recalcitrant compounds and for removal of chemical oxygen demand (COD) and toxicity from the effluents treated. AOPs also can be added into already constructed treatment trains for an improved removal efficiency for a low footprint increase of the entire system. Implementing these technologies can take place in accordance with the circular economy operating principles providing water reuse, energy recovery, and savings of resources within the frame of circulated wastewater treatment facilities Processes[34] .

### *5.3.Magnetic Field Applications*

The use of magnetic fields to enhance separation processes and removal efficiency has been an emerging and novel method used in wastewater treatment. Treatment under the influence of a magnetic field could improve the efficiency of coagulation and flocculation leading to a high rate of sedimentation, and enhanced removal of suspended solids and some dissolved contaminants. This process minimizes the use of chemical coagulants, resulting in lower operational costs and environmental hazards.

It could be more helpful to implement the random adsorption process with the use of magnetic materials or magnetically responsive particles so as to achieve selective adsorption of the heavy metals and organic pollutants and facilitate both the removal of contaminants and the reclamation of resources. An important point is that, from an environmental management perspective, magnetic technologies can play a significant role in waste reduction and minimization of chemical dependence as well as the energy efficiency of wastewater treatment processes [35].

## 6.Mechanisms of Magnetic Field Interaction

*6.1.Magnetic Flocculation*

Magnetic flocculation has emerged as a new technology for wastewater treatment, wherein magnetic particles are used to form aggregates with pollutants. Which allows them to be removed via sedimentation, or via filtration. Magnetic flocculants, that can not only improve pollutant removal efficiencies but also facilitate recovery and potential recycling of value-added materials, are said to fit well into circular economy concepts in industrial practices [36].

*6.2.Magnetic Separation*

Magnetic separation employs magnetic fields to separate ferromagnetic materials from non-magnetic components in streams of wastewater. This complementary method, post magnetic flocculation, where the magnetic or magnetically-tagged pollutants are pitched, allows for better overall treatment efficiency of the process with a larger fraction of a specific waste being reduced in volume through separation. It is resource-recovery oriented and can be integrated into existing wastewater treatment systems[37].

*6.3.Effects on Microbial Activity*

Methods of treatment which may be implemented based on magnetic principles could affect microbial populations in sewage systems. Due to the fact that biological treatment processes depend on microbial populations to break down organic pollutants, it is important to understand the influence of magnetic fields and magnetic materials on these microorganisms. An increase in certain functional groups such as the biodegraders can potentially enhance bioremediation performances as some studies indicated that magnetic exposure could change microbial community structure or enzymatic activity [5]. As such, evaluation of these interactions is important to inform treatment strategy optimization and the sustainability of these approaches over the long term.

## 7. Case Studies and Applications

*7.1. Industrial Wastewater Treatment*

The practical implementation of these separation technologies utilizing magnetic separation and flocculation strategies has made significant progress in many fields such as mining, textile and chemical industries. They have made radical developments in eliminating heavy metals, dyes, and oil-based contaminants from complex wastewater matrices. In the case of textile, functionalized magnetic nanoparticles with surfactants have been applied in this area to efficiently remove dyes and heavy metals exceeding 90% [38] . These case studies illustrate a better practice in utilizing magnetic-based technologies into industrial wastewater treatment systems as a means of making both removal of pollutants more efficient and compliance with relevant environmental regulations, by increasing efficiency of the overall wastewater treatment systems..

*7.2. Municipal Wastewater Treatment*

Highly densely populated cities, in which municipal wastewater treatment capacity and space for treatment units are under pressing limitation, have a growing interest in advanced magnetic separation technologies for municipal wastewater treatment under developing upgrading configuration. It has been demonstrated in pilot studies that magnetic seeded filtration can be coupled to existing biological treatment to enhance nutrient removal and the efficiency of sludge dewatering[39]. The aforementioned strategies assist municipalities not only achieve low levels of discharge but also lower operational expenditure and environmental impact of wastewater treatment plants.

