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Advancing Circular Economy of Water and Wastewater Using Magnetic Nanomaterials

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Authors' contributions

This work was carried out in collaboration between both authors. Author ZS designed the study, performed the statistical analysis, wrote the protocol and wrote the first draft of the manuscript. Author GWAN managed the analyses of the study and managed the literature searches. Both authors read and approved the final manuscript.

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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.

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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]. Fig. 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 as composts and nutrients (Nitrogen and phosphorus) 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. 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

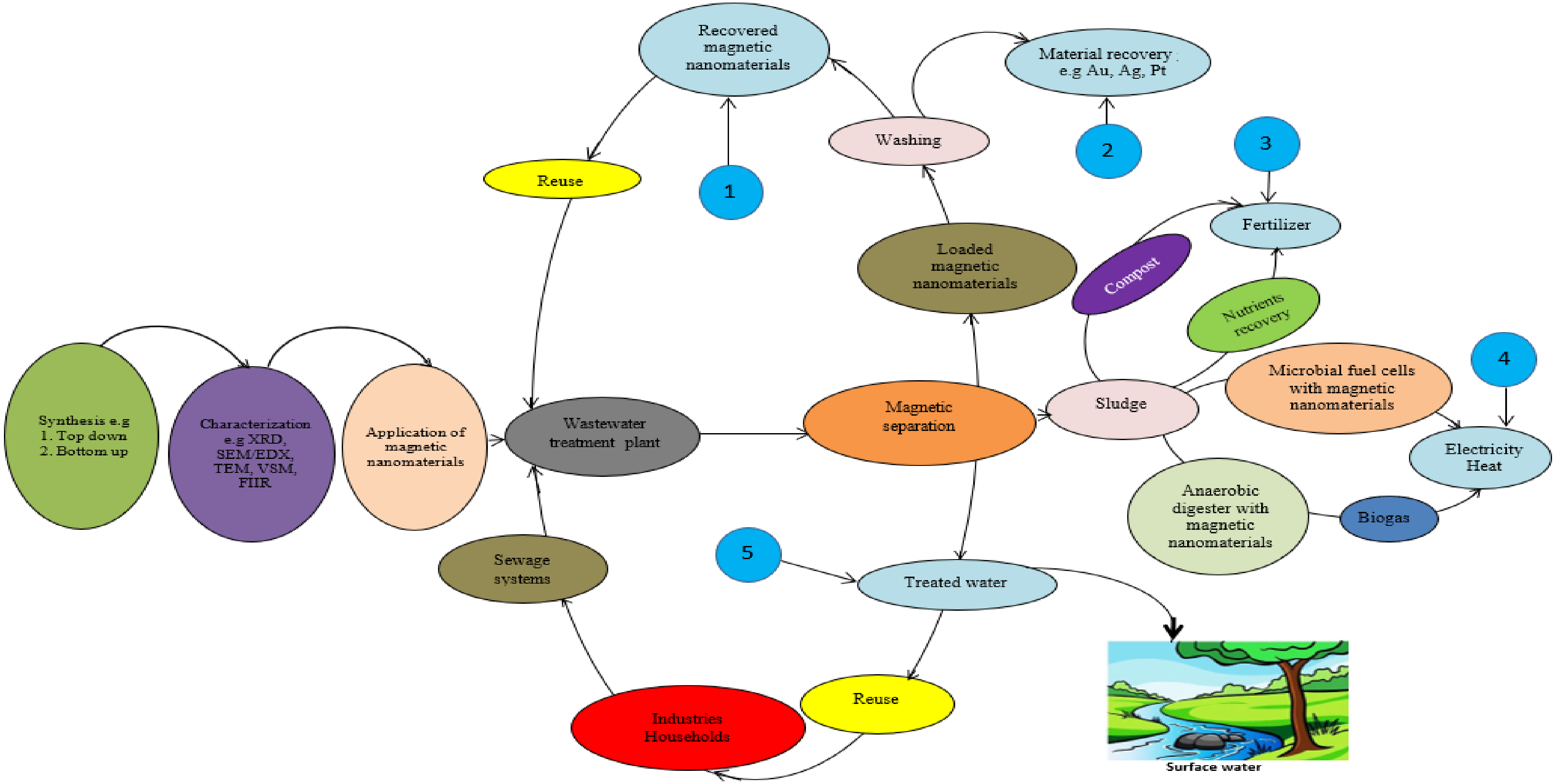

Fig. 1. Schematic application of magnetic nanomaterials in advancing circular economy of water and wastewater

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 study 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.

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 Fig. 1.

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.

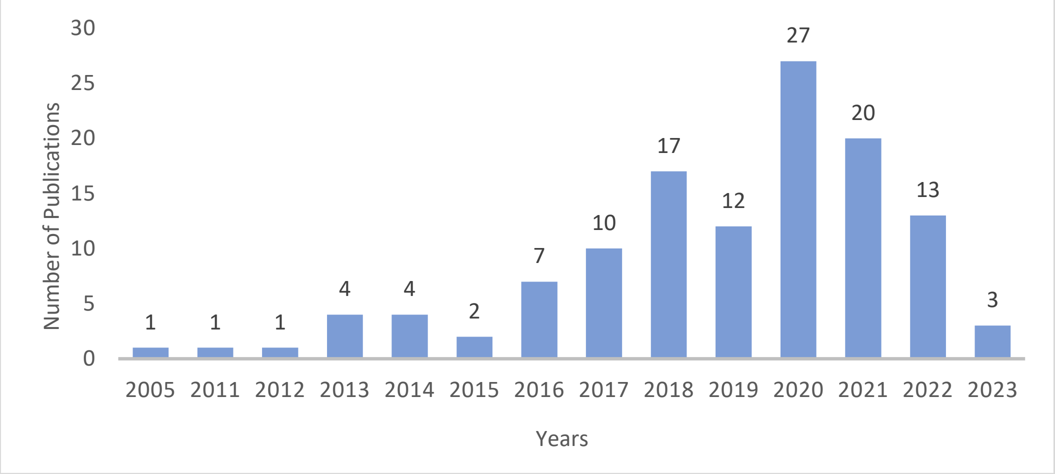

Fig. 2. Distributions of articles

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. 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].

5. ADVANTAGES 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. APPLICATION OF MAGNETIC NANOMATERIALS IN CIRCULAR WATER ECONOMY

The circular water economy aims to minimize waste and promote the recovery of valuable materials from wastewater, such as nutrients, energy, and metals. 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 Pollutants from Water and Waste Water

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.

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

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, and Flocculation	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	γ-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	Flocculation	75	[39]

S/N	Nanomaterials	Synthesis	Pollutants	Treatment methods	% Removal	References
			(TOC), turbidity, total suspended solids (TSS), and biological oxygen demand (BOD)			
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-walled carbon 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-resistant methicillin-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	Nannochloropsis oculata microalgae	Flocculation	96	[46]
30	Silver-loadedmagnetic nanoparticles (Ag-MNPs)	Sol gel	Total coliforms (TC), fecal coliforms (FC), heterotrophic bacteria (HB),	Antimicrobial assessment Adsorption	Significant (antimicrobial) COD; 55	[59]

S/N	Nanomaterials	Synthesis	Pollutants	Treatment methods	% Removal	References
			and chemical oxygen demand (COD)			
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 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 [92]. 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 [96,108–122]. 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. 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.

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COMPETING INTERESTS

Authors have declared that no competing interests exist

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