Review Article

ADVANCING CIRCULAR ECONOMY OF WATER AND WASTEWATER USING MAGNETIC NANOMATERIALS

ABSTRACT

Aims: This study explores the potential of magnetic nanomaterials in addressing water and wastewater management challenges through the circular economy approach.
Methodology: The study reviews the literature on the use of magnetic nanomaterials in water and wastewater treatment and discusses their unique properties that allow for selective pollutant removal, easy recovery, and reuse, as well as resource recovery.
Results: Magnetic nanomaterials have shown promise in enhancing the efficiency of existing treatment processes, facilitating energy recovery, enabling water reuse, precious metals recovery, and aiding in the effective recovery of nutrients. However, challenges such as long-term toxicity, optimization, and regulation need to be addressed to facilitate widespread adoption.
Conclusion: Integrating magnetic nanomaterials into water and wastewater treatment processes holds significant potential for advancing the circular economy of water and wastewater. Applying magnetic nanomaterials in water and wastewater treatment can minimize waste generation, promote resource efficiency, and offer practical solutions to remove pollutants that are challenging to remove using conventional methods.

Keywords: Circular Economy, Water and Wastewater, Magnetic Nanomaterials, Sustainability, Nutrients and Metals Recovery, Energy Recovery

1 INTRODUCTION

Water is a vital resource for humans, and its availability is critical for sustaining life and economic growth [1–3].With ever-increasing population and industrialization, the demand for clean water has significantly increased, resulting in water scarcity and deteriorating water quality [1, 3, 4]. Furthermore, wastewater from industries and households severely threatens the environment and human health[1, 4]. To address these challenges, sustainable water management practices, such as the circular economy, have gained global attention.

A circular economy focuses on minimizing waste and maximizing resource utilization [5–9]. It involves recovering, reusing, and recycling resources to create a closed-loop system that promotes environmental sustainability, economic growth, and social well-being[5, 6]. In the water sector, the circular economy aims to reduce water consumption, increase water reuse, and recover resources from wastewater to promote sustainable development[2,3, 5, 7–10].The advancement of this circular economy requires the development of new technologies and approaches to enhance the efficiency and sustainability of water management systems [3, 6].

Magnetic nanomaterials have emerged as promising tools for advancing the circular economy in the water sector [11]. These materials possess unique physicochemical properties that make them ideal for water and wastewater treatment applications[11, 12]. Magnetic nanomaterials can be synthesized in different sizes and shapes with tunable surface chemistry and magnetic properties [11, 12].They can also be functionalized with various molecules, including organic and inorganic compounds, such as carboxyl, amine, SiO_2, and hydroxyl, to enhance their selectivity and efficiency in removing contaminants from water [11].

Researchers have recently explored magnetic nanomaterials for various water and wastewater treatment processes, including adsorption, coagulation, magnetic separation, catalysis, and photodegradation[11-13].The use of magnetic nanomaterials in these processes has shown promising results[11-12], such as high removal efficiency, rapid kinetics, and easy recovery and reuse of the materials (magnetic materials themselves).Several studies have shown that magnetic nanomaterials can remove contaminants from water and wastewater, including heavy metals [14], dyes [15], and organic pollutants [15].Moreover, traditional water and wastewater treatments have not been designed to treat emerging pollutants.Several recent studies have indicated the effectiveness of magnetic nanomaterials in removing emerging pollutants such as pharmaceuticals [16], endocrine-disrupting chemicals [17], pesticides [18], PFASs [19], and microplastics [20, 21] from water and wastewater.

Furthermore, magnetic nanomaterials have also been used in resource recovery processes, such as nutrient (nitrogen and phosphorus) and precious metal (Pd, Pt, Ag, and Au) recovery, to promote circular economy in the water sector [11-12].Other essential products generated from water and wastewater treatment using magnetic nanomaterials include biogas for energy and compost as fertilizer for agricultural applications[11,12].Figure 1 summarizes the synthesis, characterization, and application of magnetic nanomaterials for advancing the circular economy of water and wastewater.The first cycle (1) indicates the path for the recovery and reuse of magnetic materials while the second cycle (2) shows material recovery, for example, Pd, Au, and Ag. The production of fertilizer from the treatment plant is indicated in the third cycle (3).Furthermore, the fourth cycle (4) shows electricity and heat production via biogas production and microbial fuel cells. compost as a fertilizer for agricultural applications. The fifth cycle (5) describes the reuse of treated water in industries/households and then generated wastewater move into the treatment plant. It also indicates the discharge of the treated water into surface water.

The concept of a circular economy in the water sector is an emerging area that has attracted significant attention from various countries, non-governmental organizations, and individuals, resulting in numerous write-ups on the topic.Tintaya et a. [22] analyzed and emphasized the incorporation of the circular economy model in water treatment plants owing to its potential benefits.The general transition of the circular economy in the water sector, such as policymaking, and recommendations were discussed for Europe [7, 23, 24], Central and Eastern Europe [25], Saudi Arabia [26], Mexico [27], Sweden [28], Finland and Sweden [29] Poland [30, 31], Thailand [26], Belgium and the Netherlands [32], China, and Europe [5]However, some studies have specifically emphasized biological treatment to obtain the best results in the circular water economy sector [6, 33, 34].The transition from a linear to a circular economy in the water sector requires a rethinking of new or combined technology that will aid the transition, as discussed in [6, 33, 34] on biological treatment.

Therefore, this research aims to provide a comprehensive review of recent advances in the use of magnetic nanomaterials for the circular economy in the water sector.This study covers the synthesis and characterization of magnetic nanomaterials and their applications in various water and wastewater treatment processes.The manuscript also discusses the challenges and opportunities for advancing the circular economy of water and wastewater using magnetic nanomaterials and provides recommendations for future research directions.