*7.3. Comparison of Techniques*

After the authors briefly compare magnetic flocculation, magnetic separation and other conventional treatment methods, they state these methods present advantages in terms of treatment time, efficacy and also (recourse) recovery potentials. The sustainability of the treatment process is enhanced by, for example, the reuse of magnetic particles and the recovery of metals or nutrients from wastewaters [40]. These are exactly the kind of technologies that fit within a circular economy, turning waste into a resource (biogaS from sludge, phosphorous from sludge for agricultural use, etc)

## 8. The Benefits of Recognized Magnetic Treatment for Wastewater

Abstract Magnetic treatment is an innovative, green technology to improve wastewater treatment process. Abstract Magnetic water treatment technology is the most commonly used technology that can impact the characteristics of suspended solids, micro-organisms and dissolved contaminants in wastewater by applying magnetic fields to industrial effluents. Some key benefits include:**(Dondajewska et al., 2019)**

*8.1 Improved removal of impurities*: Magnetic processing of liquids can enhance particle agglomeration, thus enhancing the separation of heavy metals or other water pollutants [41].

*8.2 Energy efficiency:* Compared to conventional chemical treatments which need a larger amount of energy and raw materials, it has been proven that magnetic treatment generally consumes less energy and lower dosage of chemical additives [42].

*8.3 Environmental friendly:* None when should use less chemicalsAs a result, the magnetic treatment reduces secondary pollution, making it agreener option[42].

*8.4 Cost-effectiveness:* The use of magnetic treatment can minimize the operational costs of the wastewater treatment plants by reducing chemical consumption, sludge production, and energy consumption [43](Bambic et al., 2015).

*8.5 Enhanced Biological Activity:* It has been reported that a few kinds of microorganisms which are applied to treat biological treatment regain their growth and metabolism after stimulating from magnetic fields which enhances the effectiveness of the biological treatment and measurement[44] .

## 9. Future Directions and Research

### *9.1. Technologies*

Recent advancements in the magnetic wastewater treatment technologies highlight the potential of novel approaches with superior efficiency in removing pollutants. One of the prominent innovations is the application of magnetic hydrochar, which combines the beneficial properties of hydrochar with magnetic components. This result not only allows easy recovery but also increases pollutant adsorption through improved physicochemical properties (such as porosity and surface structure) (as discussed in [45].

In addition, the research community is increasingly focusing on the development of stimuli responsive materials (for example hydrogels that respond to environmental changes) that can respond to varying concentrations of pollutants in real time. Such progress represents the evolution into complex systems that should be able not only to monitor contaminants, but also perform the treatment functions, as mentioned in [46]. Moreover, further interest was gained in adding magnetic nanoparticles (MNPs) with metals like silver or gold to be able to enhance photocatalytic activities. These improvements especially promote the breakdown of biodegradable pollutants in the presence of external magnetic fields, which maximizes treatment efficiency .[٤٧]

They, too, are considering novel approaches to catalyst design with the application of a magnetic field. Direct synthesis of such magnetic-based catalysts shown promising in optimization of their structural properties towards different electrocatalytic reactions essential to wastewater treatment. By controlling certain magnetic fields during synthesis, researchers can influence properties like particle size and orientation, leading to enhanced catalytic activity. Additionally, combining breakthroughs in this area with newly burgeoning ideas such as magnetocaloric effects could result in localized heating during electrocatalysis—which could be beneficial to overcoming reaction pathways and achieving higher efficiencies in chemical processes [17]. Continued research into synergistic or nearly synergistic materials that respond to external magnetic fields will be the key to even more cost-effective and sustainable treatment routes for wastewater.

*9.2. Potential for Scale-Up*

Abstract The application of magnetic field based technique to the wastewater treatment holds the potential to develop high environmental sustainability. They enhance the elimination of pollutants making the water systems cleaner while reducing the ecological footprints. Such as, magnetic hydrochar (A sustainable, efficient, and environmentally friendly wastewater treatment) Eight-five percent of spent magnetic hydrochar has been recovered in a magnetic field [45]. to curb waste and limit the production of virgin materials in accordance with circular economy tenets.

