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REVIEW ARTICLE

A review of Pharmaceuticals removal from water resources using magnetic iron-based nanomaterials

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Abstract

The presence of pharmaceuticals in water resources is a growing concern worldwide due to their potential health impacts on aquatic life and humans. Therefore, there is a need to develop effective and sustainable technologies for removing these contaminants from water and wastewater. Magnetic nanomaterials have emerged as promising materials for this purpose due to their fast kinetics, easy magnetic separation, and reuse. This review is important as it highlights the significance of developing sustainable technologies using magnetic iron-based nanomaterials for removing pharmaceutical contaminants from water resources. This review investigated the application of magnetic nanomaterials for removing pharmaceuticals from water resources through adsorption and advanced oxidation processes. Here, the synthesis and characterization of magnetic nanomaterials and analytical detection techniques were evaluated. The review findings indicate that magnetic nanomaterials effectively removed pharmaceuticals from water through adsorption and advanced oxidation processes. More importantly, the removal processes remained effective for many cycles. However, only 22% of the studies demonstrated the application of magnetic nanomaterials on real water samples, as 78% stopped at experiments using distilled water in the laboratory. Further research on multi-component systems and real water samples is necessary to fully evaluate the potential of magnetic nanomaterials for pharmaceutical removal from water resources.

Keywords: Contaminants of emerging concern, Pharmaceuticals, Magnetic Iron based nanomaterials, Adsorption, Advanced oxidation process

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1. Introduction

Globally, pharmaceuticals have been frequently detected in water resources such as surface water, groundwater and industrial wastewater in the last decade. In Africa, different classes of pharmaceuticals, such as antibiotics, analgesics, anticonvulsant, anti-inflammatory, and antiviral drugs etc., were detected in surface water, groundwater and industrial wastewater from Uganda (Dalahmeh et al., 2020; Nantaba et al., 2020), Kenya (K'oreje et al., 2016; K'oreje et al., 2012,), Nigeria (Folarin et al., 2019; Jennifer et al., 2020) and South Africa (Gumbi et al., 2016; Hlengwa & Mahlambi, 2020; Madikizela et al., 2017; Sibeko et al., 2019). More details on occurrences, distributions and risk assessments of pharmaceuticals in water resources across five African regions are well documented by (Shehu et al., 2022). Coincidentally, similar trends of pharmaceuticals detected in African water resources were also found in Greece (Kosma et al., 2014; Papageorgiou et al., 2016), Czech republic (Buriánková et al., 2021; Golovko et al., 2014), Poland (Kapelewska et al., 2018; Migowska et al., 2012; Styszko et al., 2021), Canada (Guerra et al., 2014), India (Diwan et al., 2009; Mohapatra et al., 2016), Iran (Mirzaei et al., 2018), Pakistan (Ashfaq et al., 2016), Qatar (Al-maadheed et al., 2019), Singapore (Tran et al., 2016), Spain (Gros et al., 2013), Croatia (Senta and Ahel 2012), Belgium (Lorenzo et al., 2018), Italy (Verlicchi et al., 2012, 2014), Germany (Rossmann et al., 2018), Malaysia (Omar et al., 2019), USA (Karthikeyan & Meyer, 2006), Vietnam (Nguyen et al., 2015), China (Hanna et al., 2018), Japan (Murata et al., 2011), Iraq (Al-Khazrajy & Boxall, 2016) and Sweden (Baresel et al., (2015). Enough evidence to declare pharmaceutical pollution as a global issue affecting water resources is documented by (Omuferen et al., 2022).

Due to the regular occurrence of pharmaceuticals in global water resources, its risks, such as the development of antibiotic resistance and toxicity to aquatic life, it is imperative to develop appropriate technologies that can specifically removal pharmaceuticals from water (Shehu et al., 2022; Wang & Wang, 2016, 2019, 2022). The conventional water and wastewater treatment methods are advanced oxidation, reverse osmosis, ultrafiltration, electrochemical methods, coagulation-flocculation, precipitation, ion exchange, and adsorption(Ajala et al. 2018). However, these technologies are not effective in the removal of pharmaceuticals from water and wastewater, and a number of these compounds are frequently detected in water bodies despite the presence of water treatment facilities (Wang et al., 2019; Wang & Chu, 2016; Wang & Zhuan, 2020). One promising approach in water or wastewater treatment is the use of nanotechnology for contaminant removal.

Nanotechnology involves the design, synthesis, characterization, and applications of structures, devices and systems at the nanometer scale (Porwal & Sharma, 2016; Qu et al., 2013). Nanomaterials have attracted attention due to unique properties such as the high surface area to volume ratio, surface reactivity, and ability to be functionalized for a specific target. Thus, nanomaterials are used as nanoadsorbents or nanocatalysts for the removal of a wide range of pollutants, including pharmaceuticals, from water and wastewater (Bhattacharya et al., 2013; Chakraborty et al., 2022; Kar et al., 2021, 2022; Kaushik et al., 2021; Lamayi et al., 2018; B. Sharma et al., 2021; Shehu & Lamayi, 2019; N. Singh et al., 2022). In recent times, numerous reported applications of nanoparticles for the removal of various pharmaceuticals in water through adsorption processes (Choina et al., 2014; Dada et al., 2021; Rosli et al., 2021; Xing et al., 2020) and advanced oxidation processes (Hojamberdiev et al. 2020; Zeng et al. 2018; Zhu et al. 2019). However, the significant setbacks of nanotechnology are the separation of the nanomaterials after treatment, instability and possible toxicity that could arise due to the nanoparticles' choice (Bhattacharya et al., 2013). These problems can be solved by using magnetic nanomaterials, the development of nanocomposites and choosing less or non-toxic nanomaterials.

Magnetic Iron based nanomaterials include; nano zerovalent Iron (Li et al., 2017; Rosická & Šembera, 2011; Vecchia et al., 2009), magnetite (Fe_3O_4) (Saeed et al., 2020), maghemite (Fe_2O_3) (Aragaw and Aragaw 2021) and magnetic metal ferrites (Bao et al., 2013). Magnetic iron nanoparticles are widely used in environmental remediation because it is less or non-toxic and sustainable. Sustainability is due to magnetism that provides easy recovery and reuse. Moreover, magnetic iron nanoparticles possess fast kinetics and high adsorptive and catalytic properties. Noteworthy, the magnetic saturation requirement of 1.0 emu/g is needed for any magnetic materials expecting magnetic separation after water treatment (Li et al., 2019).

Therefore, this study aimed to review recent contributions of nanotechnology with the aid of Magnetic iron nanoparticles toward treating water-containing pharmaceuticals. Furthermore, various synthesis methods and characterization techniques that are commonly used for Magnetic iron nanoparticles were reviewed. More importantly, this review is limited to applications of Magnetic iron nanoparticles in the advanced oxidation process (AOP) and adsorption process of conventional water treatment.

2. Method

The articles were gathered from search engines and database such as Scopus, web of science, google, pumped, Medline and google scholar from 2009 to 2021, **Fig.1**. The keywords that were used includes pharmaceutical emerging pollutant/contaminants, magnetic nanoparticle/nanomaterials, adsorption, advanced oxidation processes, and water/wastewater. From the literature search, 1000 publications were found. However, 928 articles were excluded based on; 1) Articles that exclusively investigate the application of magnetic nanomaterials in the removal of emerging pollutants other than pharmaceutical pollutants, 2) Articles that exclusively investigate the application of magnetic nanomaterials in the removal of heavy metals, dyes, microorganism and nutrients other than pharmaceutical emerging pollutants. Hence, only 72 articles (**Fig.1**) were studied in this review based on the application of magnetic nanomaterials in the removal of pharmaceuticals from water through adsorption and advanced oxidation processes.

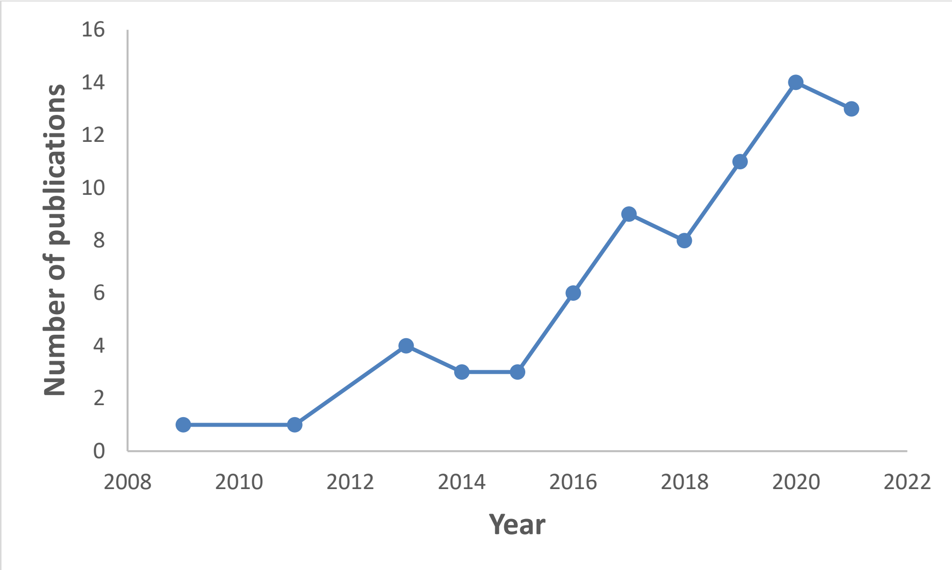

Fig. 1. Yearly distribution of publications.

3. Synthesis of Magnetic Iron-Based Nanomaterials

An essential component of nanoscience and nanotechnology is synthesizing materials like magnetic nanoparticles (Balakrishnan et al., 2021; Bao et al., 2014; Lima et al., 2014; Liyanage et al., 2020; Niu et al., 2011; Vicente-Martínez et al., 2020). Only when nanostructured materials are made available with appropriate size, shape, morphology, crystal structure, and chemical composition are new physical attributes and uses of nanoparticles possible (Balakrishnan et al., 2021; Bao et al., 2014; Lima et al., 2014; Liyanage et al., 2020; Niu et al., 2011; Vicente-Martínez et al., 2020). The qualities of a material determine how well it performs. The atomic structure, composition, microstructure, flaws, and interfaces are all influenced by the thermodynamics and kinetics of the synthesis, and these factors, in turn, depend on the characteristics. Many publications have reported various syntheses methods including co-precipitation (47%), hydrothermal (14%), sol-gel (13%), impregnation (9%), microwave-assisted (6%), green (3%), precipitation (3%), thermal decomposition (1%), sonochemical (1%), solvothermal (1%), chemical deposition (1%) and combustion (1%), **Fig. 2**. Magnetic iron-based nanomaterials synthesized through these methods have shown promising results in various water and wastewater treatment applications due to their unique properties such as high surface area, magnetic properties, and stability in harsh environments. Among the methods, co-precipitation, hydrothermal and sol-gel are known to be simple and promote surface modification of the nanomaterials. Hence, the methods were widely used in synthesizing nanomaterials for water and wastewater applications. However, co-precipitation is mostly used in nanomaterials syntheses because it can occur at ambient temperature.

However, a brief description of each synthesis is given below. Co-precipitation is a widely used method for synthesizing magnetic iron-based nanomaterials (Foroughi et al., 2019; Huang et al., 2020; Liyanage et al., 2020; Malakootian et al., 2018; Malakootian & Shiri, 2021; Wang, et al., 2020; Yegane Badi et al., 2018). This method involves the simultaneous precipitation of iron salts and a base to form iron oxide nanoparticles. The process can be performed at room temperature or higher temperatures, and the particle size can be controlled by adjusting the reaction conditions (Attia et al., 2013; Cusioli et al., 2020; D'Cruz et al., 2020; Ghosh et al., 2013; Kakavandi et al., 2014; Mashile et al., 2020; Mohammadi et al., 2021; Olusegun & Mohallem, 2020; Rocha et al., 2021; Zhang et al., 2017). Impregnation involves the deposition of iron oxide nanoparticles onto a support material by impregnating the support material with a solution containing iron salts. The process is typically performed at room temperature, and the particle size can be controlled by adjusting the reaction conditions(Liu et al., 2019; Mahmoud et al., 2021; Nodeh et al., 2018; Vicente-Martínez et al., 2020). Sol-gel synthesis involves the formation of a colloidal suspension of iron oxide nanoparticles by hydrolysis and condensation of metal alkoxides. The process is typically performed at low temperatures, and the particle size can be controlled by adjusting the reaction conditions (Amraei et al., 2016; Duan et al., 2019; Hayasi & Saadatjoo, 2017; Kollarahithlu & Balakrishnan, 2019; Kumar, Khan, et al., 2018; Mostafaloo et al., 2020; Parashar et al., 2019; Peralta et al., 2021; S. F. Soares et al., 2019). Hydrothermal synthesis involves the use of high-pressure and high-temperature conditions to promote the growth of iron oxide nanoparticles. The process is typically performed in a sealed vessel, and the particle size can be controlled by adjusting the reaction time, temperature, and pressure (Bao et al., 2013; Lu et al., 2016; Malakootian et al., 2019; Mao et al., 2016; Soares et al., 2019). Microwave-assisted synthesis involves the use of microwave radiation to promote the growth of iron oxide nanoparticles. The process is typically performed at room temperature, and the particle size can be controlled by adjusting the reaction time and power (Nasiri, Tamaddon, Hossein, et al., 2019; Nasiri, et al., 2019; Tamaddon et al., 2020). Green synthesis involves the use of natural plant extracts or other environmentally friendly materials to synthesize iron oxide nanoparticles. The process is typically performed at low temperatures, and the particle size can be controlled by adjusting the reaction conditions (Stan et al., 2017; Ye et al., 2021).