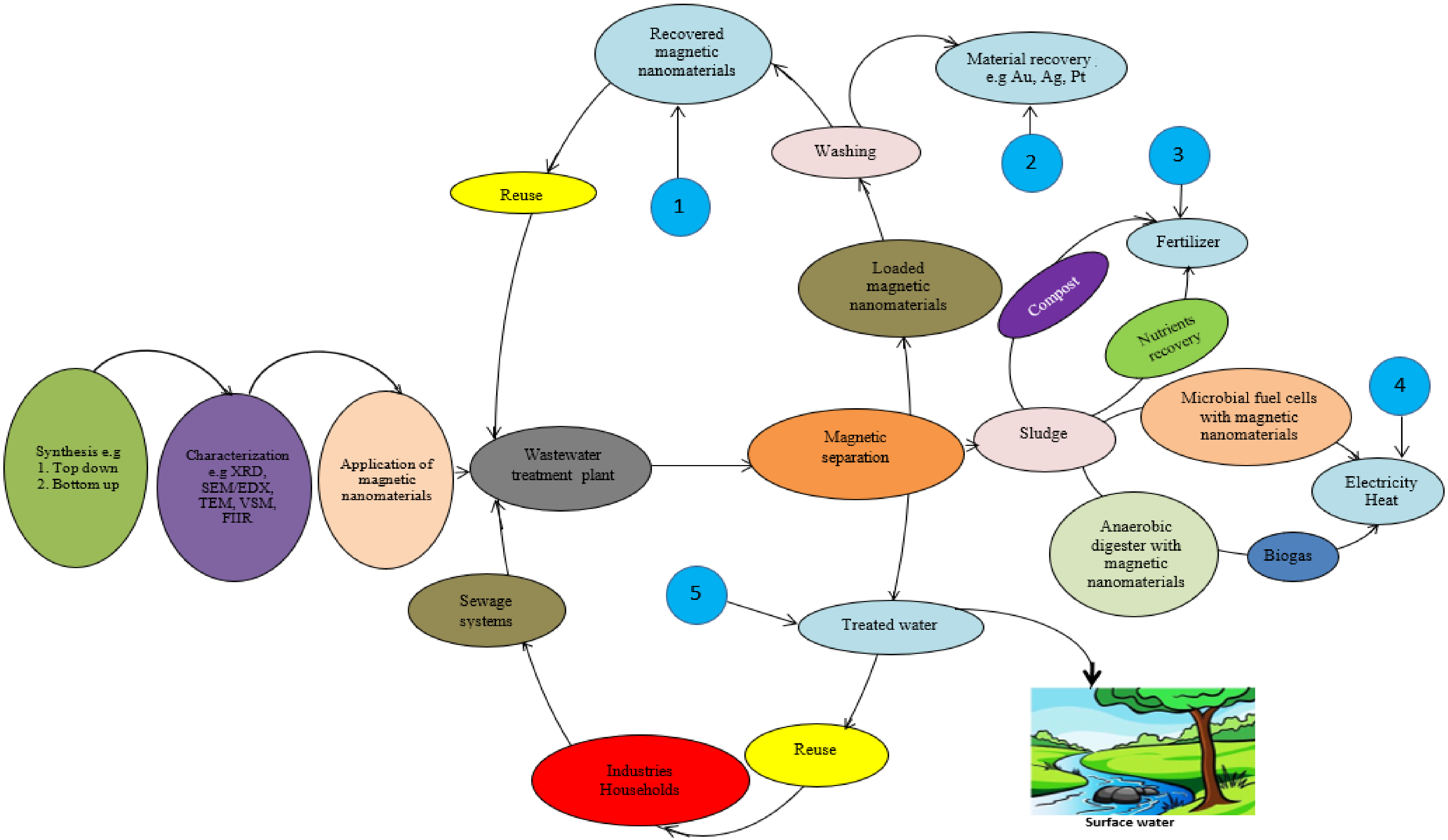

Figure 1; Schematic application of magnetic nanomaterials in advancing circular economy of water and wastewater

2 METHODS

A literature search was conducted using scientific databases, including Web of Science, Scopus, and Google Scholar, to explore the use of magnetic nanomaterials in water and wastewater treatment, circular economy, and resource recovery. Search terms such as "magnetic nanomaterials," "water treatment," "wastewater treatment," "circular economy," and "resource recovery" were used. Only articles published in English were considered, resulting in approximately 300 articles. Among these, 122 articles were included in the study on circular economy and water/wastewater and the use of magnetic nanomaterials for pollutants removal, nutrients recovery, metals recovery, and heat/electricity generation from water/wastewater.

Articles that were either unrelated to water/wastewater or did not focus on using magnetic nanomaterials for pollutants removal, nutrients recovery, metals recovery, or heat/electricity generation from water/wastewater were excluded, resulting in 178 articles being excluded. The selected articles were reviewed based on their relevance to the topic and quality of information. There were no restrictions on the journals/reports or years in which the research was conducted. However, it was found that 123 articles were published between 2005 and 2023, as shown in Figure 1.

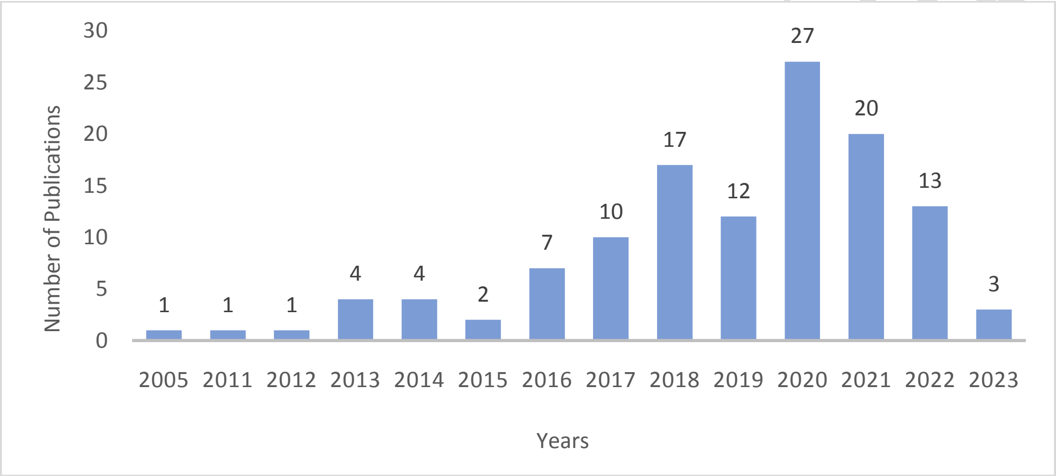

Figure 2; Distributions of articles

3 SYNTHESIS OF MAGNETIC NANOMATERIALS

The synthesis and modification of magnetic nanomaterials offers several advantages for water and wastewater treatment applications, including increased efficiency, easy separation and recovery, selectivity, and environmental sustainability [35]. Magnetic nanomaterials can be easily synthesized and functionalized with specific chemical groups or molecules to target specific contaminants. This allows for greater selectivity in water treatment, as only the targeted contaminants are removed, leaving the other components of the water untouched.The synthesis and surface modification of magnetic nanomaterials can be achieved using various methods, such as co-precipitation, sol-gel, hydrothermal, microwave-assisted methods, combustion, impregnation-pyrolysis, and ball milling.Co-precipitation is the most commonly used method owing to its simplicity, low cost, and scalability.In this method, ferrous and ferric ions are co-precipitated in an alkaline solution in the presence of precipitating agents, such as sodium hydroxide or ammonium solution [14, 16, 18,36-56]. The sol-gel method involves the hydrolysis and condensation of metal alkoxides in the presence of a surfactant to form a sol, which is then converted to a gel by aging and drying[15, 57–62]. Hydrothermal synthesis involves the use of high-pressure and high-temperature conditions to form magnetic nanomaterials[63]. Microwave-assisted synthesis involves the use of microwave radiation to induce the formation of magnetic nanomaterials[64].Combustion Synthesis: In this method, a mixture of metal salts and fuel (such as glycine, urea, or citric acid) is ignited to produce a flame [17].The heat generated by the combustion reaction causes metal salts to react and form magnetic nanoparticles [17]. The advantage of this method is that it is relatively simple and can produce nanoparticles in large quantities[17]. However, the size and shape of these particles may be difficult to control.

In Impregnation pyrolysis method, a metal ion precursor is impregnated into a carbonaceous material (such as activated carbon or carbon nanotubes) and then heated in an inert atmosphere to produce magnetic nanoparticles [65].The advantage of this method is that the carbonaceous material acts as a template, which can help control the size and shape of nanoparticles.However, this process is time-consuming and the yield may be low [65]. Ball Milling; in this method, magnetic precursors are mixed with a grinding medium (such as steel balls) and milled in a ball mill[19]. Collisions between the precursors and the grinding medium cause mechanical deformation, leading to the formation of magnetic nanoparticles.The advantage of this method is that it can produce nanoparticles with a narrow size distribution, which can be controlled by adjusting the milling time and the size of the grinding medium [19].However, this process is time-consuming, and the grinding medium may contaminate the particles.

4.0 CHARACTERIZATION OF MAGNETIC NANOMATERIALS

Characterization of magnetic nanomaterials is essential to understand their physical and chemical properties, which influence their performance in water and wastewater treatment.Common techniques for characterizing magnetic nanomaterials include X-ray diffraction, transmission electron microscopy, scanning electron microscopy, Fourier-transform infrared spectroscopy, and vibrating sample magnetometry[11, 52, 66].These techniques provide information on the particle size, morphology, crystallinity, surface chemistry, and magnetic properties of the nanomaterials[11, 52, 66].

5ADVANTAGES OF ADVANCING THE CIRCULAR ECONOMY OF WATER AND WASTEWATER USING MAGNETIC NANOMATERIALS

Advancing the circular economy of water and wastewater through the use of magnetic nanomaterials provides numerous benefits. Firstly, it allows for the recovery of valuable resources from wastewater, such as phosphorus, which can be used in agriculture. This reduces the need for virgin resources and contributes to the circular economy by closing the loop on resource use. Secondly, magnetic nanomaterials can help remove contaminants from wastewater to produce high-quality water for reuse in industrial processes and agricultural irrigation. This reduces the demand for freshwater resources and can help alleviate water scarcity issues. Thirdly, magnetic nanomaterials can improve the energy efficiency of wastewater treatment by reducing the energy required for filtration and separation, resulting in lower operating costs and lower greenhouse gas emissions. Fourthly, it can reduce waste generation by recovering valuable resources from wastewater, promoting a more sustainable use of resources. Additionally, the application of magnetic nanomaterials can reduce the chemical requirements for water and wastewater treatment, such as coagulation, which reduces the amount of sludge generated during the treatment process. Fifthly, magnetic nanomaterials can reduce the costs associated with wastewater treatment and resource recovery by generating revenue streams that offset the costs of wastewater treatment[14, 21, 60]. Sixthly, magnetic nanomaterials can be integrated with other treatment technologies to enhance contaminant removal efficiency, resulting in a more effective and efficient treatment process. Lastly, magnetic nanomaterials can be easily recovered and reused multiple times, reducing the need for frequent replacement and disposal of materials, which reduces costs and environmental impact associated with waste disposal[11, 12].