Furthermore, the integration of stimuli-responsive nanomaterials into magnetic approaches allows specific stimulation of contaminants such as heavy metals and organic compounds to remove, thereby enhancing the efficiency of elimination from water, and reducing the consumption of undesirable chemicals [47]. Other developments have emerged like pH-switchable hybrid magnetic nanoparticles that can be designed for pollutant release matching the ambient environment [46].

This has stimulated the synthesis of intelligent materials that are highly sensitive to external stimuli and that improve their pollution elimination efficiency and resource conservation. The use of photocatalytic processes with magnetic nanoparticles based on renewable energy resources such as solar power also minimizes the carbon footprint [48].These technologies are attractive alternatives to conventional approaches, especially as the need for more sustainable water management grows in response to increasing pollution worldwide. Cost-effective production and scalable applications will facilitate the integration of them into wastewater treatment frameworks[49] . Future of magnetic wastewater treatment approaches will heavily relies on collaborative research and collaborative engineering.

## 10. Conclusion

This review describes the most recent innovations and approaches for the treatment of waste waters stresses on the need of applying emerging technologies in the field of sewage treatment in order to maximise the treatment efficiency and minimise the load on the environment. Novel developments, including magnetic separation, membrane bioreactors, advanced oxidation processes and nanotechnology, can provide reasonable removal efficiencies while enabling resource recovery and energy savings. These innovations enable water sector stakeholders to enhance operational performance, decrease environmental footprints, and facilitate the transition to a circular economy. Furthermore, these innovations provide better public health benefits through safer water discharge and reuse, particularly in areas of water scarcity and increasing urban population .

*10.1. Results from the magnetic field treatment*

The application of magnetic field technologies in wastewater treatment is a new approach to enhance pollutant extraction for environmental sustainability. Magnetic adsorbents have been widely used for the removal of heavy metals and organic pollutants at high saturation adsorption rates for a wide spectrum of contaminants[49] ,[50]. Innovations in metal-organic frameworks (MOFs) and graphene-based composites that improve adsorption performance and regenerative capacity render these alternatives economically feasible.

Compared to classical methods, magnetic separation techniques are much easier to recover the adsorbents from the treated water and the magnetic property alleviates the classical methods shortcomings such as adsorbent loss [51], [47]. The efficiency is important for fast removal of pollutants. Several studies indicated that magnetic fields could be combined with chemical processes, to improve reaction kinetics and overall treatment performance [28] [17].

Nonetheless, issues still exist in terms of both scalability and economically. Despite these encouraging results in the lab, there remain major challenges for practical deployment such as cost of synthesis, long-term stability of the material and compliance with regulatory requirements ([51],([52].Such collaborations with academia and industry are called for to turn fundamental research into practical solutions.

Conclusion— Magnetic field approaches has exciting potential specifically for enhancing wastewater treatment; however, more research is necessary in regard to scalability, cost, and how these ways might fit into existing systems to reap the full benefits.

### *10.2. Suggested Areas for Further Exploration*

Magnetic wastewater treatment is still a comparatively new field, and there are some key areas where future research could significantly enhance the efficacy and application of magnetic field technologies. Especially an interdisciplinary approach combining knowledge from material science, environmental engineering, and nanotechnology to design novel magnetic materials with improved features in view of the pollutants removal process. Advancing stimuli-responsive nanomaterials— particularly those which respond to relevant environmental signals—may enable more targeted treatment approaches. In this respect the evolution of pH-sensitive materials (as highlighted in [47]), could pave way for targeted pollution control in dynamic wastewaters.