Precipitation involves the precipitation of iron salts from a solution to form iron oxide nanoparticles. The process is typically performed at room temperature, and the particle size can be controlled by adjusting the reaction conditions (Dehghan et al., 2018; Oliveira et al., 2017). Thermal decomposition involves the decomposition of iron-containing precursors at high temperatures to form iron oxide nanoparticles. The process is typically performed at high temperatures, and the particle size can be controlled by adjusting the reaction conditions (Li, Ng, et al., 2017). Sonochemical synthesis involves the use of ultrasound waves to promote the growth of iron oxide nanoparticles. The process is typically performed at room temperature, and the particle size can be controlled by adjusting the reaction time and power (Bao et al., 2014). Solvothermal synthesis involves the use of a solvent at high temperatures and pressures to promote the growth of iron oxide nanoparticles. The process is typically performed in a sealed vessel, and the particle size can be controlled by adjusting the reaction time, temperature, pressure, and solvent type (Silva et al., 2021). Chemical deposition involves the deposition of iron oxide nanoparticles onto a substrate using a chemical reaction. This method typically involves the use of a reducing agent to reduce the iron ions to form iron oxide nanoparticles on the substrate surface. Chemical deposition is a relatively simple and low-cost method for synthesizing magnetic iron-based nanomaterials. However, the particle size and distribution can be difficult to control using this method (Sayadi & Ahmadpour, 2021). Combustion synthesis involves the use of a fuel and an oxidizer to rapidly heat and combust a mixture of metal salts to form metal oxide nanoparticles. This method is typically performed at high temperatures and produces highly crystalline nanoparticles with a narrow size distribution (Al-Anazi et al., 2020b). Combustion synthesis is a relatively simple and low-cost method for synthesizing magnetic iron-based nanomaterials. However, the high-temperature conditions can lead to the formation of impurities and defects in the nanoparticles.

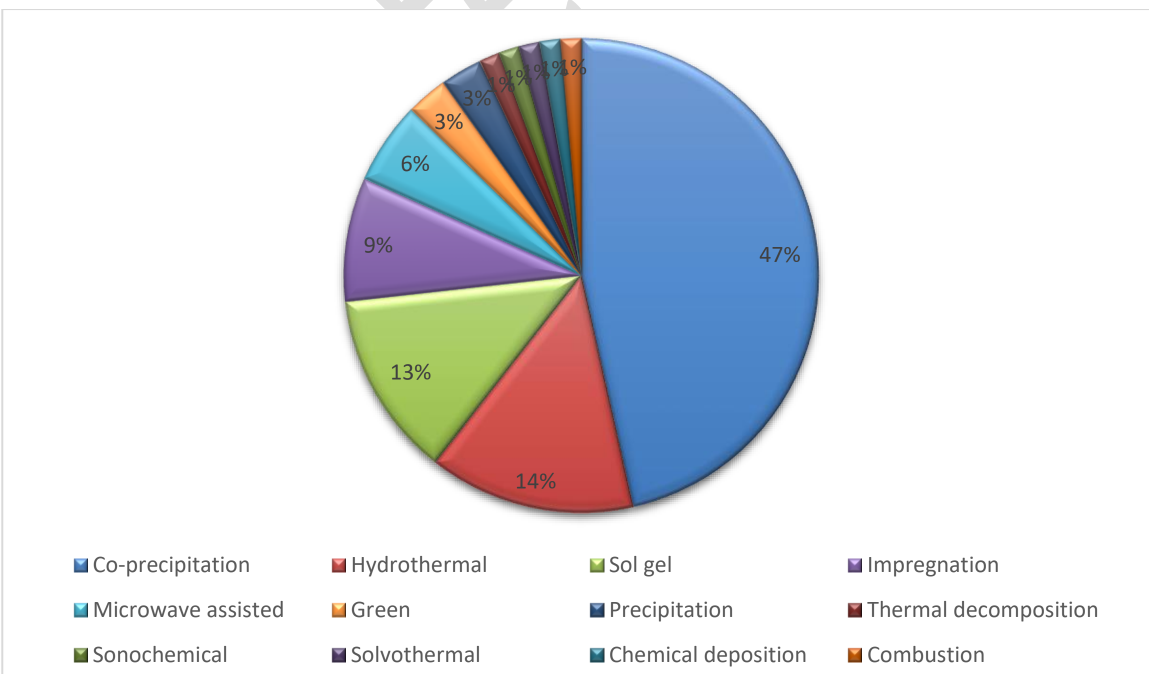

Fig. 2. Synthesis of magnetic nanomaterials by different methods

4. Characterization of Magnetic Iron-Based Nanomaterials

Characterization provides comprehensive information on nanomaterials' particle size, shape, composition and magnetic properties. Transmission electron microscopy (TEM), scanning electron microscopy (SEM), Fourier transform infrared spectroscopy (FTIR), Brunauer-Emmett-Teller (BET) surface area analyzer, Vibrating sample magnetometer, and powder X-ray diffraction (XRD) techniques are a few of the methods frequently used in the literature for magnetic nanoparticle characterization. FTIR spectra reveal the chemical linkages between the magnetic core and the organic surface layer (Bao et al. 2014; Malakootian et al. 2019; Nasiri et al. 2019; Soares et al. 2019; Tamaddon et al. 2020; Wang et al. 2020). Scanning electron microscope/Energy dispersive X-ray spectroscopy (SEM/EDX) can be used to analyze magnetic particles' surface covering and determine their constituent elements (Balakrishnan et al. 2021; Liyanage et al. 2020; Malakootian et al. 2018; Noroozi et al. 2020; Solís et al. 2021; Yegane et al. 2018). Powder XRD is used to characterize the bulk magnetic nanoparticles and identify their crystal structure (Chen et al. 2018; Malakootian and Shiri 2021; Parashar et al. 2019; Sayadi and Ahmadpour 2021). TEM provides candid pictures that can be used to determine the size and shape of nanoparticles (Akkari et al. 2018; Jonidi et al. 2017; Kumar et al. 2018; Mahmoud et al. 2021; Vicente-Martínez et al. 2020). A vibrating sample magnetometer is used to measure the magnetic properties of magnetic materials (Kumar et al. 2018; Lai et al. 2019; Mao et al. 2016; Nodeh et al. 2018). Dynamic light scattering (DLS) is used to investigate the surface charge of magnetic nanomaterials in solution (Balakrishnan et al., 2021; Lima et al., 2014; Malakootian & Shiri, 2021; Olusegun et al., 2021; Parashar et al., 2019; Sayadi & Ahmadpour, 2021). Thermogravimetric analysis (TGA) is used to measure the thermal properties of magnetic nanomaterials (Nawaz et al., 2019; Vicente-Martínez et al., 2020; Zhang et al., 2017). Brunauer-Emmett-Teller (BET) surface area analysis is the multi-point measurement of an analyte's specific surface area (m^2/g) using gas adsorption analysis, in which a solid sample is either suspended in a predetermined gaseous volume or continually flowing over by an inert gas such as nitrogen (Kakavandi et al. 2016; Kollarahithlu and Balakrishnan 2019; Li et al. 2017). Energy band gap of magnetic nanomaterials are characterized by DRS/UV/VIS spectrophotometer (Kumar et al. 2018; Malakootian et al. 2019; Nasiri et al. 2019; Nawaz et al. 2019; Sayadi and Ahmadpour 2021). In this review, the percentage of characterization techniques reported in different studies are presented in **Fig. 3**. However, since each characterization technique present a unique and independent property, the reason for high and low percentage utilization could be due to availability of the instrument to the researcher's disposal. Noteworthy, TGA and DRS/UV/VIS spectrophotometer characterization techniques were observed in unique ways. TGA techniques were widely in characterizing activated carbon and organic molecules modified magnetic nanomaterials. Whereas, DRS/UV/VIS spectrophotometer was used in determining energy band gap for magnetic nanomaterials used in advanced oxidation processes (AOPs).

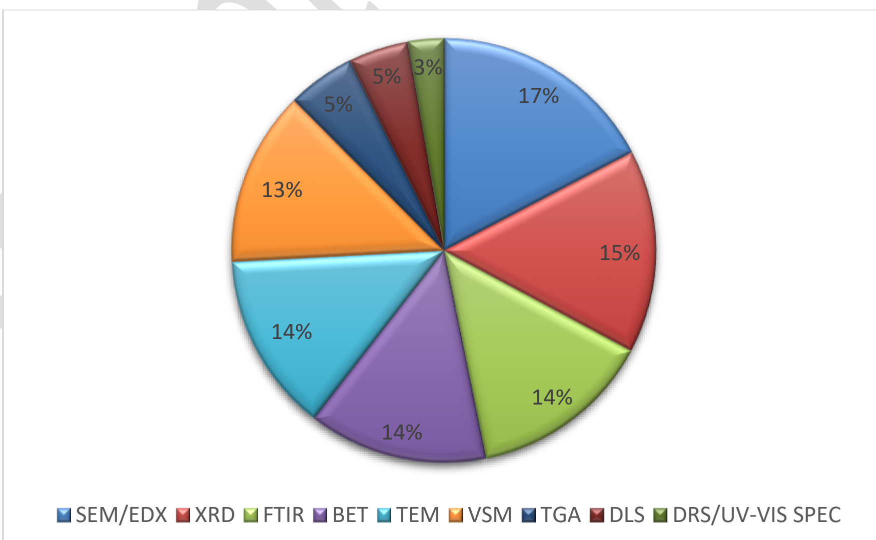

Fig. 3. Characterization techniques

5. Analytical Detection Techniques

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Analytical techniques such as gas and liquid chromatography coupled with UV or mass detectors are used for the identification and quantification of residual concentrations of pharmaceutical emerging pollutants. Also, UV/Visible spectrophotometer is used for the quantification of pharmaceuticals. For adsorption studies, 23, 15 and 1 publications reported quantification of pharmaceutical emerging pollutants using UV/Visible spectrophotometer, HPLC/UV/MS and GC//MS respectively, **Fig. 4**. Similarly, for advanced oxidation processes (AOPs), 7, and 26 publications reported quantification of pharmaceutical emerging pollutants using UV/Visible spectrophotometer, and HPLC/UV/MS respectively, **Fig. 5**. In adsorption studies, UV/Visible spectrophotometer was the most frequent used technique because the target is only quantifications while in AOPs, HPLC/UV/MS was frequently used because the goals were quantifications and identifications of degradation products.