6.0 APPLICATION OF MAGNETIC NANOMATERIALS IN CIRCULAR WATER ECONOMY

The circular economy of water and wastewater management is becoming increasingly important because of the increasing demand for water and the need to minimize waste and pollution.Magnetic nanomaterials have the potential to play a significant role in advancing the circular economy by enabling more a) removal of pollutants, b) water reuse, c) nutrient and metal recovery, and d) energy recovery.Magnetic nanomaterials have shown great potential for advancing the circular economy of water and wastewater because of their unique properties, such as high surface area, easy magnetic separation, and reusability.Hence, a) pollutant removal, b) water reuse, c) nutrient and metal recovery, and d) energy recovery will be described in detail in the following sections.

6.1 MAGNETIC NANOMATERIALS FOR REMOVAL OF POLLUTANTSFROM WATER AND WASTEWAWATER

Magnetic nanomaterials can be functionalized with specific functional groups to target and remove contaminants from water and wastewaters.This approach has several advantages over traditional water treatment methods, including enhanced removal efficiency, reduced treatment time, and improved selectivity for specific pollutants (Table 1).

One example of the use of magnetic nanomaterials in water treatment is the removal of heavy metals, such as Cu [42, 43], Cr [14, 41], and As (V) [47] from water and wastewater.Another example is the removal of organic pollutants such as dyes [15] from water.Disinfection of water and wastewater containing different types of microorganisms using magnetic nanomaterials has been found to be significant [15, 38, 47, 51, 56, 58–60, 62].More importantly, traditional water and wastewater have not been designed to treat emerging pollutants, but magnetic nanoparticles are promising for the removal of different types of emerging pollutants, such as PFASs [19], pesticides [18, 57, 65], endocrine disrupting chemicals [17], pharmaceuticals [16, 36, 40, 67], and microplastics [20, 21].In addition, the physicochemical properties of water and wastewater, such as turbidity [38, 45, 46, 55, 61], apparent color [38, 61], chemical oxygen demand [59], biological oxygen demand [39], total organic content [39], total suspended solids [39], sulfate [49, 50], nitrate [38, 44], and phosphate [48, 66], have been effectively removed by various magnetic nanomaterials.

Furthermore, the incorporation of magnetic nanomaterials into existing water and wastewater treatment has made it suitable for the advancement of the circular economy of water and wastewater.Notably, as shown in Table 1, magnetic nanomaterials have been successfully incorporated into existing water and wastewater treatment methods such as adsorption [14, 19, 20, 36–38, 41, 43, 44, 49, 54, 57, 59, 63, 66] advanced oxidation processes [16], disinfection [15, 38, 47, 51, 56, 58–60, 62], flocculation [38, 45,46, 53], coagulation [52, 55, 61], forward osmosis (membrane for desalination) [68], and filtration [21].The application of magnetic nanomaterials to different AOPs, such as photocatalysis [15, 43, 53], photo-Fenton [16], and activation of peroxymonosulfate[17, 40, 65], has been successful and effective.

Table 1 Removal of pollutants by magnetic nanomaterials

S/N	Nanomaterials	Synthesis	Pollutants	Treatment methods	% Removal	References
1	Fe_3O_4@AgNPs	Co-precipitation	Nitrate	Adsorption	100	[51]
2	Fe_3O_4	Co-precipitation	Turbidity, Total nitrogen, Color, microbial content, nitrate	Adsorption,Antimicrobial assessment,andFlocculation	Colour 64%; total organic carbon 40%; nitrate 72%; and microbial content (E.coli and Enterococci, 73%)	[52]
3	Fe_3O_4@AgNPs	Co-precipitation	Ibuprofen	Adsorption	93	[50]
4	ϒ-Fe_2O_3/Al–ZnO	Sol gel	Chlorpyrifos	Adsorption	92.33	[57]
5	Magnetic Fluorinated Vermiculite	Ball milling	Perfluorooctane sulfonate (PFOS)	Adsorption	98	[19]
6	Magnetic chitosan (Fe_3O_4/CS)	Hydrothermal	Microcystin	Adsorption	100	[63]
7	Magnetically recoverable nitrogen doped biochar	Impregnation-Pyrolysis	Metolachlor	AOP	88	[65]
8	Fe_3O_4 MNP	Co-precipitation	Ciprofloxacin	AOP	85	[16]
9	BiOCl/g-C_3N_4/Cu_2O/Fe_3O_4	Co-precipitation	Sulfamethoxazole, Ibuprofen, Acetaminophen and Antipyrine	AOP	99.5	[53]
10	$CuFe_2O_4$/GO	Co-precipitation	Metronidazole	AOP	100	[54]
11	Fe_3O_4 MNP	Co-precipitation	Cr	Adsorption	90	[55]
12	Modified magnetic nanoparticle with benzotriazole	Co-precipitation	Cu	Adsorption	99.7	[56]
13	Fe_3O_4 MNP	Co-precipitation	Cu	Adsorption	75	[36]
14	MNPs@SiO2@GOPTS- Lys	Co-precipitation	Cr	Adsorption	22	[14]
15	Fe_3O_4 MNP	Co-precipitation	Nitrate	Adsorption	86	[37]
16	Fe_3O_4 MNP	Co-precipitation	Sludge water content, Turbidity	Flocculation	Sludge water content; 90.8, Turbidity; 24.4	[38]
17	Fe_3O_4 MNP	Co-precipitation	Total organic content (TOC), turbidity, total suspended solids (TSS), and biological oxygendemand (BOD)	Flocculation	75	[39]
18	CFeO@CVD, FeO/AC composite, CoFeO, MnFeO, CuFeO, and FeO	Co-precipitation	E. coli and S. aureus	Antimicrobial assessment	99	[40]
19	Al-Fe_3O_4	Co-precipitation	Phosphate	Adsorption	90	[41]
20	Fe_3O_4 MNP	Microemulsion	Phosphate	Adsorption	100	[66]

21	Fe_3O_4@CNT	Co-precipitation	Malathion	Adsorption	82	[18]
22	Magnetic multi-walledcarbon nanotubes	Co-precipitation	Sulfate	Adsorption	93.28	[42]
23	Fe_3O_4 MNP	Co-precipitation	Sulfate	AOP	77.92	[43]
24	Magnetic-HNTs-ZnO	Co-precipitation	Non-drug resistant pathogenic E. coli and S. aureus, drug-resistantmethicillin-resistant S. aureus (MRSA)	Antimicrobial assessment	Significant	[44]
25	Magnetic $CoFe_2O_4$/diatomite	Combustion	BPA	AOP	95.54	[17]
26	$Ni_{0.6}Zn_{0.4}Fe_2O_4$ and $Ni_{0.6}Zn_{0.2}Ce_{0.2}Fe_2O_4$	Sol gel	Pathogenic microbes	Antimicrobial assessment	Significant	[58]
27	$Mn_{0.5}Zn_{0.5-x}Mg_xFe_2O_4$ NPs	Sol gel	Chloramine T, Rhodamine B Pathogenic bacteria and yeast	AOP Antimicrobial assessment	Chloramine T (90 %) Rhodamine B (95 %)	[15]
28	Fe_3O_4/CNTs	Co-precipitation	Microcystis aeruginosa	Coagulation	94.4	[45]
29	Fe_3O_4/PS	Co-precipitation	Nannochloropsisoculata microalgae	Flocculation	96	[46]
30	Silver-loadedmagnetic nanoparticles (Ag-MNPs)	Sol gel	Total coliforms (TC), fecal coliforms (FC), heterotrophic bacteria (HB), and chemical oxygen demand (COD)	Antimicrobial assessment Adsorption	Significant (antimicrobial) COD; 55	[59]
31	Fe_3O_4–dextrin–CoS	Sol Gel	Escherichia coli	Antimicrobial assessment	99	[60]
32	γ-Fe_2O_3	Co-precipitation	As (V)	Adsorption	90	[47]
33	Magnetic- Moringa seeds extract	Co-precipitation	Turbidity	Coagulation	90	[48]
34	CuFeO/CNT and C–FeO@CVD750	Co-precipitation	Staphylococcus aureus and E. coli	Antimicrobial assessment	99	[49]
35	Magnetic coagulant based on Moringa oleifera seed extract	Sol gel	Turbidity, Apparent color	Coagulation	Turbidity; 90 Apparent colourr; 85	[61]
36	Silver-coated $Ni_{0.5}Zn_{0.5}Fe_2O_4$	Sol gel	Escherichia coli	Antimicrobial assessment	99	[62]
37	Nano-Fe_3O_4	NR	Polyethylene (PE), polypropylene (PP), polystyrene (PS) and polyethylene terephthalate (PET)	Adsorption	80	[20]
38	Magnetic POM supported ionic liquid phase (magPOM-SILP)	NR	Polystyrene	Filtration	100	[21]