Third, it is essential to investigate the scalability and cost-effectiveness of such technologies. Future research should focus more towards actual wastewater treatment rather than purely synthetic wastewater treatment as mentioned in([53] to understand the performance and limitations of magnetic methods more shedingly. Improvement of operational parameters in magnetic separation could also lead to improvements in efficiency but with continued reduction in costs.

Also, material recovery challenges are going to need to be addressed to ensure sustainability. The development of magnetic hydrochar mentioned in [45] offers a novel strategy to combine the high performance of adsorption with high convenience of recovery by external magnets.

Ultimately, encouraging joint initiatives between academia and the corporate side will narrow the gap between lab discoveries and real-world applications. Comprehensive lifecycle assessments will be needed to determine the environmental impact of deploying these technologies at scale and remain compliant within regulations. This collaborative model will not only help overcome existing barriers, but will also act as a incubator of innovative approaches towards resource recovery enhanced wastewater treatment, in a way that emphasizes environmental sustainability.

## References

[1] A. C. W. Yap, H. S. Lee, J. L. Loo, and N. S. Mohd, “Investigation of the magnetic effects on water properties using permanent magnets,” in *AIP Conference Proceedings*, AIP Publishing, 2019. Accessed: Apr. 16, 2025. [Online]. Available: https://pubs.aip.org/aip/acp/article-abstract/2157/1/020016/788870

[2] J. Wang, L. Zhu, X. Li, and K. Xie, “Study and Application status of Biomagnetic effect in Wastewater Treatment,” in *2015 4th International Conference on Sustainable Energy and Environmental Engineering*, Atlantis Press, 2016, pp. 543–546. Accessed: Apr. 16, 2025. [Online]. Available: https://www.atlantis-press.com/proceedings/icseee-15/25849774

[3] E. Szatyłowicz and I. Skoczko, “Magnetic field usage supported filtration through different filter materials,” *Water*, vol. 11, no. 8, p. 1584, 2019.

[4] M. Krzemieniewski, M. Debowski, W. Janczukowicz, and J. Pesta, “Effect of the Constant magnetic Field on the composition of dairy wastewater and and W domestic sewage,” *Pol. J. Environ. Stud.*, vol. 13, no. 1, pp. 45–53, 2004.

[5] H. Zhang, Y. Peng, P. Yang, X. Wang, X. Peng, and L. Li, “Response of process performance and microbial community to ammonia stress in series batch experiments,” *Bioresour. Technol.*, vol. 314, p. 123768, 2020.

[6] Yadollahpour Ali, R. Samaneh, R. Zohre, and J. Mostafa, “Magnetic water treatment in environmental management: A review of the recent advances and future perspectives,” *Curr. World Environ.*, vol. 9, no. 3, pp. 1008–1016, 2014.

[7] N. K. Boufa, “Investigation of the Effect of Magnetic Field on some Physical Properties of Water,” *Int. Sci. Technol. J.*, vol. 26, p. 18, 2021.

[8] M. O. Karkush, M. D. Ahmed, and S. Al-Ani, “Magnetic Field Influence on The Properties of Water Treated by Reverse Osmosis.,” *Eng. Technol. Appl. Sci. Res.*, vol. 9, no. 4, 2019, Accessed: Jul. 01, 2025. [Online]. Available: https://pdfs.semanticscholar.org/cd57/b1e0a47b910e27f60aec169a489764050583.pdf

[9] S. M. Ahmed, “Effect of magnetic water on engineering properties of concrete,” *Al-Rafidain Eng. J.*, vol. 17, no. 1, pp. 71–82, 2009.

[10] S. Linley, T. Leshuk, and F. X. Gu, “Magnetically Separable Water Treatment Technologies and their Role in Future Advanced Water Treatment: A Patent Review,” *CLEAN – Soil Air Water*, vol. 41, no. 12, pp. 1152–1156, Dec. 2013, doi: 10.1002/clen.201100261.