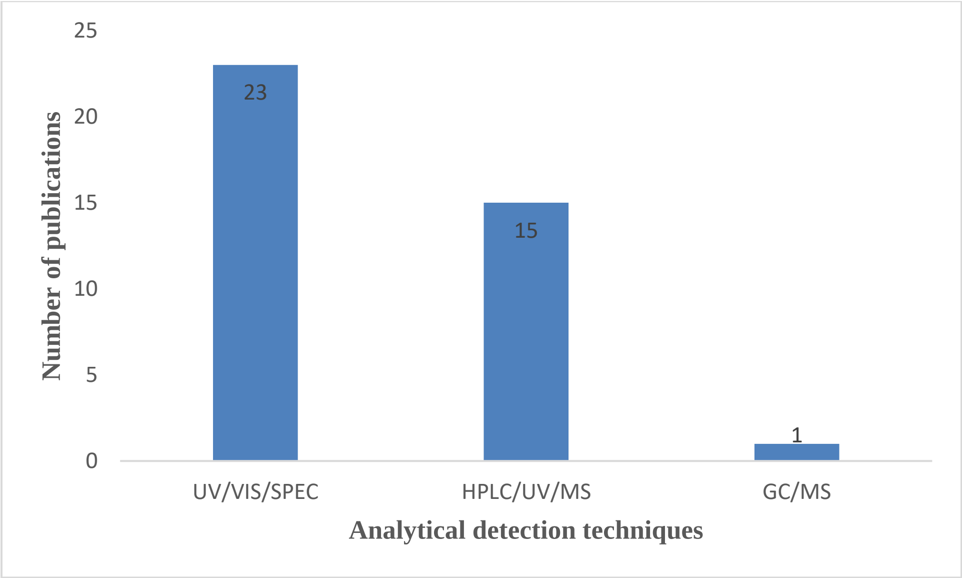

Fig. 4. Analytical detection techniques for adsorption studies

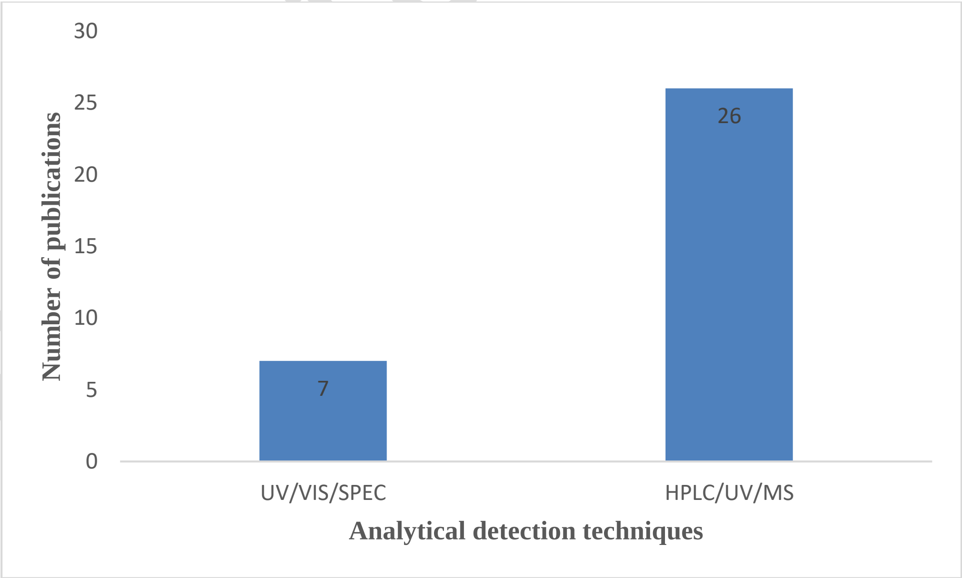

Fig. 5. Analytical detection techniques for advanced oxidation processes

6. Stability and Colloidal Stability of Iron-Based Magnetic Nanomaterials for Water and Wastewater Treatment

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Iron-based magnetic nanomaterials have shown great water and wastewater treatment potential due to their unique magnetic properties and high reactivity(Aragaw et al., 2021). However, these materials' stability and colloidal stability are critical factors that need to be considered for their efficient application. In terms of stability, iron-based magnetic nanomaterials are generally stable in aqueous solutions. However, iron-based magnetic nanomaterials are exposed to various environmental conditions in water and wastewater treatment, such as pH, temperature, and ionic strength, which can affect their stability (Mylon et al., 2004). For example, at low pH values, iron-based magnetic nanomaterials can undergo dissolution, which can lead to a decrease in their effectiveness for water treatment. Colloidal stability is another important factor influencing iron-based magnetic nanomaterials' performance in water and wastewater treatment (Marinin, 2012). The colloidal stability of these materials refers to their ability to remain suspended in solution without aggregation or settling (Wu et al., 2008). Colloidal stability can be affected by factors such as surface charge, particle size, and the presence of other ions (Mylon et al., 2004). The colloidal stability of these materials can be improved by modifying their surface properties through functionalization with organic or inorganic compounds (Akawa et al., 2020, 2021). Surface modification can enhance the electrostatic and steric repulsion between particles, preventing them from agglomerating and improving their colloidal stability (Mao et al., 2016).

The stability of these materials can be evaluated by measuring their aggregation behavior under different conditions. For example, dynamic light scattering (DLS) and zeta potential measurements can be used to determine these materials' size distribution and surface charge (Balakrishnan et al., 2021; Lima et al., 2014; Malakootian & Shiri, 2021; Olusegun et al., 2021; Parashar et al., 2019; Sayadi & Ahmadpour, 2021).

7. Pharmaceuticals Removal from Water Resources

In recent time, the demand for pharmaceuticals for humans and animals have increased due to the rapid increase of the global population. Conversely, this leads to an increase in pharmaceutical production. The endpoint of pharmaceutical residue from pharmaceutical industrial wastewater and solid waste is water resources. These have tremendous negative effects on aquatic and terrestrial lives. To regenerate water resources, there is a need to look for the best and most sustainable technology that can remove pharmaceuticals from various sources such as freshwater, groundwater, seawater, and wastewater, etc. Therefore, magnetic nanomaterials stand as the best materials due to their effectiveness in adsorption and degradation of pharmaceuticals, easy separation from treated water and reuse for several cycles with losing their capacity. The schematic representation of magnetic nanomaterials in the removal of pharmaceuticals from water through adsorption process and advanced oxidation processes is given in **Fig. 6**. More details of the adsorption process and advanced oxidation processes for the removal of pharmaceuticals are given in sections 7.1 and 7.2, respectively.

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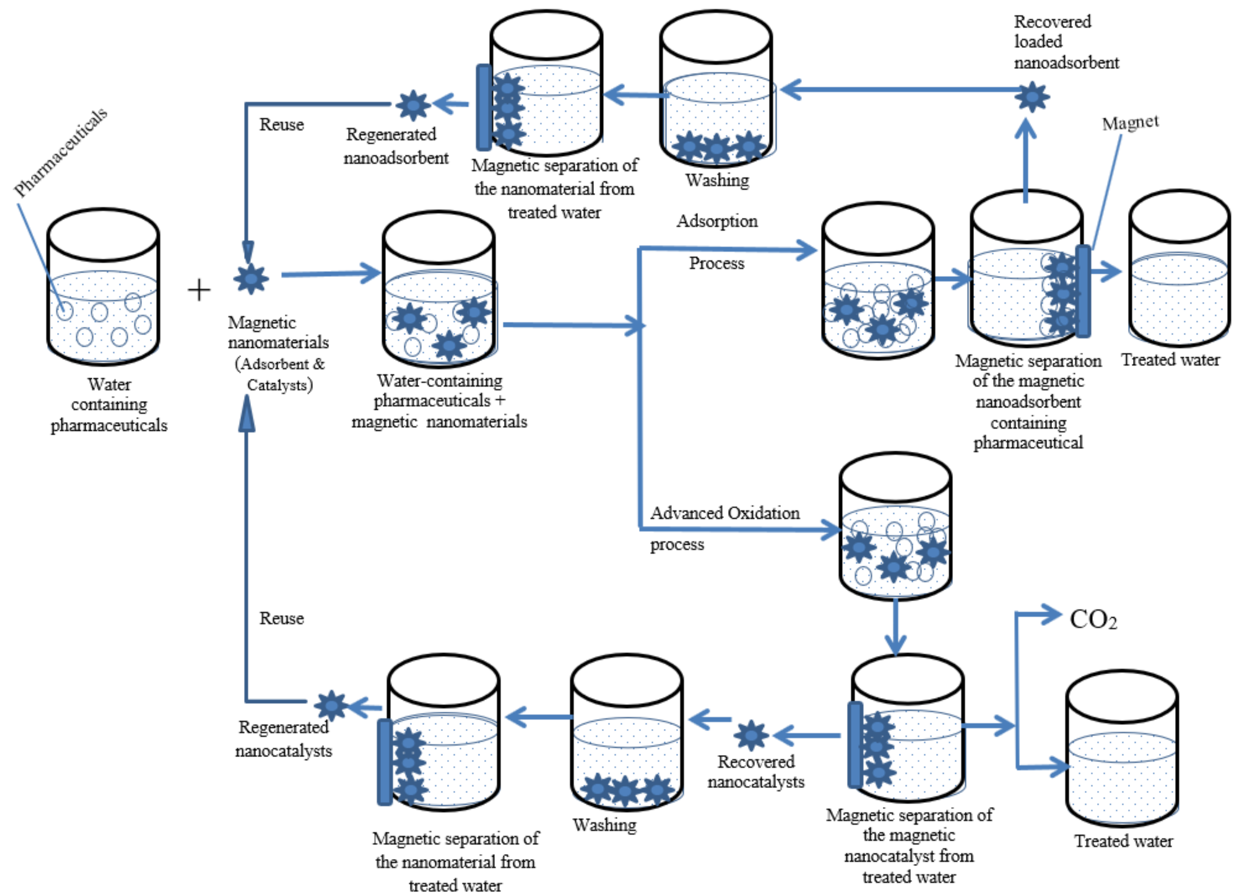

Fig. 6. Schematic representation of removal of pharmaceuticals from water resources through adsorption and advanced oxidation processes by magnetic iron-based nanomaterials

7.1 Removal of Pharmaceutical By Adsorption Process

Adsorption is a widely used technique for removing pharmaceuticals from water resources. Magnetic iron-based nanomaterials have a high surface area and strong magnetic properties, making them excellent adsorbents for removing pharmaceuticals from water resources, Table 1. The adsorption process involves the attraction of pharmaceutical molecules to the surface of magnetic iron-based nanomaterials. The pharmaceuticals then bind to the surface of the magnetic iron-based nanomaterials, which can be easily removed from the water using a magnetic field. The mechanism of removal of pharmaceuticals by adsorption process using magnetic iron-based nanomaterials is based on the principle of the Van der Waals forces, pore filling/size-selective adsorption, electrostatic interactions, hydrogen bonding, π-π interaction/stacking hydrophobic interaction (Zhuang, Chen, et al., 2020; Zhuang, Cheng, et al., 2019; Zhuang, Liu, et al., 2019, 2020; Zhuang, Zhu, et al., 2020). Several factors, such as pH, concentration, temperature, and contact time, influence pharmaceuticals' adsorption on magnetic iron-based nanomaterials, as in **Table 1**.

Various studies have shown that magnetic iron-based nanomaterials such as Fe_3O_4, Fe_2O_3, cysteine-modified silane-coated magnetic nanomaterial, Magnetic genipin-crosslinked chitosan/graphene oxide-SO_3H, Fe_3O_4-beta-cyclodextrin, and Fe_3O_4/GO etc., can effectively remove various pharmaceuticals such as ibuprofen, paracetamol, and tetracycline etc. from water resources, Table 1. Modifying the magnetic iron-based nanomaterials' surface with different functional groups such as carboxyl, amine, and hydroxyl can improve adsorption, as observed from several studies in **Table 1**.

Table 1. Adsorption of Pharmaceuticals by magnetic nanomaterials

S/N	Magnetiic Nanomaterials	Synthesis methods	Pharmaceuticals	Optimum Conditions	% Removal	Adsorption capacities (mg/g)	Detection technique	Reusability Cycle	Ref.
1	AC/Fe_3O_4	Co-precipitation	Ceftriaxone	pH ; 3.14, contact time ;90 minutes, Iniatial concentration ; 10 mg/L, Adsorbent dosage ;1.99 g, Temperature ;298 K	97.18	28.93	HPLC/UV-Visible Detector	6	(Yegane et al. 2018)
2	$CoFe_2O_4$/AC@Ch	Co-precipitation	Ciprofloxacin	pH ; 5, contact time ; 15 minutes, Iniatial concentration ; 10 mg/L, Adsorbent dosage ; 0.1 g, Temperature ; 298K	93.5	188.68	UV/Vis spectrophotometer	3	(Malakootian et al., 2018)
3	Fe_3O_4/Biochar	Co-precipitation	Ibuprofen	pH ; 8, contact time ; 5 minutes, Iniatial concentration ; 700 mg/L, Adsorbent dosage ; 2.5 g, Temperature ; 298K	99.2	39.9	UV/Vis spectrophotometer	5	(Liyanage et al., 2020)
4	Magnetic graphene-anchored zeolite imidazolate (Fe_3O_4/ZIF-8-G)	Co-precipitation	Tetracycline	pH ; 6, contact time ; 10 hours, Initial concentration ; 200 mg/L, Adsorbent dosage ; 0.2 g, Temperature ; 308 K	96.5	382.58 Freundlich	HPLC-MS	5	(Wang et al. 2020)
5	Fe_3O_4@C	Sonochemical	Sulfamethoxazole	pH ; 6.7, contact time ; 24 hours, Initial concentration ; 100 mg/L, Adsorbent dosage ; 1.0 g, Temperature ; 298K	89	1200	HPLC-MS	9	(Bao et al., 2014)
6	Fe_3O_4@SiO_2/SiTMC	Sol gel	Sulfamethoxazole	pH ; 5, contact time ; 24 hours, Initial concentration ; 40 mg/L, Adsorbent dosage ; 0.05 g, Temperature ; 298K	NR	598	UV/Vis spectrophotometer	4	(Soares et al. 2019)
7	Maghemite(γ-Fe_2O_3)	Precipitation/Oxidation	Diclofenac	pH ; 7, contact time ; 24 hours, Iniatial concentration ; 500 mg/L, Adsorbent dosage ; 0.1 g, Temperature ; 298 K	NR	252	UV/Vis spectrophotometer	5	(Oliveira et al., 2017)
8	Magnetic poly (styrene-2-acrylamido-2-methyl propanesulfonic acid) (St-AMPS)	Sol gel	Diclofenac, DCF Ceftriaxone, CFX	pH ; 4, contact time ; 60 minutes, Iniatial concentration ; 50 mg/L, Adsorbent dosage ; 0.1 g, Temperature ; 298K	DCF;91.3 CFX; 94.5	DCF;150.602 CFX;119.904	UV/Vis spectrophotometer	4	(Hayasi & Saadatjoo, 2017)
9	Fe_3O_4@Cuttlebone magnetic nanocomposite	Co-precipitation	Tetracycline	pH ; 5, contact time ; 90 minutes, Iniatial concentration ; 8 mg/L, Adsorbent dosage ; 0.2 g, Temperature ; 298 K	80.15	14.94	HPLC/UV-Visible Detector	NR	(Malakootian & Shiri, 2021)
10	$NiFe_2O_4$	Sol gel	Oxycarbazepine	pH ; 2.5, contact time 5 hour), Iniatial concentration ; 0.144	88.66	0.1034	UV/Vis spectrophotometer	6	(Parashar et al., 2019)