NR= Not reported, AOP = Advanced oxidation process

6.2 MAGNETIC NANOMATERIALS FOR WATER REUSE

Overall, magnetic nanomaterials can be used to remove contaminants (as described in Section 5.1) such as pathogens, organic matter, and nutrients from wastewater, thus allowing the reuse of treated water.The magnetic separation technique allows for the easy recovery and regeneration of nanomaterials, making them a sustainable and cost-effective solution for water reuse.Water scarcity is a growing global concern, and the use of treated wastewater for non-potable purposes is an effective way to address this issue[11, 12].Non-portable usage includes irrigation, industrial processes, and toilet flushing etc.Thus, by using recycled water, freshwater resources can be conserved and the amount of wastewater released into the environment can be reduced[11, 12].Moreover, magnetic nanomaterials can be used to treat wastewater for drinking purposes.In addition to wastewater treatment, magnetic nanoparticles can be employed in the treatment of surface water, such as lake and river water, for drinking purposes[11, 12].

6.3 RECOVERY OF NUTRIENTS AND METALS

The circular water economy aims to minimize the waste of water resources and promote the recovery of valuable materials from wastewater, such as nutrients, energy, and metals.Magnetic nanomaterials play a significant role in the recovery of nutrients, and meals from wastewater, providing a sustainable and cost-effective solution for resource recovery.For example, magnetic nanoparticles have been used to recover phosphorus[69–76] and nitrogen [77–85] from wastewater, which can then be used as fertilizers in agriculture.Magnetic nanoparticles can also be used to recover metals (such as copper, nickel, and zinc) [86–89] and precious metals (such as Ag, Au, Pd, Pt, and Rh) [87, 90, 91] from industrial wastewater, reducing the environmental impact of metal mining, and reduce the need for expensive disposal methods.The recovered nutrients and metals can then be reused in industrial processes, thereby creating a closed-loop system that reduces waste and conserves resources.

6.4 RECOVERY OF ENERGY

Energy recovery is a critical aspect of the circular water economy as it can help offset the energy required for water treatment processes.Magnetic nanomaterials can also be used to recover energy from wastewater by generating electricity [91]. Microbial fuel cells (MFCs) use bacteria to break down organic matter in wastewater and generate electricity[91]. Magnetic nanoparticles can be used to immobilize bacteria on an electrode, thereby enhancing the efficiency of the MFC and increasing the power output [93–107].Additionally, magnetic nanoparticles can be used to improve the production and recovery of methane from the anaerobic digestion of organic matter in wastewater treatment plants, which can then be used as a renewable energy source [35].Anaerobic digestion produces biogas that needs to be purified before it can be used as fuel [35].Biogas upgrading is an expensive and energy-intensive process, but research has shown that magnetic nanoparticles can reduce costs and increase efficiency [96, 108–123].Iron oxide nanoparticles coated with various functional groups can be added to anaerobic digesters to benefit methane production through hydrogenotrophic methanogenesis by fixing endogenous CO_2 or homoacetogenesis, increasing methane content, and reducing the need for costly upgrading processes [35].This technology can improve the efficiency of anaerobic digestion and reduce greenhouse gas emissions, making biogas a viable and cost-effective renewable energy source [35].

7.0 CHALLENGES, OPPORTUNITIES AND RECOMMENDATIONS FOR FUTURE RESEARCH DIRECTIONS

The circular economy of water and wastewater management is critical for meeting the growing global water demand and mitigating the water scarcity crisis. However, conventional wastewater treatment methods are energy intensive and generate significant amounts of waste. The emerging field of magnetic nanomaterials holds great promise for advancing the circular economy of water and wastewater by offering opportunities for resource recovery and reducing the environmental impacts of wastewater treatment. In this context, the challenges and opportunities for advancing the circular economy of water and wastewater using magnetic nanomaterials are discussed below, along with recommendations for future research.

7.1 CHALLENGES

- Technical challenges: One of the major technical challenges in advancing the circular economy of water and wastewater using magnetic nanomaterials is the optimization of their properties to effectively remove contaminants and recover resources. This includes optimizing their size, surface chemistry, and magnetic properties.
- Regulatory challenges: The use of nanomaterials in wastewater treatment is a relatively new area of research, and regulatory bodies may require more data on their safety and environmental impact before approving their use at an industrial scale.
- Economic challenges: While the use of magnetic nanomaterials has the potential to reduce the overall cost of wastewater treatment, the cost of producing and scaling up the technology may be a barrier to its widespread adoption.

7.2 OPPORTUNITIES

- Development of new technologies: Advancements in the use of magnetic nanomaterials in wastewater treatment can lead to the development of new technologies that are more efficient, cost-effective, and environmentally sustainable.
- Optimization of existing processes: Further research can focus on optimizing the performance of magnetic nanomaterials in existing treatment processes to improve their efficiency and reduce their environmental impact.
- Identification of new applications: There may be new applications for magnetic nanomaterials in water management, such as water quality monitoring and remediation.

7.3 RECOMMENDATIONS FOR FUTURE RESEARCH DIRECTIONS

- Safety and environmental impact assessment: Future research should focus on evaluating magnetic nanomaterials' safety and environmental impact, including their toxicity and potential for bioaccumulation in the environment.
- Optimization of magnetic nanomaterials: Research can focus on optimizing the properties of magnetic nanomaterials to improve their performance in wastewater treatment, including their size, surface chemistry, and magnetic properties.
- Development of cost-effective production methods: Future research can focus on developing cost-effective methods of producing magnetic nanomaterials, including the use of sustainable and environmentally friendly materials.
- Scaling up and implementation: Research should focus on scaling up the production and application of magnetic nanomaterials in wastewater treatment to make the technology more accessible to the water industry. This includes identifying potential barriers to scalability and developing strategies to overcome them.
- Integration with other technologies: Magnetic nanomaterials can be integrated with other technologies, such as membrane filtration and advanced oxidation processes, to improve the overall efficiency of wastewater treatment. Future research can focus on identifying potential integration opportunities and optimizing their performance.

8 CONCLUSIONS

The advancement of circular economy principles in the water sector presents a promising pathway towards sustainable water use and resource recovery. The use of magnetic nanomaterials in water and wastewater treatment represents an innovative approach that can facilitate the recovery of valuable resources from wastewater, reduce water consumption, and minimize waste. However, the implementation of this technology has challenges, including scalability, cost, and potential environmental impacts. To fully realize the potential of magnetic nanomaterials in advancing circular economy principles, future research should focus on developing cost-effective magnetic nanomaterials, optimizing the magnetic separation process, conducting life cycle assessments, and developing magnetic nanomaterial-based technologies that can be easily integrated into existing wastewater treatment plants. We can create a more sustainable and resilient water future for all by addressing these challenges and capitalizing on the opportunities.