[11] J. Liu, G. Chen, B. Yan, W. Yi, and J. Yao, “Biodiesel production in a magnetically fluidized bed reactor using whole-cell biocatalysts immobilized within ferroferric oxide-polyvinyl alcohol composite beads,” *Bioresour. Technol.*, vol. 355, p. 127253, 2022.

[12] J. Farahbakhsh, V. Vatanpour, M. R. Ganjali, and M. R. Saeb, “Magnetic nanoparticles in wastewater treatment,” in *Magnetic Nanoparticle-Based Hybrid Materials*, Elsevier, 2021, pp. 547–589. Accessed: Apr. 16, 2025. [Online]. Available: https://www.sciencedirect.com/science/article/pii/B9780128236888000363

[13] N. S. Zaidi, J. Sohaili, K. Muda, and M. Sillanpää, “Magnetic Field Application and its Potential in Water and Wastewater Treatment Systems,” *Sep. Purif. Rev.*, vol. 43, no. 3, pp. 206–240, Jul. 2014, doi: 10.1080/15422119.2013.794148.

[14] Y. Wang *et al.*, “Application of magnetic fields to wastewater treatment and its mechanisms: a review,” *Sci. Total Environ.*, vol. 773, p. 145476, 2021.

[15] H. Liu *et al.*, “A review of magnetically driven swimming microrobots: Material selection, structure design, control method, and applications,” *Rev. Adv. Mater. Sci.*, vol. 62, no. 1, p. 20230119, Sep. 2023, doi: 10.1515/rams-2023-0119.

[16] E. Chibowski and A. Szcześ, “Magnetic water treatment–A review of the latest approaches,” *Chemosphere*, vol. 203, pp. 54–67, 2018.

[17] Y. Sun, H. Lv, H. Yao, Y. Gao, and C. Zhang, “Magnetic field-assisted electrocatalysis: Mechanisms and design strategies,” *Carbon*

*Energy*, vol. 6, no. 10, p. e575, Oct. 2024, doi: 10.1002/cey2.575.

[18] Y. Wang *et al.*, "Application of magnetic fields to wastewater treatment and its mechanisms: a review," *Sci. Total Environ.*, vol. 773, p. 145476, 2021.

[19] Y. Sun, H. Lv, H. Yao, Y. Gao, and C. Zhang, "Magnetic field-assisted electrocatalysis: Mechanisms and design strategies," *Carbon Energy*, vol. 6, no. 10, p. e575, Oct. 2024, doi: 10.1002/cey2.575.

[20] H. Banejad and E. Abdosalehi, "The effect of magnetic field on water hardness reducing," in *thirteenth international water technology conference, IWTC*, 2009, pp. 117–128. Accessed: Jul. 01, 2025. [Online]. Available: https://aquavital.hr/wp-content/uploads/2023/07/The_Effect_of_Magnetic_Field_on_Water_Ha.pdf

[21] K. Lv, J. Han, C.-T. Yang, C.-M. Cheng, Y.-M. Luo, and X.-L. Wang, "A category of hierarchically porous tin (IV) phosphonate backbone with the implication for radioanalytical separation," *Chem. Eng. J.*, vol. 302, pp. 368–376, 2016.

[22] H. Wang, "Role of environmental degradation and energy use for agricultural economic growth: Sustainable implications based on ARDL estimation," *Environ. Technol. Innov.*, vol. 25, p. 102028, 2022.

[23] C. A. McMahon, "Investigation of the quality of water treated by magnetic fields," 2009, Accessed: May 24, 2025. [Online]. Available: https://sear.unisq.edu.au/8399/1/McMahon_2009.pdf

[24] O. Mosin and I. Ignatov, "Basic concepts of magnetic water treatment," *Eur. J. Mol. Biotechnol.*, vol. 4, no. 2, pp. 72–85, 2014.