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				mg/L, Adsorbent dosage ; 0.6 g, Temperature ; 303K					
11	MFe_2O_4 (M = FeII, MnII, CoII, ZnII)	hydrothermal	Tetracycline Oxytetracycline Chlortetracycline	pH ; 6.9, contact time; 5 minutes Initial concentration ; 100 ug/L, adsorbent ; 1.0 g	98.7	NA	UPLC-MS/MS	9	(Bao et al., 2013)
12	Fe_3O_4@C	Hyrothermal	Tetracycline	pH ; 5, contact time ; 140 minutes, Initial concentration ; 30 mg/L, adsorbent ; 0.5 g, Temperature ; 298 K	73.3	7.61	UV/Vis spectrophotometer	NR	(Soares et al. 2019)
13	ZIF-8@SiO_2@Fe_3O_4	Sol gel	ceftazidime	pH ; 6.3, contact time ; 30 minutes, initial concentration ; 1 mg/L, Temperature; 294.6 K	90	96.84	HPLC-Visible Detector	5	(Duan and Sun 2019)
14	Fe_3O_4-g-CN@PEI-β-CD	Co-precipitation	Tetracycline	pH ; 9.2, contact time ; 20 minutes, Initial concentration ; 265 mg/L, adsorbent ; 0.008 g, Temperature ; 317.1 K	98	833.33	HPLC-Visible Detector	NR	(Foroughi et al., 2019)
15	-NH_2-functionalized Fe_3O_4@SiO_2 nanoparticles (MNPNH2)	Co-precipitation	Diclofenac	pH ; 5, contact time ; 6 hours, Initial concentration ; 50 mg/L, adsorbent ; 0.1 g, Temperature ; 298 K	97	565	UV/Vis spectrophotometer	5	(Huang et al., 2020)
16	Fe_3O_4/C	Hydrothermal	ciprofloxacin	pH ; 7, contact time ; 3 hours, I initial concentration ; 10 mg/L, adsorbent ; 0.1 g, Temperature ; 303 K	98.2	90.1	UV/Vis spectrophotometer	5	(Mao et al., 2016)
17	Magnetic nanoparticle-decorated graphene oxide (GO-MNPs-SiO_2)	Impregnation	Naproxen	pH ; 5, contact time ; 60 minutes, Initial concentration ; 50 mg/L, adsorbent ; 0.1 g	83 - 94	31.25	UV/Vis spectrophotometer	18	(Nodeh et al., 2018)
18	Fe_3O_4/AC	Co-precipitation	Amoxicillin, Carbamazepine, Diclofenac	Adsorbent ; 0.34 g, Initial concentration ; 5 mg/L, Temperature ; 333 K	70 77 84	NR	HPLC/UV-Visible Detector	NR	(Rocha et al., 2021)
19	$CoFe_2O_4$@methycellulose (MC)	Microwave assisted method	Tetracycline	pH ; 6, contact time ; 75 minutes, Iniatial concentration ; 16 mg/L, adsorbent ; 0.18 g, Temperature ; 323 K	79.45	12.9	HPLC/UV-Visible Detector	5	(Nasiri et al., 2021)
20	Kaolinite supported $CoFe_2O_4$ (KCF)	Co-precipitation	Doxycycline	contact time ; 12 hours, Initial concentration ; 100 mg/L, adsorbent ; 0.15 g, Temperature ; 333 K	68	400	UV/Vis spectrophotometer	3	(Olusegun & Mohallem, 2020)

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21	Magnetic mesoporous carbon/β-cyclodextrin–chitosan (MMPC/CycChit)	Co-precipitation	Danofloxacin Enrofloxacin Levofloxacin	pH ; 7, contact time ; 30 minutes, Initial concentration ; 10 mg/L, adsorbent ; 0.36 g, Temperature ; 298 K	98.7 99.1 96.8	130 195 165	HPLC-PDA	8	(Mashile et al. 2020)
22	Fe_3O_4	Green	Sulfamethoxazole Trimethoprim Tetracycline Erythromycin Ampicillin Piperacillin tazobactam	pH ; 5.5, contact time ;120 minutes, Initial concentration ; 0.05 mg/mL, adsorbent ; 0.1 g, Temperature ; 303 K	90	0.9905 – 25.641	HPLC-DAD-MS	NR	(Stan et al., 2017)
23	Ni0.5Zn0.5Fe_2O_4 magnetic nanoparticles	Co-precipitation	Diclofenac	pH ; 3.2, contact time ; 60 minutes, Initial concentration ; 20 mg/L, adsorbent ; 1.2 g, Temperature ; 298 K	57.15	52.91	UV/Vis spectrophotometer	5	(Mohammadi et al. 2021)
24	Magnetic genipin-crosslinked chitosan/graphene oxide-SO_3H	Impregnation	Ibuprofen (IP) Tetracycline (TC)	pH ; 4, contact time ; 120 minutes, IB; 10 mg/L, TC; 200 mg/L, pH 4, adsorbent ; 0.5 g, Temperature ; 313 K	NR	IB; 113.27 to 138.16 mg/g TC; 473.25 to 556.28 mg/g Freundlich	UV/Vis spectrophotometer	5	(Liu et al., 2019)
25	Moringa oleifera Lam. seed husks functionalized with iron nanoparticles MOM-Fe_3O_4	Co-precipitation	Metformin	pH ; 7, contact time ; 1440 minutes, Initial concentration ; 10 mg/L, adsorbent ; 1.0 g, Temperature ; 298 K	93.9	65.01 mg/g	UV/Vis spectrophotometer	NR	(Cusioli et al., 2020)
26	Magnetic silica-based nanoadsorbent	Sol-gel	Ibuprofen (IBU) Diclofenac (DCF)	pH ; 5.5, contact time ; 24 hours, Initial concentration ; 10 mg/L, adsorbent ; 0.2 g, Temperature ; 298 K	IBU; 68.7 DCF; 83	35	HPLC-UVD	8	(Peralta et al., 2021)
27	Magnetic activated carbon-(AC-Fe_3O_4)	Co-precipitation	Promazine	pH ; 8.5, contact time ; 6 minutes, Initial concentration ; 40 mg/L, adsorbent ; 0.01 g	99.97	101.01	UV/Vis spectrophotometer	5	(D'Cruz et al., 2020)
28	Fe_3O_4- beta-cyclodextrin	Co-precipitation	Naproxen (NAP), Carbamazepine (CBZ)	pH ; 7, contact time ; 120 minutes, Initial concentration ; 20 mg/L, adsorbent ; 0.1 g, Temperature 298 K	NAP; 80.2 CBZ; 75	NAP; 0.45, CBZ; 0.51	UV/Vis spectrophotometer	3	(Ghosh et al., 2013)
29	Powder activated carbon (PAC) combined with Fe_3O_4 magnetite nanoparticles (MNPs) (MNPs-PAC),	Co-precipitation	Amoxicillin	Temperature 20 ºC, pH 5, 1 g adsorbent, concentration 50 mg/L and 90 minutes, pH ; 5, contact time ; 90 minutes, Initial concentration ; 50 mg/L, adsorbent ; 1 g, Temperature ; 293 K	95.3	142.85	UV/Vis spectrophotometer	NR	(Kakavandi et al., 2014)

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30	Cysteine-modified silane-coated magnetic nanomaterial	Sol gel	Ibuprofen	pH ; 6, Initial concentration ; 50 mg/L, adsorbent ; 30 mg,	82.9	138.1	UV/Vis spectrophotometer	3	(Kollarahithlu & Balakrishnan, 2019)
31	Fe_3O_4/GO	Co-precipitation	Chlorpheniramine	pH ; 10, contact time ; 24 hours, Initial concentration ; 200 mg/L, adsorbent ; 1.0 g,	NR	470	GC-MS	NR	(Li et al. 2016)
32 mech	Magnetic graphene oxide	Co-precipitation	Tetracycline	pH ; 4, Initial concentration ; 50 mg/L, adsorbent ; 0.19 g, Temperature ; 298 K	78	174	UV/Vis spectrophotometer	5	(Li et al. 2017)
33	$MgFe_2O_4$/gama-Fe_2O_3	Hydrothermal	Minocycline	pH ; 7, contact time ; 24 hours, Initial concentration ; 100 mg/L, adsorbent ; 0.025 g	NR	118.8	UV/Vis spectrophotometer	4	(Lu et al., 2016)
34	Fe_3O_4–MoO_3 and Fe_3O_4–MoO_3-AC	Impregnation	Ciprofloxacin	pH ; 7, contact time ; 60 minutes, Initial concentration ; 20 mg/L, adsorbent ; 0.05 g	Tap water; 95 Waste water; 91 Seawater; 91.5	47. 294	UV/Vis spectrophotometer	5	(Mahmoud et al., 2021)
35	Magnetic core-modified silver nanoparticles	Ipregnation	Ibuprofen	pH ; 7, contact time ; 45 minutes, adsorbent ; 0.07 g, Temperature ; 298 K	93	NR	HPLC-UVD	4	(Vicente-Martínez et al., 2020)
36	Magnetic nanoparticles coated zeolite Gama-Fe_2O_3-Zeolite	Co-precipitation	Diclofenac-Na (DCF), Naproxen (Nap), Gemfibrozil (Gem) and Ibuprofen (IB)	pH ; 2, contact time ; 10 minutes, , adsorbent ; 1.0 g	IB;98.75 Nap; 99.7 DCF; 99.58 and Gem;99.13	NR	HPLC-MS	NR	(Attia et al. 2013)
37	Lignin-based magnetic nanoparticle adsorbent (LMNA)	Green	Diclofenac	pH ; 5, contact time ; 720 minutes, Iniatial concentration ; 10 mg/L, adsorbent ; 0.05 g, Temperature ; 320 K	80	106.4	UV/Vis spectrophotometer	5	(Ye et al., 2021)
38	Eggshell membrane (ESM)-derived $MgFe_2O_4$	Thermal decomposition	Doxycycline	pH ; 5, adsorbent ; 0.05 g, Temperature ; 298 K	96	308.51	UV/Vis spectrophotometer	4	(Li et al. 2017)
39	Fe_3O_4@graphene (Fe_3O_4@G)	Co-precipitation	Oxytetracycline (OTC) and tetracycline (TC)	pH ; 7, Initial concentration ; 1 mg/L, adsorbent ; 0.06 g	Greater than 89	OTC; 336 TC; 423	HPLC-UVD	10	(Zhang et al., 2017)

NR; Not reported

7.2 Removal of Pharmaceutical by Advanced Oxidation Process

Advanced Oxidation Processes (AOP) are technologies that generate reactive oxygen species such as hydroxyl radicals (OH·) or sulfate radicals for oxidation of traceable organic contaminants or some inorganic pollutants or to increase wastewater biodegradability as a pre-treatment condition before biological treatment (Deng & Zhao, 2015; Wang & Xu, 2012). There are two advanced Oxidation Processes which are dark and light-driven. The dark advanced oxidation process includes; Ozone (O_3), Fenton (Fe^{2+} + H_2O_2), Electrolysis (electrodes + current), and Sonolysis (Ultrasounds). The light-driven advanced oxidation process includes; Photolysis (UV + H_2O_2), Photocatalysis (light + catalyst) and Photo-Fenton (solar light + Fenton). Mechanisms of AOPs (Kommineni et al., 2008) are 1) the Formation of oxidants (e.g. hydroxyl radicals), 2) the reaction of these oxidants with organic compounds in the water-producing biodegradable intermediates, and 3) the reaction of biodegradable intermediates with oxidants referred to as mineralization (i.e. production of water, carbon dioxide and inorganic salts).