REFERENCES

1. Ghimire U, Sarpong G, Gude VG. Transitioning wastewater treatment plants toward circular economy and energy sustainability. ACS Omega. 2021;6(18):11794–803.
2. Sauvé S, Lamontagne S, Dupras J, Stahel W. Circular economy of water: Tackling quantity, quality and footprint of water. Environ Dev. 2021;39:1–10.
3. Tóth AJ, Fózer D, Mizsey P, Varbanov PS, Klemeš JJ. Physicochemical methods for process wastewater treatment: Powerful tools for circular economy in the chemical industry. Rev Chem Eng. 2022;1–29.
4. Kiselev A, Magaril E, Panepinto D, Rada EC, Ravina M, Zanetti MC. Sustainable energy management benchmark at wastewater treatment plant. Sustain. 2021;13(22):1–11.
5. Neczaj E, Grosser A. Circular Economy in Wastewater Treatment Plant–Challenges and Barriers. Proceedings. 2018;2(614):1–7.
6. Dzihora Y, Stolyarenko H. BIOLOGICAL WASTEWATER TREATMENT IN CONTEXT OF CIRCULAR ECONOMY. Water Water Purif Technol. 2020;(2):3–10.
7. European Environment Agency;EEA. Beyond water quality-Sewage treatment in a circular economy [Internet]. Luxembourg; 2022. Available from: http://europa.eu
8. UNESCO-i-WSSM. Water Reuse within a Circular Economy Context [Internet]. Serie II. Global Water security issues serie. Global Water Security Issues (GWSI): UNESCO Publishing, Paris; 2020. 218 p. Available from: https://unesdoc.unesco.org/ark:/48223/pf0000374715.locale=en
9. CEWP. Circular Economy of Water - Waste Water Treatment. 2020.
10. Jazbec M, Mukheibir P, Turner A. Transitioning the Water Industry with the Circular Economy, prepared for the Water Services Association of Australia, Institute for Sustainable Futures [Internet]. University of Technology Sydney; 2020. Available from: www.isf.uts.edu.au
11. Baresel C, Schaller V, Jonasson C, Johansson C, Bordes R, Chauhan V, et al. Functionalized magnetic particles for water treatment. Heliyon [Internet]. 2019;5:1–7. Available from: https://doi.org/10.1016/j.heliyon.2019.e02325
12. Govan J. Recent advances in magnetic nanoparticles and nanocomposites for the remediation of water resources. Magnetochemistry. 2020;6(4):1–47.
13. Dhiman S, Sharma C, Kumar A, Pathak P. Microplastics in Aquatic and Food Ecosystems : Remediation Coupled with Circular Economy Solutions to Create Resource from Waste. 2023;
14. Plohl O, Simonič M, Kolar K, Gyergyek S, Fras Zemljič L. Magnetic nanostructures functionalized with a derived lysine coating applied to simultaneously remove heavy metal pollutants from environmental systems. Sci Technol Adv Mater [Internet]. 2021;22(1):55–71. Available from: https://doi.org/10.1080/14686996.2020.1865114
15. Maksoud MIAA, El-sayyad GS, El-khawaga AM, Elkodous MA, Abokhadra A, Elsayed MA, et al. Nanostructured Mg substituted Mn-Zn ferrites : A magnetic recyclable catalyst for outstanding photocatalytic and antimicrobial potentials. J Hazard Mater [Internet]. 2020;399:1–19. Available from: https://doi.org/10.1016/j.jhazmat.2020.123000
16. Lima MJ, Leblebici ME, Dias MM, Lopes JCB, Silva CG, Silva AMT, et al. Continuous flow photo-Fenton treatment of ciprofloxacin in aqueous solutions using homogeneous and magnetically recoverable catalysts. Environ Sci Pollut

Res. 2014;21(19):11116–25.

17. Tan Y, Li C, Sun Z, Bian R, Dong X, Zhang X, et al. Natural diatomite mediated spherically monodispersed CoFe 2 O 4 nanoparticles for efficient catalytic oxidation of bisphenol A through activating peroxymonosulfate. Chem Eng J [Internet]. 2020;388:1–14. Available from: https://doi.org/10.1016/j.cej.2020.124386
18. Makvand ME, Sabzalipour S, Cheraghi M, Orak N. Evaluation of Efficiency of Iron Oxide Nanoparticles (Fe3O4@CNT) in Removal of Malathion in Aqueous Medium Using Response Surface Methodology (RSM). Pollution. 2022;8(1):281–93.
19. Du Z, Deng S, Zhang S, Wang W, Wang B, Huang J, et al. Selective and Fast Adsorption of Perfluorooctanesulfonate from Wastewater by Magnetic Fluorinated Vermiculite. Environ Sci Technol. 2017;51(14):8027–35.
20. Shi X, Zhang X, Gao W, Zhang Y, He D. Removal of microplastics from water by magnetic nano-Fe3O4. Sci Total Environ [Internet]. 2022;802:1–8. Available from: https://doi.org/10.1016/j.scitotenv.2021.149838
21. Misra A, Zambrzycki C, Kloker G, Kotyrba A, Anjass MH, Franco Castillo I, et al. Water Purification and Microplastics Removal Using Magnetic Polyoxometalate-Supported Ionic Liquid Phases (magPOM-SILPs). Angew Chemie - Int Ed. 2020;59(4):1601–5.
22. Tintaya A, Andrea P, Valeria AD, Ignacio TLJ, Gladys LIFV, Jaime LG. CIRCULAR ECONOMY AND ITS INCORPORATION IN WATER TREATMENT PLANTS. In: 25th International Congress on Project Management and Engineering Alcoi. 2021. p. 1112–23.
23. Smol M, Adam C, Preisner M. Circular economy model framework in the European water and wastewater sector. J Mater Cycles Waste Manag [Internet]. 2020;1–16. Available from: https://doi.org/10.1007/s10163-019-00960-z
24. Ziegler R. Viewpoint - Water innovation for a circular economy: The contribution of grassroots actors. Water Altern. 2019;12(2):774–87.
25. Danuta L. The Water - wastewater - sludge Sector and the Circular Economy. Comp Econ Res. 2018;21(4):122–37.
26. Surinkul N, Threedeach S, Chiemchaisri W, Chiemchaisri C. Circular economy approach for wastewater treatment farming in Bangpakong River basin. In: IOP Conference Series: Earth and Environmental Science. 2020. p. 1–7.
27. Casiano Flores C, Bressers H, Gutierrez C, de Boer C. Towards circular economy – a wastewater treatment perspective, the Presa Guadalupe case. Manag Res Rev. 2018;41(5):554–71.
28. Ekman Burgman L. What sewage sludge is and conflicts in Swedish circular economy policymaking. Environ Sociol [Internet]. 2022;8(3):292–301. Available from: https://doi.org/10.1080/23251042.2021.2021603
29. Lehtoranta S, Laukka V, Vidal B, Heiderscheidt E, Postila H, Nilivaara R, et al. Circular Economy in Wastewater Management—The Potential of Source-Separating Sanitation in Rural and Peri-Urban Areas of Northern Finland and Sweden. Front Environ Sci. 2022;10:1–18.
30. KALEMBA K. Circular Economy in Wastewater Treatment Plant. Archit Civ Eng Environ. 2020;13(4):93–7.
31. Kacprzak MJ, Kupich I. The specificities of the circular economy (CE) in the municipal wastewater and sewage sludge sector — local circumstances in Poland. Clean Technol Environ Policy [Internet]. 2023;25(2):519–35. Available