[25] N. T. Y. Sawaftah, "Optimization of Calcium Sulfate Scale Reduction Using Magnetic Field," PhD Thesis, An-Najah National University, 2017. Accessed: May 25, 2025. [Online]. Available: https://repository.najah.edu/bitstreams/c38539b2-aaa7-40c9-83bd-e9e04620c0d6/download

[26] G. H. Abdulrazzaq, "Reducing the water hardness by using electromagnetic polarization method," *Al-Khwarizmi Eng. J.*, vol. 12, no. 4, pp. 111–116, 2016.

[27] I. Roi, I. Vaskina, K. Jozwiakowski, R. Vaskin, and I. Kozii, "Influence of the Magnetic Field Gradient on the Efficiency of Magnetic Water Treatment," in *Advances in Design, Simulation and Manufacturing III*, V. Ivanov, I. Pavlenko, O. Liaposhchenko, J. Machado, and M. Edl, Eds., in Lecture Notes in Mechanical Engineering. , Cham: Springer International Publishing, 2020, pp. 387–395. doi: 10.1007/978-3-030-50491-5_37.

[28] N. S. Zaidi, J. Sohaili, K. Muda, and M. Sillanpää, "Magnetic Field Application and its Potential in Water and Wastewater Treatment Systems," *Sep. Purif. Rev.*, vol. 43, no. 3, pp. 206–240, Jul. 2014, doi: 10.1080/15422119.2013.794148.

[29] J. Farahbakhsh, V. Vatanpour, M. R. Ganjali, and M. R. Saeb, "Magnetic nanoparticles in wastewater treatment," in *Magnetic Nanoparticle-Based Hybrid Materials*, Elsevier, 2021, pp. 547–589. Accessed: May 24, 2025. [Online]. Available: https://www.sciencedirect.com/science/article/pii/B9780128236888000363

[30] D. Ghernaout and N. Elboughdiri, "Magnetic field application: an underappreciated outstanding technology," *Open Access Libr. J.*, vol. 7, no. 1, pp. 1–12, 2020.

[31] P. Kewu and L. Yatian, "Applications and recent advances of magnetism in wastewater treatment," *Environ. Technol.*, vol. 1, pp. 26–28, 2003.

[32] A. Ulusoy, A. Atılgan, R. Rolbiecki, B. Jagosz, and S. Rolbiecki, "Innovative Approaches for Sustainable Wastewater Resource Management," *Agriculture*, vol. 14, no. 12, p. 2111, 2024.

[33] G. Tchobanoglus, F. Burton, and H. D. Stensel, "Wastewater engineering: treatment and reuse," *Am. Water Works Assoc. J.*, vol. 95, no. 5, p. 201, 2003.

[34] M. C. Berman, D. J. G. Marino, M. V. Quiroga, and H. Zagarese, "Occurrence and levels of glyphosate and AMPA in shallow lakes from the

Pampean and Patagonian regions of Argentina," *Chemosphere*, vol. 200, pp. 513–522, 2018.

[35] S. Pouresmaeil, M. Nosrati, and S. Ebrahimi, "Operating control for enrichment of hydrogen-producing bacteria from anaerobic sludge and kinetic analysis for vinasse inhibition," *J. Environ. Chem. Eng.*, vol. 7, no. 3, p. 103090, 2019.

[36] A. Chrysargyris, E. Papakyriakou, S. A. Petropoulos, and N. Tzortzakis, "The combined and single effect of salinity and copper stress on growth and quality of Mentha spicata plants," *J. Hazard. Mater.*, vol. 368, pp. 584–593, 2019.

[37] M. Coha, G. Farinelli, A. Tiraferri, M. Minella, and D. Vione, "Advanced oxidation processes in the removal of organic substances from produced water: Potential, configurations, and research needs," *Chem. Eng. J.*, vol. 414, p. 128668, 2021.

[38] C. T. Yavuz *et al.*, "Low-Field Magnetic Separation of Monodisperse $Fe_3$ $O_4$ Nanocrystals," *Science*, vol. 314, no. 5801, pp. 964–967, Nov. 2006, doi: 10.1126/science.1131475.