In this process, magnetic iron-based nanomaterials are added to the water, and then a reactive species is generated, such as hydrogen peroxide or ozone (Liu et al., 2021; Liu & Wang, 2023; Tang & Wang, 2018; Wang & Tang, 2021). These reactive species then react with the pharmaceuticals, breaking them down into simpler, non-toxic compounds. The magnetic iron-based nanomaterials play a critical role in this process, as they help to generate and distribute the reactive species throughout the water. Several AOPs such as photocatalysis, photo-fenton, Fenton-like system, peroxymonosulfate (PMS), Sono-Fenton system, Persulfate (PS) system, UV/chlorine system, and Peroxydisulfate (PDS) system using different magnetic iron-based nanomaterials were investigated for degradation of pharmaceuticals, as shown in Table 2. The use of magnetic iron-based nanomaterials in AOPs has shown high removal efficiency and can be improved by modifying the magnetic iron-based nanomaterials' surface with different functional groups, **Table 2.**

Table 2. Advanced oxidation processes for degradation of pharmaceuticals by magnetic nanomaterials

S/N	Magnetic Nanomaterials (Catalysts)	Synthesis methods	Type of Advanced Oxidation Processes	Pharmaceuticals	Optimum Conditions	% Removal	Detection Technique	Reusability Cycle	Ref.
1	$CuFe_2O_4$@methyl cellulose (MC)	Microwave-assisted method	Photocatalysis $CuFe_2O_4$@MC/UV	Ciprofloxacin	pH; 7, Concentration; 3 mg/L, Time; 90 minutes	Synthetic; 80.26 Real sample;8 072.87	HPLC-UV detector	4	(Tamaddon et al., 2020)
2	nano$CoFe_2O_4$@methyl cellulose (MC)	Microwave-assisted method	Photocatalysis nano$CoFe_2O_4$@MC/UV	Metronidazole	pH ; 11, Concentration; 5 mg/L, Time ; 120 minutes, Catalyst; 0.2 g	85.3	HPLC-UV detector	4	(Nasiri et al. 2019)
3	$ZnFe_2O_4$@carboxymethylcellulose (CMC)	Hydrothermal	Photocatalysis $ZnFe_2O_4$@CMC/UV	Ciprofloxacin	pH ; 7, Concentration ; 5 mg/L, Time ; 100 minutes, Catalyst ; 0.1 g	75 Synthetic and real water	HPLC-UV detector	5	(Malakootian et al., 2019)
4	Fe_3O_4–graphene oxide	Co-precipitation	Fenton system Fe_3O_4–GO/H_2O_2 Peroxymonosulfate (PMS) system Fe3O4–GO/PMS	Ssulfamethoxazole, Norfloxacin, Tetracycline and Flumequine	pH 11, Concentration; 5 mg/L, Time 120 minutes, Catalyst 0.2 g,	83.3	HPLC-DAD detector	4	(Solís et al., 2021)

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			peroxydisulfate (PDS) system Fe_3O_4–GO/PDS						
5	$CuFe_2O_4$/GO	Co-precipitation	Peroxymonosulfate (PMS) $CuFe_2O_4$/GO/PMS	Metronidazole	pH ; 5, Concentration ; 30 mg/L, Time ; 120 minutes, Catalyst ; 0.2 g, PMS; 2 mM	100	HPLC-UV detector	5	(Noroozi et al., 2020)
6	$CoFe_2O_4$	Co-precipitation	Peroxymonosulfate (PMS) system $CoFe_2O_4$/PMS	Ampicillin	pH ; 7, Time ; 25 minutes, catalyst ; 0.1 g, PMS ; 0.2 mM	90	HPLC-MS	5	(Balakrishnan et al., 2021)
7	Maghemite nanoparticles	Co-precipitation	Photocatalysis Maghemite nanoparticles - UV/vis light	Tetracycline	Concentration; 83 ug/L, Time ; 60 minutes, 10 mg catalyst; 10 tetracycline.	40	UV–vis spectrophotometer	NR	(Olusegun et al., 2021)
8	Ag-$CuFe_2O_4$@WO_3	Chemical deposition	Photocatalysis Ag-$CuFe_2O_4$@WO_3/UV	Gemfibrozil (GEM), Tamoxifen (TAM)	pH ; 5, Concentration ; 5 mg/L, Time ; 150 minutes, Catalyst; 0.2 g	GEM (81%) TAM (83%)	UV–vis spectrophotometer	5	(Sayadi & Ahmadpour, 2021)
9	$CoFe_2O_4$-GO	Hydrothermal	Peroxymonosulfate (PMS) $CoFe_2O_4$-GO/PMS	Norfloxacin	pH ; 7, Concentration ; 15 µM, Catalyst ; 0.3 g, Temperature ; 298 K	64.1	HPLC-UVD	4	(Chen et al., 2018)
10	$CuFe_2O_4$@MC	Microwave-assisted method	Photocatalysis CuFe2O4@MC-UV	Ciprofloxacin	pH; 7, Concentration ; 3 mgL, Tme 90 minutes, Catalyst ; 0.2 g	80.74% (synthetic sample) and 72.87% (real sample)	UV spectrophotometer, HPLC-UVD(real wastewater sample)	4	(Nasiri et al. 2019)
11	Fe_3O_4 MNP	Co-precipitation	Photo-Fenton system Fe_3O_4/ H_2O_2/Uv-vis	Ciprofloxacin	pH ; 2.8, Concentration ; 2.0 mg /L, Time; 1.8 minutes, H_2O_2 ; 2.50 mM, 500 W m^{-2}	85	UV–vis spectrophotometer	NR	(Lima et al., 2014)
12	$BiFeO_3$	Sol gel	Photocatalysis $BiFeO_3$/visible light	Ciprofloxacin	pH; 6, Concentration ; 1 mg/L, Time ; 46 minutes, Catalyst ; 2.5 g, Temperature ; 303 K	100	UV/VIS Spectrophotometer	NR	(Mostafaloo et al., 2020)
13	Fe_3O_4@C	Co-precipitation	Photo-Fenton system Fe_3O_4@C/H_2O_2/UV	Tetracycline	Concentration ; 20 mg/L, Time ; 50 minutes, Catalyst ; 0.15 g, H_2O_2 ; 3 mM	99	HPLCUVD	5	(Kakavandi et al., 2016)
14	Humic acid coated Fe_3O_4 magnetic nanoparticles (Fe_3O_4/HA)	Co-precipitation	Fenton system Fe_3O_4/HA/H_2O_2	Sulfathiazole	Fe_3O_4 (3 g) and 10 mg/L of free HA or Fe_3O_4 (3 g) presoaked with 10 mg/L of HA, Time ; 120 minutes	95	HPLC-PDA	3	(Niu et al., 2011)
15	Fe_3O_4/Mn_3O_4	Impregnation method	Fenton system Fe_3O_4/Mn_3O_4/H_2O_2	Sulfamethazine	pH ; 3, Concentration ; 20 mg/L, Catalyst ; 0.5 g, Temperautre ; 308 K, H_2O_2 ; 6 mM	94	HPLC-DAD	5	(Wan & Wang, 2017)
16	$ZnFe_2O_4$	Hydrothermal	Photo-Fenton system $ZnFe_2O_4$/H_2O_2/vis light	Tetracycline	pH ; 4, Concentration ; 40 mg/L, Time ; 40 minutes, Temperature ; 313 K, H_2O_2 ; 40 nmM	94.2	HPLC-MS	5	(Xiang et al., 2020)

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17	Fe_3O_4 @α-MnO_2	Hydrothermal	Persulfate (PS) system Fe_3O_4 @α-MnO_2/PS	Ciprofloxacin	Concentration ; 50 mg/L, Time ; 90 minutes, Catalyst ; 1.0 g, Temperature ; 298 K, $Na_2S_2O_8$; 2.0 g	90	HP LC-UVD	5	(Zhao et al. 2014)
18	Magnetic nanocomposite ($ZnO@Fe_3O_4$)	Precipitation	Sonocatalytic system $ZnO@Fe_3O_4$/US	Amoxicillin	pH ; 3, Concentration ; 10 mg/L, Time ; 120 minutes, catalyst ; 0.8 g , US power (60 W)	90	HPLC-UVD	5	(Dehghan et al. 2018)
19	Fe_3O_4	Co-precipitation	Sono-Fenton system US/Fe_3O_4/H_2O_2	Tetracycline	pH ; 3, Time ; 60 minutes, US power (80 W), 150 mmol/L H_2O_2, Catalyst ; 1.0 g	93.7	HPLC-UVD	3	(Hou et al., 2015)
20	Fe_3O_4	Co-precipitation	Sono-Fenton system US/Fe_3O_4/H_2O_2	Levofloxacin	pH ; 6, Concentration ; 20 mg/L; Time ; 150 minutes, Catalyst ; 1.0 g, H_2O_2 ; 5.0 mmol/L; Ultrasound power, 195 W	99	HPLC-MS/MS	NR	(Wei et al., 2015)
21	Magnetic titanium carbide (Ti_3C_2Tx) MXene	Co-precipitation	UV/chlorine system Magnetic (Ti3C2Tx)/UV/chlorine	Diclofenac	pH ; 7, Concentration ; 30 mg/L, Time ; 90 minutes, Catalyst ; 3 g, Chlorine concentration ; 30 mg/L	100	HPLC-MS	4	(Jang et al., 2020)
22	AC@Fe_3O_4	Co-precipitation	Persulfate (PS) system AC@Fe_3O_4/PS	Tetracycline	40 mM PS, 10 mg/L TC, 0.4 g/L catalyst and pH 3.0) for a period 180 min	99.8	HPLC-UVD	5	(Jonidi et al. 2017)
23	BiOCl/g-C_3N_4/Cu_2O/Fe_3O_4	Co-precipitation	Photocatalysis BiOCl/g-C_3N_4/Cu_2O/Fe_3O_4/sunlight	Sulfamethoxazole	pH ; 6.5, Concentration ; 100 µM , Time (Xe lap) ; 60 minutes, Time (natural sunlight) ; 120 minutes, catalyst ;0.2 g, Temperature ; 303 K	99.5 (visible light), 92.1(natural sunlight)	HPLC-MS	5	(Kumar et al. 2018)
24	ZnO/Fe_3O_4-Sepiolite	Co-precipitation	Photocatalysis ZnO/Fe_3O_4-Sepiolite/sola light	Ibuprofen	Concentration ; 10 mg/L, Time ; 8 0.25 g catalyst ; 0.25 g, Temperature 311 K, 18 hrs	89	HPLC-UVD	3	(Akkari et al., 2018)
25	Zn1.0Fe_2.0O_4	Combustion	Fenton-like redox system $Zn_{1.0}Fe_{2.0}O_4$	Diclofenac	pH ; 5, Concentration ; 10 µM, Time ; 60 minutes, catalyst ; 0.17 g, Temperature ; 333 K	90	HPLC-PDA	NR	(Al-Anazi et al., 2020a)
26	g-C_3N_4/TiO_2/Fe_3O_4@SiO_2	Sol-gel	Photocatalysis g-C_3N_4/TiO_2/Fe_3O_4@SiO_2/visible light	Ibuprofen	pH ; 7, Time ; 15 minutes, 330 W m^{-2},	97	HPLC-UVD	3	(Kumar, Khan, et al., 2018)
27	$MnFe_2O_4$/bio-char composite	coprecipitation	Photo-Fenton system $MnFe_2O_4$/bio-char/H_2O_2/visible light	Tetracycline	pH ; 5.5, Concentration ; 40 mg/L, Time ; 2 hours, H_2O_2; 100 mmol/ L	95	UV-Vis spectrophotometer	4	(Lai et al., 2019)
28	Multi-walled carbon nanotubes (MWCNTs) -$NiFe_2O_4$ (NiFe-CNT)	Hydrothermal	Photo-Fenton system (MWCNTs) -$NiFe_2O_4$ (NiFe-CNT)/H_2O_2/visible light	Sulfamethoxazole	pH ; 3, Concentration ; 5 mg/L, Time ; 2 hours, catalyst ; 0.025 g, H_2O_2 ; 1 µL/mL	100	HPLC-UVD	5	(Nawaz et al., 2019)
29	rGO-Ag0/Fe_3O_4	Impregnation	Peroxydisulfate (PDS) system PDS/rGO-Ag0/Fe_3O_4	Acetaminophen, Ibuprofen,	pH ; 4, Time ; 160 minutes, Catalyst ; 0.1 g, PDS ; (10 µM, 1 mM)	99	HPLC-DAD	NR	(Park et al., 2018)
30	Biochar-TiO_2 magnetic nanocomposites	Solvothermal	Photocatalysis Biochar-TiO_2 magnetic/UV	Sulfadiazine (SDZ) Oxolinic acid	Time ; 1 hour, catalyst ; 0.1 g, SDZ (5 mg/L) and OXA (10 mg/L	SDZ; 87 OXA; 98	HPLC-UV	NR	(Silva et al., 2021)
31	ZIF-8/MnFe2O4	Hydrothermal	Photo- Fenton system ZIF-8/$MnFe_2O_4$/H_2O_2/visible light	Tetracycline	pH 3, Time ; 90 minutes, catalyst ; 0.3 g, concentration ; 10 mg/L, H_2O_2 50 mM	92	UV–vis spectrophotometer	5	(Wang et al. 2020)
32	TiO_2/Fe_3O_4	Hydrothermal method	Photo-Fenton system TiO_2/Fe_3O_4/H_2O_2/UV	Tetracycline	pH; 7, Concentration 50 mg/L,Time ; 60 minutes, Catalyst ; 0.3 g, Temperature 298 K,	98	UV–vis spectrophotometer	5	(Yu et al., 2019)
33	$CuFe_2O_4$	Sol gel	Fenton system $CuFe_2O_4$/H_2O_2	Amoxicillin	pH ; 4, 50 mg/L, Time ; 30 minutes, Catalyst ; 90 mg, Temperature ; 293 K,	99.27	HPLC-Visible Detector	5	(Amraei et al., 2016)