from: https://doi.org/10.1007/s10098-021-02178-w
32. Mbavarira TM, Grimm C. A systemic view on circular economy in the water industry: Learnings from a belgian and dutch case. Sustain. 2021;13(6):1–62.
33. Andrade MPN de, Mello GSL de. WASTE WATER TREATMENT AND CIRCULAR ECONOMY. Vol. 27, GCSP-IMT Seminar. 2019.
34. Nielsen PH. Microbial biotechnology and circular economy in wastewater treatment. Microb Biotechnol. 2017;0(0):000–000.
35. Wei J, Hao X, van Loosdrecht MCM, Li J. Feasibility analysis of anaerobic digestion of excess sludge enhanced by iron: A review. Renew Sustain Energy Rev. 2018;89:16–26.
36. Al-Jabri MTK, Devi MG, Al Abri M. Synthesis, characterization and application of magnetic nanoparticles in the removal of copper from aqueous solution. Appl Water Sci [Internet]. 2018;8(8):1–7. Available from: https://doi.org/10.1007/s13201-018-0872-x
37. Pourzamani HR, Mengelīzadeh N, Jalil M. Nitrate Removal from Aqueous Solutions by Magnetic Nanoparticle. J Environ Heal Sustain Dev. 2017;2(1):187–95.
38. Hwang JH, Han DW. Optimization and modeling of reduction of wastewater sludge water content and turbidity removal using magnetic iron oxide nanoparticles (MION). J Environ Sci Heal - Part A Toxic/Hazardous Subst Environ Eng. 2015;50(13):1307–15.
39. Chhetri T, Cunningham G, Suresh D, Shanks B, Kannan R, Upendran A, et al. Wastewater Treatment Using Novel Magnetic Nanosponges. Water (Switzerland). 2022;14(3):1–12.
40. Pinto M, Ramalho PSF, Moreira NFF, Gonçalves AG, Nunes OC, Pereira MFR, et al. Application of magnetic nanoparticles for water purification. Environ Adv [Internet]. 2020;2:1–8. Available from: https://doi.org/10.1016/j.envadv.2020.100010
41. Xu J, Luu L, Tang Y. Phosphate removal using aluminum-doped magnetic nanoparticles. Desalin Water Treat. 2017;58:239–48.
42. Alimohammadi V, Sedighi M, Jabbari E. Optimization of sulfate removal from wastewater using magnetic multi-walled carbon nanotubes by response surface methodology. Water Sci Technol. 2017;76(10):2593–602.
43. Davoodi H, Gholami RM, Ghasemi S. Investigation Sulphate removal of Synthetic Wastewater by iron oxide nanoparticles. Hum Environ. 2018;45:1–12.
44. Jee S, Kim M, Shinde SK, Ghodake GS, Sung J. ZnO and Fe 3 O 4 nanostructures on halloysite nanotubes for anti- bacterial assessments. Appl Surf Sci [Internet]. 2020;509:1–10. Available from: https://doi.org/10.1016/j.apsusc.2020.145358
45. Wu X, Xu G, Wang J. Ultrasound-assisted coagulation for Microcystis aeruginosa removal using Fe3O4-loaded carbon nanotubes. RSC Adv. 2020;10:13525–31.
46. Chu F, Wan T, Chen H, Wu C, Kao P. Magnetophoretic Harvesting of Nannochloropsis oculata Using Iron Oxide Immobilized Beads. Water. 2020;12:2–11.
47. Zeng H, Zhai L, Qiao T, Yu Y, Zhang J, Li D. Efficient removal of As(V) from aqueous media by magnetic nanoparticles prepared with Iron-containing water treatment residuals. Sci Rep. 2020;10(1):1–12.
48. Triques CC, Fagundes-Klen MR, Suzaki PYR, Mateus GAP, Wernke G,

Bergamasco R, et al. Influence evaluation of the functionalization of magnetic nanoparticles with a natural extract coagulant in the primary treatment of a dairy cleaning-in-place wastewater. J Clean Prod [Internet]. 2020;243:1–34. Available from: https://doi.org/10.1016/j.jclepro.2019.118634

49. Santos ASGG, Ramalho PSF, Viana AT, Lopes AR, Gonçalves AG, Nunes OC, et al. Feasibility of using magnetic nanoparticles in water disinfection. J Environ Manage. 2021;288(1–14).

50. Vicente-Martínez Y, Caravaca M, Soto-Meca A, Solana-González R. Magnetic core-modified silver nanoparticles for ibuprofen removal: an emerging pollutant in waters. Sci Rep [Internet]. 2020;10(1):1–10. Available from: https://doi.org/10.1038/s41598-020-75223-1

51. Vicente-Martínez Y, Caravaca M, Soto-Meca A, Martín-Pereira MÁ, García-Onsurbe MDC. Adsorption studies on magnetic nanoparticles functionalized with silver to remove nitrates from waters. Water (Switzerland). 2021;13(13):1–16.

52. Lakshmanan R, Rajaraman P, Okoli C, Boutonnet M, Järås S, Rajarao GK. Application of magnetic nanoparticles for wastewater treatment using response surface methodology. In: Technical Proceedings of the 2013 NSTI Nanotechnology Conference and Expo, NSTI-Nanotech 2013. 2013. p. 690–3.

53. Kumar A, Kumar A, Sharma G, Al-Muhtaseb AH, Naushad M, Ghfar AA, et al. Quaternary magnetic BiOCl/g-C3N4/Cu2O/Fe3O4 nano-junction for visible light and solar powered degradation of sulfamethoxazole from aqueous environment. Chem Eng J [Internet]. 2018;334:462–78. Available from: http://dx.doi.org/10.1016/j.cej.2017.10.049

54. Noroozi R, Gholami M, Farzadkia M, Jonidi Jafari A. Catalytic potential of CuFe2O4/GO for activation of peroxymonosulfate in metronidazole degradation: study of mechanisms. J Environ Heal Sci Eng. 2020;18(2):947–60.

55. Yazid NA, Joon YC. Co-precipitation synthesis of magnetic nanoparticles for efficient removal of heavy metal from synthetic wastewater. In: AIP Conference Proceedings. 2019. p. 1–11.

56. jadidian R, Parham H, haghtalab S, Asrarian R. Removal of copper from industrial water and wastewater using magnetic iron oxide nanoparticles modified with benzotriazole. Adv Mater Res. 2014;829:742–6.

57. Boulares M, Chamam B, Mejri A, Wahab MA, Haddouk A, Mir L El, et al. Robust Magnetic -Fe2O3/Al–ZnO Adsorbent for Chlorpyriphos Removal inWater. Water (Switzerland). 2022;12:1–15.

58. Hammad ABA, Hemdan BA, Nahrawy AM El. Facile synthesis and potential application of Ni0 . 6Zn0 . 4Fe2O4 and Ni0 . 6Zn0 . 2Ce0 . 2Fe2O4 magnetic nanocubes as a new strategy in sewage treatment. J Environ Manage [Internet]. 2020;270:1–14. Available from: https://doi.org/10.1016/j.jenvman.2020.110816

59. Najafpoor A, Norouzian-ostad R, Alidadi H, Rohani-bastami T. Effect of magnetic nanoparticles and silver-loaded magnetic nanoparticles on advanced wastewater treatment and disinfection. J Mol Liq [Internet]. 2020;303:1–7. Available from: https://doi.org/10.1016/j.molliq.2020.112640

60. Amini MH, Beyki MH. Enhanced E . coli Capturing Efficacy Over Magnetic Dextrin – Cobalt Sulfide Nanohybrid as a Promising Water Disinfection System. J Inorg Organomet Polym Mater [Internet]. 2021;(0123456789). Available from: https://doi.org/10.1007/s10904-021-01876-8

61. Santos TRT, Silva MF, Nishi L, Vieira AMS. Development of a magnetic coagulant based on Moringa oleifera seed extract for water treatment. Environ Sci Pollut Res. 2016;1–10.
62. Asadi S, Moeinpour F. Inactivation of Escherichia coli in water by silver - coated - Ni 0 . 5 Zn 0 . 5 Fe 2 O 4 magnetic nanocomposite : a Box – Behnken design optimization. Appl Water Sci [Internet]. 2019;9(1):1–9. Available from: https://doi.org/10.1007/s13201-019-0901-4
63. He Y, Wu P, Li G, Li L, Yi J, Wang S. Optimization on preparation of Fe3O4/chitosan as potential matrix material for the removal of microcystin-LR and its evaluation of adsorption properties. Int J Biol Macromol [Internet]. 2019;1–46. Available from: https://doi.org/10.1016/j.ijbiomac.2019.11.209
64. Aragaw TA, Bogale FM, Aragaw BA. Iron-based nanoparticles in wastewater treatment: A review on synthesis methods, applications, and removal mechanisms. J Saudi Chem Soc [Internet]. 2021;25(8):101280. Available from: https://doi.org/10.1016/j.jscs.2021.101280
65. Liu C, Chen L, Ding D, Cai T. From rice straw to magnetically recoverable nitrogen doped biochar : E ffi cient activation of peroxymonosulfate for the degradation of metolachlor. Appl Catal B Environ [Internet]. 2019;254:312–20. Available from: https://doi.org/10.1016/j.apcatb.2019.05.014
66. Lakshmanan R, Okoli C, Boutonnet M, Järås S, Rajarao GK. Microemulsion prepared magnetic nanoparticles for phosphate removal: Time efficient studies. J Environ Chem Eng. 2014;2(1):185–9.
67. Kumar A, Khan M, Zeng X, Lo IMC. Development of g-C3N4/TiO2/Fe3O4@SiO2 heterojunction via sol-gel route: A magnetically recyclable direct contact Z-scheme nanophotocatalyst for enhanced photocatalytic removal of ibuprofen from real sewage effluent under visible light. Chem Eng J [Internet]. 2018;353:645–56. Available from: https://doi.org/10.1016/j.cej.2018.07.153
68. Hafiz M, Hassanein A, Talhami M, Al-Ejji M, Hassan MK, Hawari AH. Magnetic nanoparticles draw solution for forward osmosis: Current status and future challenges in wastewater treatment. J Environ Chem Eng [Internet]. 2022;10(6):1–22. Available from: https://doi.org/10.1016/j.jece.2022.108955
69. Choi J, Chung J, Lee W, Lim HS, Kim JO. Recovery of phosphate by magnetic iron oxide particles and iron oxide nanotubes in water. Water Air Soil Pollut [Internet]. 2016;227(5):1–11. Available from: http://dx.doi.org/10.1007/s11270-016-2781-7
70. Drenkova-tuhtan A. Phosphorus elimination and recovery from wastewater and process water with reusable nanocomposite magnetic particles. In: 3rd European Sustainable Phosphorus Conference 2018, Helsinki, Finlandia Hall, 11-13 June 2018. 3rd European Sustainable Phosphorus Conference 2018, Helsinki, Finlandia Hall; 2018. p. 2–3.
71. Drenkova-Tuhtan A, Mandel K, Paulus A, Meyer C, Hutter F, Gellermann C, et al. Phosphate recovery from wastewater using engineered superparamagnetic particles modified with layered double hydroxide ion exchangers. Water Res [Internet]. 2013;47(15):5670–7. Available from: http://dx.doi.org/10.1016/j.watres.2013.06.039
72. Drenkova-Tuhtan A, Schneider M, Franzreb M, Meyer C, Gellermann C, Sextl G, et al. Pilot-scale removal and recovery of dissolved phosphate from secondary wastewater effluents with reusable ZnFeZr adsorbent @ Fe3O4/SiO2 particles with magnetic harvesting. Water Res [Internet].