[39] A. Chrysargyris, E. Papakyriakou, S. A. Petropoulos, and N. Tzortzakis, "The combined and single effect of salinity and copper stress on growth and quality of Mentha spicata plants," *J. Hazard. Mater.*, vol. 368, pp. 584–593, 2019.

[40] A. Daxini, C. O'Donoghue, M. Ryan, C. Buckley, A. P. Barnes, and K. Daly, "Which factors influence farmers' intentions to adopt nutrient management planning?," *J. Environ. Manage.*, vol. 224, pp. 350–360, 2018.

[41] R. Dondajewska, A. Kozak, J. Rosińska, and R. Gołdyn, "Water quality and phytoplankton structure changes under the influence of effective microorganisms (EM) and barley straw–Lake restoration case study," *Sci. Total Environ.*, vol. 660, pp. 1355–1366, 2019.

[42] Z. Liao, "Environmental policy instruments, environmental innovation and the reputation of enterprises," *J. Clean. Prod.*, vol. 171, pp. 1111–1117, 2018.

[43] D. G. Bambic *et al.*, "Spatial and hydrologic variation of Bacteroidales, adenovirus and enterovirus in a semi-arid, wastewater effluent-impacted watershed," *Water Res.*, vol. 75, pp. 83–94, 2015.

[44] S. Talekar, A. F. Patti, R. Vijayraghavan, and A. Arora, "An integrated green biorefinery approach towards simultaneous recovery of pectin and polyphenols coupled with bioethanol production from waste pomegranate peels," *Bioresour. Technol.*, vol. 266, pp. 322–334, 2018.

[45] H. Meng *et al.*, "Magnetic hydrochar for sustainable wastewater management," *Npj Mater. Sustain.*, vol. 3, no. 1, p. 7, 2025.

[46] A. I. Visan and I. Negut, "Environmental and Wastewater Treatment Applications of Stimulus-Responsive Hydrogels," *Gels*, vol. 11, no. 1, p. 72, 2025.

[47] I. Salahshoori, A. Yazdanbakhsh, M. N. Jorabchi, F. Z. Kazemabadi, H. A. Khonakdar, and A. H. Mohammadi, "Recent advances and applications of stimuli-responsive nanomaterials for water treatment: A comprehensive review," *Adv. Colloid Interface Sci.*, p. 103304, 2024.

[48] H. B. Truong, X. C. Nguyen, and J. Hur, "Recent advances in g–C3N4–based photocatalysis for water treatment: Magnetic and floating photocatalysts, and applications of machine-learning techniques," *J. Environ. Manage.*, vol. 345, p. 118895, 2023.

[49] M. S. Akhtar, S. Ali, and W. Zaman, "Innovative adsorbents for pollutant removal: Exploring the latest research and applications," *Molecules*, vol. 29, no. 18, p. 4317, 2024.

[50] S. Moosavi, C. W. Lai, S. Gan, G. Zamiri, O. Akbarzadeh Pivehzhani, and M. R. Johan, "Application of Efficient Magnetic Particles and Activated Carbon for Dye Removal from Wastewater," *ACS Omega*, vol. 5, no. 33, pp. 20684–20697, Aug. 2020, doi: 10.1021/acsomega.0c01905.

[51] A. Mudhoo and M. Sillanpää, "Magnetic nanoadsorbents for micropollutant removal in real water treatment: a review," *Environ. Chem. Lett.*, vol. 19, no. 6, pp. 4393–4413, Dec. 2021, doi: 10.1007/s10311-021-01289-6.

[52] V. Phouthavong *et al.*, "Magnetic adsorbents for wastewater treatment: advancements in their

synthesis methods," *Materials*, vol. 15, no. 3, p. 1053, 2022.

[53] N. A. Qasem, R. H. Mohammed, and D. U. Lawal, "Removal of heavy metal ions from wastewater: A comprehensive and critical review," *Npj Clean Water*, vol. 4, no. 1, pp. 1–15, 2021.