NR; Not reported

8. Recycling and Reuse Experiments

Recyclability and reusability of magnetic nanomaterials are essential factors for practical application in water and wastewater treatment. To achieve recyclability and reusability, desorption experiments must be carried out using an appropriate desorbing agent at the end of each adsorption cycle. It is worth noting that some desorbing agents include ethano/water (Chen et al. 2018; D'Cruz et al. 2020; Hayasi and Saadatjoo 2017; Kakavandi et al. 2014; Kumar et al. 2018; Malakootian et al. 2019; Nasiri et al. 2019; Noroozi et al. 2020; Soares et al. 2019; Tamaddon et al. 2020), distilled water (Dehghan et al. 2018; Hou et al. 2015; Jonidi et al. 2017; Kakavandi et al. 2016; Kumar et al. 2018; Niu et al. 2011; Xiang et al. 2020; Yegane et al. 2018), dilute HCl solution (Jang et al., 2020; Vicente-Martínez et al., 2020; Zhang et al., 2017), methanol/water (Bao et al., 2014; Liyanage et al., 2020; Parashar et al., 2019), dilute NaOH (Lu et al., 2016), dilute NaOH/methanol (Mahmoud et al., 2021; Nodeh et al., 2018), thermal degradation (Mashile et al., 2020; Solís et al., 2021), ultrasonication (Ghosh et al., 2013), and water/acetone (Li et al., 2016; Stan et al., 2017). Furthermore, another significant factor for practical application catalysts and adsorbents is separation. Thus, magnetic nanomaterials are easily separated from the solution with the aid of an external magnetic field. All the publications reported the separation of the magnetic nanomaterials from the treated water or wastewater using an external magnetic field.

The percentage distribution of reuse and non-reuse of magnetic nanomaterials for the removal of pharmaceuticals from water was evaluated. About 78% of articles reported the reuse of magnetic nanomaterials for the removal of pharmaceuticals from water through adsorption and advanced oxidation processes. Most of the reusability studies were carried out between three and four cycles without the materials losing their efficiency. However, despite the fact that the magnetic nanomaterials were easily separated, 22% of the literature did not carry out reusability. This could be probably due to the researchers' interest since the materials were recovered.

9. Real Water Samples Application

The composition of water resources samples such as lake, river, sea, groundwater, and wastewater, etc. differ largely from distilled water used in laboratory experiments. Hence, newly developed magnetic materials' capability must be demonstrated with environmental water samples to understand the feasibility of the materials before the pilot scale. From the articles reviewed, 78% of publications did not carry out real water sample analysis and these represent a large portion of the research. Thus, more research is needed for real water samples. The other portion that reported real water analysis is 22%. Though the portion is very small, results demonstrated that the magnetic nanoparticles were effective in removal of pharmaceuticals from river water (Attia et al. 2013; Lai et al. 2019; Stan et al. 2017; Wang et al. 2020), lake water (Huang et al. 2020; Wang et al. 2020; Zhang et al. 2017), seawater (Attia et al., 2013; Vicente-Martínez et al., 2020), industrial wastewater (Attia et al. 2013; Kumar et al. 2018; Malakootian and Shiri 2021; Mashile et al. 2020; Nasiri et al. 2019; Olusegun and Mohallem 2020; Rocha et al. 2021; Stan et al. 2017; Vicente-Martínez et al. 2020; Wang et al. 2020; Ye et al. 2021), medical wastewater (Wang et al. 2020), urban wastewater (Solís et al., 2021), pool water (Zhang et al., 2017) and tap water (Lai et al. 2019; Stan et al. 2017; Vicente-Martínez et al. 2020; Wang et al. 2020; Zhang et al. 2017). These indicate that magnetic nanomaterials have good prospects for water and wastewater treatment.

10. Drawbacks of Magnetic Iron-Based Nanomaterials

Magnetic iron-based nanomaterials have shown promise for the removal of pharmaceuticals from water (Abdel Maksoud et al., 2020). However, it is important to consider several drawbacks associated with these materials. One limitation is that they may not be effective for the removal of all types of pharmaceuticals, especially those that are highly soluble and do not adsorb well onto the surface of the nanomaterials (Wu et al., 2008). This can limit their overall effectiveness in water treatment applications. Another drawback is the cost associated with the production and functionalization of magnetic iron-based nanomaterials (Leonel et al., 2021; Singh et al., 2020). These processes can be expensive and may require specialized equipment and expertise, making the widespread implementation of these materials in water treatment systems economically challenging. Furthermore, there are concerns about the potential environmental impacts of using magnetic iron-based nanomaterials for water treatment (Guo et al., 2013; Leonel et al., 2021). While these materials are generally considered safe, their long-term effects on the environment are not well understood. Thorough studies are needed to assess any potential risks associated with their use. Additionally, the stability of magnetic iron-based nanomaterials in water is a concern (Aragaw et al., 2021; Sharma et al., 2015; Singh et al., 2021). Over time, these materials can undergo degradation or aggregation, which can limit their effectiveness for water treatment. It is crucial to ensure that these materials maintain their stability and performance over extended periods to ensure their efficacy in water treatment applications.

11. Summary, Conclusion and Future Prospects

In this work, synthesis, characterization and application of magnetic nanomaterials in the removal of pharmaceuticals from water through adsorption and advanced oxidation processes were investigated. Several synthesis methods reported in the articles studied are Co-precipitation, sol-gel, hydrothermal, solvothermal, sonochemical, microwave-assisted, impregnation, thermal decomposition, combustion, chemical deposition, and green. However, co-precipitation was the most frequent synthesis method reported due to the following: 1) It is simple, 2) It can be carried out at an ambient temperature and 3) Scalable productions. The characterization techniques frequently reported in the evaluation of magnetic nanomaterials include SEM/EDX, XRD, FTIR, DRS/UV/VIS, TEM, DLS, TGA, BET and VSM. Only three analytical techniques were used in the detection of the pharmaceuticals from the literature evaluated. These analytical techniques are gas chromatography, UV/Visible spectrophotometry, and high-performance liquid chromatography (HPLC) coupled with either UV or mass spectrophotometry (MS) as HPLC/UV/MS. Noteworthy, UV/Visible spectrophotometry was mostly used in pharmaceuticals' residual analysis after adsorption because the interest is just quantification, but in advanced oxidation processes, since degradation products are of interest, HPLC/UV/MS was frequently used. Furthermore, in studies where real water analysis was conducted, HPLC/UV/MS was used regardless of whether the removal process was based on adsorption or advanced oxidation processes. This indicates the sensitivity and effectiveness of HPLC/UV/MS over UV/Visible spectrophotometry.

Overall, the application of magnetic nanomaterials in the removal of pharmaceuticals from water through the adsorption process and advanced oxidation processes was found to be promising. The magnetic nanoparticles were separated from the solution by external magnetic field, regenerated using various desorbing agents and reused for several cycles while maintaining its efficiency. Quite a portion of about 78 % of publications reported the reuse of the magnetic nanoparticles. Some of the desorbing agents reported in the works of literature are ethanol/water, methanol/water, acetonitrile/water, 0.1 M NaOH, 0.1 M HCl and acetone/water. Although only 22% of research was demonstrated with real water samples, the results were almost the same as the ones carried out using the synthetic solution. Although magnetic nanoparticles are excellent adsorbents and catalysts for removing pharmaceuticals from water, according to the results of this review, the following factors must be taken into account to enable large-scale water and wastewater treatments;

- Researchers need to make sure that more magnetic materials are developed, non-toxic materials are used for coatings and functionalization, and ecotoxicity testing is done from the manufacturing stage of nanomaterials to water treatment.
- Since batch methods are frequently employed, there is a need for continuous (column) treatment.
- For effective water treatment, real water sample treatment and a particular magnetic separator technology are required.
- Researchers should employ HPLC/MS as an analytical technique to quantify the residual levels of medications because of their sensitivity.
- Costs related to research initiatives should be estimated. A partnership between academics and NGOs, the government, businesses, or funding organizations would encourage the rapid actualization of magnetic nanoparticles for treating pharmaceutical-containing water.

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Competing Interests

No conflict of interest.

References

Abdel Maksoud, M. I. A., Elgarahy, A. M., Farrell, C., Al-Muhtaseb, A. H., Rooney, D. W., & Osman, A. I. (2020). Insight on water remediation application using magnetic nanomaterials and biosorbents. Coordination Chemistry Reviews, 403, 213096. https://doi.org/10.1016/j.ccr.2019.213096

Ajala, O. J., Nwosu, F. O., & Ahmed, R. K. (2018). Adsorption of atrazine from aqueous solution using unmodified and modified bentonite clays. Applied Water Science, 8(7), 1–11. https://doi.org/10.1007/s13201-018-0855-y

Akawa, M. N., Dimpe, K. M., & Nomngongo, P. N. (2020). Amine-functionalized magnetic activated carbon as an adsorbent for preconcentration and determination of acidic drugs in environmental water samples using HPLC-DAD. Open Chemistry, 18(1), 1218–1229. https://doi.org/10.1515/chem-2020-0162

Akawa, M. N., Dimpe, K. M., & Nomngongo, P. N. (2021). Ultrasonic assisted magnetic solid phase extraction based on the use of magnetic waste-tyre derived activated carbon modified with methyltrioctylammonium chloride adsorbent for the preconcentration and analysis of non-steroidal anti-inflammatory drugs in . Arabian Journal of Chemistry, 14(9), 103329. https://doi.org/10.1016/j.arabjc.2021.103329

Akkari, M., Aranda, P., Belver, C., Bedia, J., Ben Haj Amara, A., & Ruiz-Hitzky, E. (2018). Reprint of ZnO/sepiolite heterostructured materials for solar photocatalytic degradation of pharmaceuticals in wastewater. Applied Clay Science, 160, 3–8. https://doi.org/10.1016/j.clay.2018.02.027

Al-Anazi, A., Abdelraheem, W. H., Scheckel, K., Nadagouda, M. N., O'Shea, K., & Dionysiou, D. D. (2020a). Novel franklinite-like synthetic zinc-ferrite redox nanomaterial: synthesis, and evaluation for degradation of diclofenac in water. Applied Catalysis B: Environmental, 275, 1–23. https://doi.org/10.1016/j.apcatb.2020.119098

Al-Anazi, A., Abdelraheem, W. H., Scheckel, K., Nadagouda, M. N., O'Shea, K., & Dionysiou, D. D. (2020b). Novel franklinite-like synthetic zinc-ferrite redox nanomaterial: synthesis, and evaluation for degradation of diclofenac in water. Applied Catalysis B: Environmental, 275. https://doi.org/10.1016/j.apcatb.2020.119098

Al-Khazrajy, O. S. A., & Boxall, A. B. A. (2016). Risk-based prioritization of pharmaceuticals in the natural environment in Iraq. Environmental Science and Pollution Research, 23(15), 15712–15726. https://doi.org/10.1007/s11356-016-6679-0

Al-maadheed, S., Goktepe, I., Binti, A., Lati, A., & Shomar, B. (2019). Journal of Water Process Engineering Antibiotics in hospital e ffl uent and domestic wastewater treatment plants in. Journal of Water Process Engineering, 28, 60–68. https://doi.org/10.1016/j.jwpe.2019.01.005

Amraei, B., Kalantary, R. R., Jafari, A. J., & Gholami, M. (2016). Efficiency of CuFe2O4 Bimetallic in Removing Amoxicillin from Aqueous Solutions. J Mazandaran Univ Med Sci, 27(147), 259–275.