2017;109:77–87. Available from: http://dx.doi.org/10.1016/j.watres.2016.11.039

73. Gulyás A, Genç S, Can ZS, Semerci N. Phosphate recovery from sewage sludge supernatants using magnetic nanoparticles. J Water Process Eng [Internet]. 2021;40:1–9. Available from: https://doi.org/10.1016/j.jwpe.2020.101843
74. Tu YJ, You CF, Chang CK, Chen MH. Application of magnetic nano-particles for phosphorus removal/recovery in aqueous solution. J Taiwan Inst Chem Eng [Internet]. 2015;46:148–54. Available from: http://dx.doi.org/10.1016/j.jtice.2014.09.016
75. Xiao X, Liu S, Zhang X, Zheng S. Phosphorus removal and recovery from secondary effluent in sewage treatment plant by magnetite mineral microparticles. Powder Technol [Internet]. 2017;306:68–73. Available from: http://dx.doi.org/10.1016/j.powtec.2016.10.066
76. Li R, Wang JJ, Zhou B, Awasthi MK, Ali A, Zhang Z, et al. Recovery of phosphate from aqueous solution by magnesium oxide decorated magnetic biochar and its potential as phosphate-based fertilizer substitute. Bioresour Technol. 2016;215(225):209–14.
77. Kara B, Gulyá A, Semerci N, Can ZS, Genç S. Adsorption of Ammonium and Phosphate Ions : Comparing the Adsorption Performances of the Bare & Composite Magnetite Nanoparticles. In: EurAsia Waste Management Symposium, 26-28 October, İstanbul/Türkiye. İstanbul/Türkiye; 2020. p. 2–5.
78. Siddeeg SM, Tahoon MA, Rebah F Ben. Simultaneous removal of calconcarboxylic acid, NH4+ and PO43- from pharmaceutical effluent using iron oxide-biochar nanocomposite loaded with Pseudomonas putida. Processes. 2019;7(11):1–8.
79. Sugawara T, Matsuura Y, Anzai T, Miura O. Removal of ammonia nitrogen from water by magnetic zeolite and high-gradient magnetic separation. IEEE Trans Appl Supercond. 2016;26(4):50–3.
80. Song J, Srivastava V, Kohout T, Sillanpää M, Sainio T. Montmorillonite-anchored magnetite nanocomposite for recovery of ammonium from stormwater and its reuse in adsorption of Sc3+. Nanotechnol Environ Eng [Internet]. 2021;6(3):1–14. Available from: https://doi.org/10.1007/s41204-021-00151-y
81. Shadi AMH, Kamaruddin MA, Niza NM, Emmanuel MI, Ismail N, Hossain S. Effective removal of organic and inorganic pollutants from stabilized sanitary landfill leachate using a combined Fe2O3 nanoparticles/electroflotation process. J Water Process Eng [Internet]. 2021;40:1–9. Available from: https://doi.org/10.1016/j.jwpe.2021.101988
82. Xin X, Yang H, Guan L, Liu S, Liu J. Responses of Nitrogen and Phosphorus Removal Performance and Microbial Community to Fe3O4@SiO2 Nanoparticles in a Sequencing Batch Reactor. Appl Biochem Biotechnol. 2021;193(2):544–59.
83. Zare K, Sadegh H, Shahryari-Ghoshekandi R, Asif M, Tyagi I, Agarwal S, et al. Equilibrium and kinetic study of ammonium ion adsorption by Fe3O4 nanoparticles from aqueous solutions. J Mol Liq [Internet]. 2016;213:345–50. Available from: http://dx.doi.org/10.1016/j.molliq.2015.08.045
84. Zhang LJ, Zhang X, Liang HF, Xie Y, Tao HC. Ammonium removal by a novel magnetically modified excess sludge. Clean Technol Environ Policy [Internet]. 2018;20(10):2181–9. Available from: https://doi.org/10.1007/s10098-018-1524-

4
85. Crane RA, Sapsford DJ. Towards “Precision Mining” of wastewater: Selective recovery of Cu from acid mine drainage onto diatomite supported nanoscale zerovalent iron particles. Chemosphere [Internet]. 2018;202:339–48. Available from: https://doi.org/10.1016/j.chemosphere.2018.03.042
86. Aghaei E, Alorro RD, Encila AN, Yoo K. Magnetic adsorbents for the recovery of precious metals from leach solutions and wastewater. Metals (Basel). 2017;7(12):1–32.
87. Wei X. Acid mine drainage: Sludge dewatering, metal recovery and synthesis of magnetite nanoparticles. Grad Theses, Diss Probl Reports [Internet]. 2005; Available from: https://researchrepository.wvu.edu/etd/2347
88. Hutchins D. Continuous flow process for recovery of metal contaminants from industrial wastewaters with magnetic nanocomposites [Internet]. 2018. Available from: https://digitalcommons.mtech.edu/grad_rsch/183
89. Amuanyena MON, Kandawa-Schulz M, Kwaambwa HM. Magnetic Iron Oxide Nanoparticles Modified with Moringa Seed Proteins for Recovery of Precious Metal Ions. J Biomater Nanobiotechnol. 2019;10(02):142–58.
90. Lin TL, Lien HL. Effective and selective recovery of precious metals by thiourea modified magnetic nanoparticles. Int J Mol Sci. 2013;14(5):9834–47.
91. Yaqoob AA, Khatoon A, Setapar SHM, Umar K, Parveen T, Ibrahim MNM, et al. Outlook on the role of microbial fuel cells in remediation of environmental pollutants with electricity generation. Vol. 10, Catalysts. 2020. 1–34 p.
92. Türker OC, Baran T, Yakar A, Türe C, Saz Ç. Novel chitosan based smart cathode electrocatalysts for high power generation in plant based-sediment microbial fuel cells. Carbohydr Polym [Internet]. 2020;239(April):1–11. Available from: https://doi.org/10.1016/j.carbpol.2020.116235
93. Sambavi SM, Vishali S, Varjani S, Mullai P. <p>Electricity generation in a microbial fuel cell using iron oxide nanoparticles</p>. Indian J Exp Biol. 2020;58(August):571–7.
94. Han TH, Khan MM, Kalathil S, Lee J, Cho MH. Simultaneous enhancement of methylene blue degradation and power generation in a microbial fuel cell by gold nanoparticles. Ind Eng Chem Res. 2013;52(24):8174–81.
95. Rahimnejad M, Ghasemi M, Najafpour GD, Ismail M, Mohammad AW, Ghoreyshi AA, et al. Synthesis, characterization and application studies of self-made Fe 3O4/PES nanocomposite membranes in microbial fuel cell. Electrochim Acta. 2012;85:700–6.
96. Zhang F, Brastad KS, He Z. Integrating forward osmosis into microbial fuel cells for wastewater treatment, water extraction and bioelectricity generation. Environ Sci Technol. 2011;45(15):6690–6.
97. Zinadini S, Zinatizadeh AA, Rahimi M, Vatanpour V, Bahrami K. Energy recovery and hygienic water production from wastewater using an innovative integrated microbial fuel cell–membrane separation process. Energy [Internet]. 2017;141:1350–62. Available from: https://doi.org/10.1016/j.energy.2017.11.057
98. Bavasso I, Bracciale MP, Sbardella F, Puglia D, Dominici F, Torre L, et al. Sulfonated Fe3O4/PES nanocomposites as efficient separators in microbial fuel cells. J Memb Sci. 2021;620:1–10.
99. Alatraktchi FAZ a., Zhang Y, Angelidaki I. Nanomodification of the electrodes in microbial fuel cell: Impact of nanoparticle density on electricity production and microbial community. Appl Energy. 2014;116:216–22.