Aragaw, T. A., Bogale, F. M., & Aragaw, B. A. (2021). Iron-based nanoparticles in wastewater treatment: A review on synthesis methods, applications, and removal mechanisms. Journal of Saudi Chemical Society, 25(8), 101280. https://doi.org/10.1016/j.jscs.2021.101280

Ashfaq, M., Nawaz, K., Rasool, S., Mustafa, G., Saif-ur-rehman, M., Faizan, M., Sun, Q., & Yu, C. (2016). Occurrence and ecological risk assessment of fluoroquinolone antibiotics in hospital waste of Lahore , Pakistan. Environmental Toxicology and Pharmacology, 42, 16–22. https://doi.org/10.1016/j.etap.2015.12.015

Attia, T. M. S., Hu, X. L., & Qiang, Y. Da. (2013). Synthesized magnetic nanoparticles coated zeolite for the adsorption of pharmaceutical compounds from aqueous solution using batch and column studies. Chemosphere, 93, 2076–2085. https://doi.org/10.1016/j.chemosphere.2013.07.046

Balakrishnan, R. M., Ilango, I., Gamana, G., Bui, X. T., & Pugazhendhi, A. (2021). Cobalt ferrite nanoparticles and peroxymonosulfate system for the removal of ampicillin from aqueous solution. Journal of Water Process Engineering, 40, 1–10. https://doi.org/10.1016/j.jwpe.2020.101823

Bao, X., Qiang, Z., Chang, J., Ben, W., & Qu, J. (2014). Synthesis of carbon-coated magnetic nanocomposite (Fe 3 O 4 @ C) and its application for sulfonamide antibiotics removal from water. Journal of Environmental Sciences, 26(5), 962–969. https://doi.org/10.1016/S1001-0742(13)60485-4

Bao, X., Qiang, Z., Ling, W., & Chang, J. H. (2013). Sonohydrothermal synthesis of MFe2O4 magnetic nanoparticles for adsorptive removal of tetracyclines from water. Separation and Purification Technology, 117, 104–110. https://doi.org/10.1016/j.seppur.2013.03.046

Baresel, C., Cousins, A. P., Ek, M., Ejhed, H., Allard, A.-S., Magnér, J., Westling, K., Fortkamp, U., Wahlberg, C., Hörsing, M., & Söhr, S. (2015). Pharmaceutical residues and other emerging substances in the effluent of sewage treatment plants Review on concentrations, quantification, behaviour, and removal options. In Number B (Issue April). www.ivl.se

Bhattacharya, S., Saha, I., Mukhopadhyay, A., Chattopadhyay, D., & Chand, U. (2013). Role of nanotechnology in water treatment and purification: Potential applications and implications. International Journal of Chemical

Science and Technology, 3(3), 59–64.
Buriánková, I., Kuchta, P., Molíková, A., Sovová, K., Výravský, D., Rulík, M., Novák, D., Lochman, J., & Vítˇezová, M. (2021). Antibiotic Resistance in Wastewater and Its Impact on a Receiving River: A Case Study of WWTP Brno-Modˇrice, Czech Republic. Water, 13, 1–18. https://doi.org/10.3390/w13162309
Chakraborty, A., Samriti, Ruzimuradov, O., Gupta, R. K., Cho, J., & Prakash, J. (2022). TiO2 nanoflower photocatalysts: Synthesis, modifications and applications in wastewater treatment for removal of emerging organic pollutants. Environmental Research, 212. https://doi.org/10.1016/j.envres.2022.113550
Chen, L., Ding, D., Liu, C., Cai, H., Qu, Y., Yang, S., Gao, Y., & Cai, T. (2018). Degradation of norfloxacin by CoFe2O4-GO composite coupled with peroxymonosulfate: A comparative study and mechanistic consideration. Chemical Engineering Journal, 334, 273–284. https://doi.org/10.1016/j.cej.2017.10.040
Choina, J., Bagabas, A., Fischer, C., Flechsig, G., Kosslick, H., Alshammari, A., & Schulz, A. (2014). The influence of the textural properties of ZnO nanoparticles onadsorption and photocatalytic remediation of water frompharmaceuticals. Catalysis Today, 1–8. https://doi.org/10.1016/j.cattod.2014.05.014
Cusioli, L. F., Quesada, H. B., de Brito Portela Castro, A. L., Gomes, R. G., & Bergamasco, R. (2020). Development of a new low-cost adsorbent functionalized with iron nanoparticles for removal of metformin from contaminated water. Chemosphere, 247, 125852. https://doi.org/10.1016/j.chemosphere.2020.125852
D'Cruz, B., Madkour, M., Amin, M. O., & Al-Hetlani, E. (2020). Efficient and recoverable magnetic AC-Fe3O4 nanocomposite for rapid removal of promazine from wastewater. Materials Chemistry and Physics, 240(August 2019), 122109. https://doi.org/10.1016/j.matchemphys.2019.122109
Dada, A. O., Inyinbor, A. A., Bello, O. S., & Tokula, B. E. (2021). Novel plantain peel activated carbon – supported zinc oxide nanocomposites (PPAC - ZnO - NC) for adsorption of chloroquine synthetic pharmaceutical used for COVID - 19 treatment. Biomass Conversion and Biorefinery, 1–13. https://doi.org/10.1007/s13399-021-01828-9
Dalahmeh, S., Björnberg, E., Elenström, A. K., Niwagaba, C. B., & Komakech, A. J. (2020). Pharmaceutical pollution of water resources in Nakivubo wetlands and Lake Victoria, Kampala, Uganda. Science of the Total Environment, 710, 1–8. https://doi.org/10.1016/j.scitotenv.2019.136347
Dehghan, S., Kakavandi, B., & Kalantary, R. R. (2018). Heterogeneous sonocatalytic degradation of amoxicillin using ZnO@Fe3O4 magnetic nanocomposite: Influential factors, reusability and mechanisms. Journal of Molecular Liquids, 264, 98–109. https://doi.org/10.1016/j.molliq.2018.05.020
Deng, Y., & Zhao, R. (2015). Advanced Oxidation Processes (AOPs) in Wastewater Treatment. Current Pollution Reports, 1(3), 167–176. https://doi.org/10.1007/s40726-015-0015-z
Diwan, V., Tamhankar, A. J., Aggarwal, M., Sen, S., Khandal, R. K., & Lundborg, C. S. (2009). Detection of antibiotics in hospital effluents in India Detection of antibiotics in hospital effluents in India. CURRENT SCIENCE, 97(12), 1752–1755.
Duan, H., Hu, X., & Sun, Z. (2019). Magnetic zeolite imidazole framework material-8 as an effective and recyclable adsorbent for removal of ceftazidime from aqueous solution. Journal of Hazardous Materials, 1–8. https://doi.org/10.1016/j.jhazmat.2019.121406
Folarin, O., Otitoloju, A., Amaeze, N., & Saliu, J. (2019). Occurrence of Acetaminophen , Amoxicillin , Diclofenac and Methylparaben in Lagos and Ologe Lagoons , Lagos , Nigeria. J. Appl. Sci. Environ. Manage., 23(12), 2143–2149. https://doi.org/https://dx.doi.org/10.4314/jasem.v23i12.10
Foroughi, M., Hossein, M., Azqhandi, A., & Kakhki, S. (2019). Bio-inspired, high, and fast adsorption of tetracycline from aqueous media using Fe3O4-g-CN@PEI--CD nanocomposite: Modeling by response surface methodology (RSM), boosted regression tree (BRT), and general regression neural network (GRNN). Journal of Hazardous Materials, 1–39. https://doi.org/10.1016/j.jhazmat.2019.121769
Ghosh, S., Badruddoza, A. Z. M., Hidajat, K., & Uddin, M. S. (2013). Adsorptive removal of emerging contaminants from water using superparamagnetic Fe3O4 nanoparticles bearing aminated β-cyclodextrin. Journal of Environmental Chemical Engineering, 1(3), 122–130. https://doi.org/10.1016/j.jece.2013.04.004
Golovko, O., Kumar, V., Fedorova, G., Randak, T., & Grabic, R. (2014). Seasonal changes in antibiotics , antidepressants / psychiatric drugs , antihistamines and lipid regulators in a wastewater treatment plant. CHEMOSPHERE, 111, 418–426. https://doi.org/10.1016/j.chemosphere.2014.03.132
Gros, M., Rodríguez-mozaz, S., & Barceló, D. (2013). Rapid analysis of multiclass antibiotic residues and some of their metabolites in hospital , urban wastewater and river water by ultra-high-performance liquid chromatography coupled to quadrupole-linear ion trap tandem mass spectrometry. Journal of Chromatography A, 1292, 173–188. https://doi.org/10.1016/j.chroma.2012.12.072
Guerra, P., Kim, M., Shah, A., Alaee, M., & Smyth, S. A. (2014). Occurrence and fate of antibiotic , analgesic / anti-in fl ammatory , and antifungal compounds in fi ve wastewater treatment processes. Science of the Total

Environment, The, 473–474, 235–243. https://doi.org/10.1016/j.scitotenv.2013.12.008
Gumbi, B. P., Moodley, B., Birungi, G., & Ndungu, P. G. (2016). Detection and quanti fi cation of acidic drug residues in South African surface water using gas chromatography-mass spectrometry. Chemosphere, 1–9. https://doi.org/10.1016/j.chemosphere.2016.10.105
Guo, H., Ma, F., Feng, X., Lou, X., & Tade, M. O. (2013). Application of iron oxide based nanomaterials (NMs) in magnetic assisted chemical separation (MACS) processes for water/wastewater treatment. Advanced Materials Research, 610–613, 1242–1251. https://doi.org/10.4028/www.scientific.net/AMR.610-613.1242
Hanna, N., Sun, P., Sun, Q., Li, X., Yang, X., Ji, X., Zou, H., Ottoson, J., Nilsson, L. E., Berglund, B., Dyar, O. J., Tamhankar, A. J., & Stålsby Lundborg, C. (2018). Presence of antibiotic residues in various environmental compartments of Shandong province in eastern China: Its potential for resistance development and ecological and human risk. Environment International, 114, 131–142. https://doi.org/10.1016/j.envint.2018.02.003
Hayasi, M., & Saadatjoo, N. (2017). Preparation of magnetic nanoparticles functionalized with novel adsorbents for removal of pharmaceuticals from aqueous solutions. Adv Polym Technol., 1–13. https://doi.org/10.1002/adv.21852
Hlengwa, N. B., & Mahlambi, P. N. (2020). SPE-LC-PDA method development and application for the analysis of selected pharmaceuticals in river and wastewater samples from South Africa. Water SA, 46(3), 514–522. https://doi.org/10.17159/wsa/2020.v46.i3.8662
Hojamberdiev, M., Czech, B., G€oktas, A. C., Yubuta, K., & Kadirova, Z. C. (2020). SnO 2 @ ZnS photocatalyst with enhanced photocatalytic activity for the degradation of selected pharmaceuticals and personal care products in model wastewater. Journal of Alloys and Compounds, 827, 1–13. https://doi.org/10.1016/j.jallcom.2020.154339
Hou, L., Wang, L., Royer, S., & Zhang, H. (2015). Ultrasound-assisted heterogeneous Fenton-like degradation of tetracycline over a magnetite catalyst. In Journal of Hazardous Materials (Vol. 302). Elsevier B.V. https://doi.org/10.1016/j.jhazmat.2015.09.033
Huang, L., Mao, N., Yan, Q., Zhang, D., & Shuai, Q. (2020). Magnetic Covalent Organic Frameworks for the Removal of Diclofenac Sodium from Water. ACS Applied Nano Materials, 3(1), 319–326. https://doi.org/10.1021/acsanm.9b01969
Jang, J., Shahzad, A., Woo, S. H., & Lee, D. S. (2020). Magnetic Ti3C2Tx (Mxene) for diclofenac degradation via the ultraviolet/chlorine advanced oxidation process. Environmental Research, 182, 1–10. https://doi.org/10.1016/j.envres.2019.108990
Jennifer, A., Oluseyi, T., Drage, D. S., Harrad, S., & Abdallah, M. A. (2020). Occurrence , seasonal variation and human exposure to pharmaceuticals and personal care products in surface water , groundwater and drinking water in Lagos State , Nigeria. Emerging Contaminants, 6, 124–132. https://doi.org/10.1016/j.emcon.2020.02.004
Jonidi Jafari, A., Kakavandi, B., Jaafarzadeh, N., Rezaei Kalantary, R., Ahmadi, M., & Akbar Babaei, A. (2017). Fenton-like catalytic oxidation of tetracycline by AC@Fe3O4 as a heterogeneous persulfate activator: Adsorption and degradation studies. Journal of Industrial and Engineering Chemistry, 45, 323–333. https://doi.org/10.1016/j.jiec.2016.09.044
K'oreje, K. O., Demeestere, K., De Wispelaere, P., Vergeynst, L., Dewulf, J., & Van Langenhove, H. (2012). From multi-residue screening to target analysis of pharmaceuticals in water: Development of a new approach based on magnetic sector mass spectrometry and application in the Nairobi River basin, Kenya. Science of the Total Environment, 437, 153–164. https://doi.org/10.1016/j.scitotenv.2012.07.052
K'oreje, K. O., Kandie, F. J., Vergeynst, L., Abira, M. A., Van Langenhove, H., Okoth, M., & Demeestere, K. (2018). Occurrence, fate and removal of pharmaceuticals, personal care products and pesticides in wastewater stabilization ponds and receiving rivers in the Nzoia Basin, Kenya. Science of the Total Environment, 637–638, 336–348. https://doi.org/10.1016/j.scitotenv.2018.04.331
K'oreje, K. O., Vergeynst, L., Ombaka, D., De Wispelaere, P., Okoth, M., Van Langenhove, H., & Demeestere, K. (2016). Occurrence patterns of pharmaceutical residues in wastewater, surface water and groundwater of Nairobi and Kisumu city, Kenya. Chemosphere, 149, 238–244. https://doi.org/10.1016/j.chemosphere.2016.01.095
Kakavandi, B., Esrafili, A., Mohseni-Bandpi, A., Jafari, A. J., & Kalantary, R. R. (2014). Magnetic Fe3O4@C nanoparticles as adsorbents for removal of amoxicillin from aqueous solution. Water Science and Technology, 69(1), 147–155. https://doi.org/10.2166/wst.2013.568
Kakavandi, B., Takdastan, A., Jaafarzadeh, N., Azizi, M., Mirzaei, A., & Azari, A. (2016). Application of Fe3O4@C catalyzing heterogeneous UV-Fenton system for tetracycline removal with a focus on optimization by a response surface method. Journal of Photochemistry and Photobiology A: Chemistry, 314, 178–188.