100. Madondo NI, Tetteh EK, Rathilal S, Bakare BF. Synergistic effect of magnetite and bioelectrochemical systems on anaerobic digestion. Bioengineering. 2021;8(12):1–12.
101. Tripathi B, Pandit S, Sharma A, Chauhan S, Mathuriya AS, Dikshit PK, et al. Modification of Graphite Sheet Anode with Iron (II, III) Oxide-Carbon Dots for Enhancing the Performance of Microbial Fuel Cell. Catalysts. 2022;12(9):1–16.
102. Sarma MK, Quadir MGA, Bhaduri R, Kaushik S, Goswami P. Composite polymer coated magnetic nanoparticles based anode enhances dye degradation and power production in microbial fuel cells. Biosens Bioelectron [Internet]. 2018;1–30. Available from: http://dx.doi.org/10.1016/j.dineu.2015.08.001
103. Das I, Das S, Das S, Ghangrekar MM. Proficient Sanitary Wastewater Treatment in Laboratory and Field-Scale Microbial Fuel Cell with Anti-Biofouling Cu 0.5 Mn 0.5 Fe 2 O 4 as Cathode Catalyst. J Electrochem Soc. 2021;168(5):1–9.
104. Di Palma L, Bavasso I, Sarasini F, Tirillò J, Puglia D, Dominici F, et al. Synthesis, characterization and performance evaluation of Fe3O4/PES nano composite membranes for microbial fuel cell. Eur Polym J [Internet]. 2018;99(December 2017):222–9. Available from: https://doi.org/10.1016/j.eurpolymj.2017.12.037
105. Kumar GG, Joseph Kirubaharan C, Yoo DJ, Kim AR. Graphene/poly(3,4-ethylenedioxythiophene)/Fe3O4 nanocomposite – An efficient oxygen reduction catalyst for the continuous electricity production from wastewater treatment microbial fuel cells. Int J Hydrogen Energy [Internet]. 2016;41(30):13208–19. Available from: http://dx.doi.org/10.1016/j.ijhydene.2016.05.099
106. Madondo NI, Rathilal S, Bakare BF, Tetteh EK. Application of Magnetite-Nanoparticles and Microbial Fuel Cell on Anaerobic Digestion: Influence of External Resistance. Microorganisms. 2023;11(3):643–64.
107. Barrena R, Vargas-García M del C, Capell G, Barańska M, Puntes V, Moral-Vico J, et al. Sustained effect of zero-valent iron nanoparticles under semi-continuous anaerobic digestion of sewage sludge: Evolution of nanoparticles and microbial community dynamics. Sci Total Environ. 2021;777:1–12.
108. Chen JL, Steele TWJ, Stuckey DC. The effect of Fe 2 NiO 4 and Fe 4 NiO 4 Zn magnetic nanoparticles on anaerobic digestion activity. Sci Total Environ [Internet]. 2018;642:276–84. Available from: https://doi.org/10.1016/j.scitotenv.2018.05.373
109. Heikal G, Shakroum M, Vranayova Z, Abdo A. Impact of Nanoparticles on Biogas Production from Anaerobic Digestion of Sewage Sludge. J Ecol Eng. 2022;23(8):222–40.
110. Yazdani M, Ebrahimi-Nik M, Heidari A, Abbaspour-Fard MH. Improvement of biogas production from slaughterhouse wastewater using biosynthesized iron nanoparticles from water treatment sludge. Renew Energy. 2019;135:496–501.
111. Zhang Z, Guo L, Wang Y, Zhao Y, She Z, Gao M, et al. Application of iron oxide (Fe3O4) nanoparticles during the two-stage anaerobic digestion with waste sludge: Impact on the biogas production and the substrate metabolism. Renew Energy [Internet]. 2020;146:2724–35. Available from: https://doi.org/10.1016/j.renene.2019.08.078
112. Amen TWM, Eljamal O, Khalil AME, Sugihara Y, Matsunaga N. Methane yield

enhancement by the addition of new novel of iron and copper-iron bimetallic nanoparticles. Chem Eng Process - Process Intensif [Internet]. 2018;130:253–61. Available from: https://doi.org/10.1016/j.cep.2018.06.020
113. Tetteh EK, Amo-Duodu G, Rathilal S. Exploring CO2 Bio-Mitigation via a Biophotocatalytic/ Biomagnetic System for Wastewater Treatment and Biogas Production. Appl Sci. 2022;12(14):1–9.
114. Amo-Duodu G, Tetteh EK, Rathilal S, Armah EK, Adedeji J, Chollom MN, et al. Effect of engineered biomaterials and magnetite on wastewater treatment: Biogas and kinetic evaluation. Polymers (Basel). 2021;13(24).
115. Amo-Duodu G, Kweinor Tetteh E, Rathilal S, Chollom MN. Synthesis and characterization of magnetic nanoparticles: Biocatalytic effects on wastewater treatment. Mater Today Proc [Internet]. 2022;62:S79–84. Available from: https://doi.org/10.1016/j.matpr.2022.02.091
116. Kweinor Tetteh E, Amo-Duodu G, Rathilal S. Biogas production from wastewater: Comparing biostimulation impact of magnetised-chitosan and -titania chitosan. Mater Today Proc [Internet]. 2022;62:S85–90. Available from: https://doi.org/10.1016/j.matpr.2022.02.092
117. Kweinor Tetteh E, Rathilal S. Biogas production from wastewater treatment: Evaluating anaerobic and biomagnetic systems. Water-Energy Nexus [Internet]. 2021;4:165–73. Available from: https://doi.org/10.1016/j.wen.2021.11.004
118. Abdallah MS, Hassaneen FY, Faisal Y, Mansour MS, Ibrahim AM, Abo-Elfadl S, et al. Effect of Ni-Ferrite and Ni-Co-Ferrite nanostructures on biogas production from anaerobic digestion. Fuel [Internet]. 2019;254:1–8. Available from: https://doi.org/10.1016/j.fuel.2019.115673
119. Abdelsalam E, Samer M, Attia YA, Abdel-Hadi MA, Hassan HE, Badr Y. Influence of zero valent iron nanoparticles and magnetic iron oxide nanoparticles on biogas and methane production from anaerobic digestion of manure. Energy [Internet]. 2017;120:842–53. Available from: http://dx.doi.org/10.1016/j.energy.2016.11.137
120. Song X, Liu J, Jiang Q, Zhang P, Shao Y, He W, et al. Enhanced electron transfer and methane production from low-strength wastewater using a new granular activated carbon modified with nano-Fe3O4. Chem Eng J [Internet]. 2019;374(March):1344–52. Available from: https://doi.org/10.1016/j.cej.2019.05.216
121. Lizama AC, Figueiras CC, Pedreguera AZ, Ruiz Espinoza JE. Enhancing the performance and stability of the anaerobic digestion of sewage sludge by zero valent iron nanoparticles dosage. In: Bioresource Technology for Bioenergy, Bioproducts and Environmental Sustainability,16-19 September, Sitges, Spain. 2018. p. 352–9.
122. Tetteh EK, Rathilal S. Kinetics and nanoparticle catalytic enhancement of biogas production from wastewater using a magnetized biochemical methane potential (Mbmp) system. Catalysts. 2020;10(10):1–19.