https://doi.org/10.1016/j.jphotochem.2015.08.008
Kapelewska, J., Kotowska, U., Karpi, J., Kowalczuk, D., Arciszewska, A., & Anna, Ś. (2018). Occurrence , removal , mass loading and environmental risk assessment of emerging organic contaminants in leachates , groundwaters and wastewaters. Microchemical Journal, 137, 292–301. https://doi.org/10.1016/j.microc.2017.11.008
Kar, P., Aggarwal, D., Shukla, K., & Gupta, R. K. (2022). Defect State Modulation of TiO 2 Nanostructures for Photocatalytic Abatement of Emerging Pharmaceutical Pollutant in Wastewater Effluent . Advanced Energy and Sustainability Research, 3(5), 2100162. https://doi.org/10.1002/aesr.202100162
Kar, P., Shukla, K., Jain, P., & Gupta, R. K. (2021). An activated carbon fiber supported Fe2O3@bismuth carbonate heterojunction for enhanced visible light degradation of emerging pharmaceutical pollutants. Reaction Chemistry and Engineering, 6(11). https://doi.org/10.1039/d1re00250c
Karthikeyan, K. G., & Meyer, M. T. (2006). Occurrence of antibiotics in wastewater treatment facilities in Wisconsin , USA. Science of the Total Environment, 361, 196–207. https://doi.org/10.1016/j.scitotenv.2005.06.030
Kaushik, J., Kumar, V., Garg, A. K., Dubey, P., Tripathi, K. M., & Sonkar, S. K. (2021). Bio-mass derived functionalized graphene aerogel: A sustainable approach for the removal of multiple organic dyes and their mixtures. New Journal of Chemistry, 45(20), 9073–9083. https://doi.org/10.1039/d1nj00470k
Kollarahithlu, S. C., & Balakrishnan, R. M. (2019). Adsorption of ibuprofen using cysteine-modified silane-coated magnetic nanomaterial. Environmental Science and Pollution Research, 26(33), 34117–34126. https://doi.org/10.1007/s11356-018-3272-8
Kommineni, S., Chowdhury, Z., Kavanaugh, M., Mishra, D., & Crouè, J. P. (2008). Advanced oxidation of methyl-tertiary butyl ether: Pilot study findings and full-scale implications. Journal of Water Supply: Research and Technology - AQUA, 57(6), 403–418. https://doi.org/10.2166/aqua.2008.094
Kosma, C. I., Lambropoulou, D. A., & Albanis, T. A. (2014). Investigation of PPCPs in wastewater treatment plants in Greece : Occurrence , removal and environmental risk assessment. Science of the Total Environment, 466–467, 421–438. https://doi.org/10.1016/j.scitotenv.2013.07.044
Kumar, A., Khan, M., Zeng, X., & Lo, I. M. C. (2018). 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. Chemical Engineering Journal, 353, 645–656. https://doi.org/10.1016/j.cej.2018.07.153
Kumar, A., Kumar, A., Sharma, G., Al-Muhtaseb, A. H., Naushad, M., Ghfar, A. A., & Stadler, F. J. (2018). Quaternary magnetic BiOCl/g-C3N4/Cu2O/Fe3O4 nano-junction for visible light and solar powered degradation of sulfamethoxazole from aqueous environment. Chemical Engineering Journal, 334, 462–478. https://doi.org/10.1016/j.cej.2017.10.049
Lai, C., Huang, F., Zeng, G., Huang, D., Qin, L., Cheng, M., Zhang, C., Li, B., Yi, H., Liu, S., Li, L., & Chen, L. (2019). Fabrication of novel magnetic MnFe2O4/bio-char composite and heterogeneous photo-Fenton degradation of tetracycline in near neutral pH. Chemosphere, 224, 910–921. https://doi.org/10.1016/j.chemosphere.2019.02.193
Lamayi, D. W., Shehu, Z., Kwarson, P. S., & Clay, M. (2018). Aqueous Phase Removal of Fluoride as Fluorosis agent Using Montmorillonite Clay as a Natural Nanoadsorbent. Nanochemistry Research, 3(2), 219–226. https://doi.org/10.22036/ncr.2018.02.012
Leonel, A. G., Mansur, A. A. P., & Mansur, H. S. (2021). Advanced Functional Nanostructures based on Magnetic Iron Oxide Nanomaterials for Water Remediation: A Review. Water Research, 190, 116693. https://doi.org/10.1016/j.watres.2020.116693
Li, C. M., Chen, C. H., & Chen, W. H. (2016). Different influences of nanopore dimension and pH between chlorpheniramine adsorptions on graphene oxide-iron oxide suspension and particle. Chemical Engineering Journal, 307, 447–455. https://doi.org/10.1016/j.cej.2016.08.107
Li, J., Chen, Y., Wu, Q., Wu, J., & Xu, Y. (2019). Synthesis of sea-urchin-like Fe3O4/SnO2 heterostructures and its application for environmental remediation by removal of p-chlorophenol. Journal of Materials Science, 54(2), 1341–1350. https://doi.org/10.1007/s10853-018-2899-7
Li, J., Ng, D. H. L., Ma, R., Zuo, M., & Song, P. (2017). Eggshell membrane-derived MgFe2O4 for pharmaceutical antibiotics removal and recovery from water. Chemical Engineering Research and Design, 126, 123–133. https://doi.org/10.1016/j.cherd.2017.07.005
Li, J., Zhou, Q., Liu, Y., & Lei, M. (2017). Recyclable nanoscale zero-valent iron-based magnetic polydopamine coated nanomaterials for the adsorption and removal of phenanthrene and anthracene. Science and Technology of Advanced Materials, 18(1), 3–16. https://doi.org/10.1080/14686996.2016.1246941

https://doi.org/10.37819/nanofab.9.1797

Li, M. fang, Liu, Y. guo, Zeng, G. ming, Liu, S. bo, Hu, X. jiang, Shu, D., Jiang, L. hua, Tan, X. fei, Cai, X. xi, & Yan, Z. li. (2017). Tetracycline absorbed onto nitrilotriacetic acid-functionalized magnetic graphene oxide: Influencing factors and uptake mechanism. Journal of Colloid and Interface Science, 485, 269–279. https://doi.org/10.1016/j.jcis.2016.09.037

Lima, M. J., Leblebici, M. E., Dias, M. M., Lopes, J. C. B., Silva, C. G., Silva, A. M. T., & Faria, J. L. (2014). Continuous flow photo-Fenton treatment of ciprofloxacin in aqueous solutions using homogeneous and magnetically recoverable catalysts. Environmental Science and Pollution Research, 21(19), 11116–11125. https://doi.org/10.1007/s11356-014-2515-6

Liu, Y., Liu, R., Li, M., Yu, F., & He, C. (2019). Removal of pharmaceuticals by novel magnetic genipin-crosslinked chitosan/graphene oxide-SO3H composite. Carbohydrate Polymers, 220(February), 141–148. https://doi.org/10.1016/j.carbpol.2019.05.060

Liu, Y., & Wang, J. (2023). Multivalent metal catalysts in Fenton/Fenton-like oxidation system: A critical review. In Chemical Engineering Journal (Vol. 466). https://doi.org/10.1016/j.cej.2023.143147

Liu, Y., Zhao, Y., & Wang, J. (2021). Fenton/Fenton-like processes with in-situ production of hydrogen peroxide/hydroxyl radical for degradation of emerging contaminants: Advances and prospects. Journal of Hazardous Materials, 404, 124191. https://doi.org/10.1016/j.jhazmat.2020.124191

Liyanage, A. S., Canaday, S., Pittman, C. U., & Mlsna, T. (2020). Rapid remediation of pharmaceuticals from wastewater using magnetic Fe3O4/Douglas fir biochar adsorbents. Chemosphere, 258, 1–39. https://doi.org/10.1016/j.chemosphere.2020.127336

Lorenzo, P., Adriana, A., Jessica, S., Carles, B., Pierre, S., & Marta, L. (2018). Antibiotic resistance in urban and hospital wastewaters and their impact on a receiving freshwater ecosystem. Chemosphere, 206, 70–82. https://doi.org/10.1016/j.chemosphere.2018.04.163

Lu, L., Li, J., Yu, J., Song, P., & Ng, D. H. L. (2016). A hierarchically porous MgFe2O4/γ-Fe2O3 magnetic microspheres for efficient removals of dye and pharmaceutical from water. Chemical Engineering Journal, 283, 524–534. https://doi.org/10.1016/j.cej.2015.07.081

Madikizela, L. M., Mdluli, P. S., & Chimuka, L. (2017). An initial assessment of naproxen, ibuprofen and diclofenac in ladysmith water resources in South Africa using molecularly imprinted solid-phase extraction followed by high performance liquid chromatography-photodiode array detection. South African Journal of Chemistry, 70, 145–153. https://doi.org/10.17159/0379-4350/2017/v70a21

Mahmoud, M. E., Saad, S. R., El-Ghanam, A. M., & Mohamed, R. H. A. (2021). Developed magnetic Fe3O4–MoO3-AC nanocomposite for effective removal of ciprofloxacin from water. Materials Chemistry and Physics, 257(April 2020), 123454. https://doi.org/10.1016/j.matchemphys.2020.123454

Malakootian, M., Nasiri, A., Asadipour, A., Faraji, M., & Kargar, E. (2019). A facile and green method for synthesis of ZnFe2O4@CMC as a new magnetic nanophotocatalyst for ciprofloxacin removal from aqueous media. MethodsX, 6, 1575–1580. https://doi.org/10.1016/j.mex.2019.06.018

Malakootian, M., Nasiri, A., & Mahdizadeh, H. (2018). Preparation of CoFe 2 O 4 /activated carbon@chitosan as a new magnetic nanobiocomposite for adsorption of ciprofloxacin in aqueous solutions. Water Science and Technology, 78(10), 2158–2170. https://doi.org/10.2166/wst.2018.494

Malakootian, M., & Shiri, M. A. (2021). Investigating the removal of tetracycline antibiotic from aqueous solution using synthesized Fe 3 O 4 @ Cuttlebone magnetic nanocomposite Investigating the removal of tetracycline antibiotic from aqueous solution using synthesized Fe 3 O 4 @ Cuttlebone ma. Desalination and Water Treatment, 221, 343–358. https://doi.org/10.5004/dwt.2021.27033

Mao, H., Wang, S., Lin, J., Wang, Z., & Ren, J. (2016). Modification of a magnetic carbon composite for ciprofloxacin adsorption. Journal of Environmental Sciences, 1–9. https://doi.org/10.1016/j.jes.2016.05.048

Marinin, A. (2012). Synthesis and characterization of superparamagnetic iron oxide nanoparticles coated with silica.

Mashile, G. P., Dimpe, K. M., & Nomngongo, P. N. (2020). A Biodegradable Magnetic Nanocomposite as a Superabsorbent for the Simultaneous Removal of Selected Fluoroquinolones from Environmental Water Matrices: Isotherm, Kinetics, Thermodynamic Studies and Cost Analysis. Polymers, 12, 1–25. https://doi.org/10.3390/polym12051102

Migowska, N., Caban, M., Stepnowski, P., & Kumirska, J. (2012). Science of the Total Environment Simultaneous analysis of non-steroidal anti-in fl ammatory drugs and estrogenic hormones in water and wastewater samples using gas chromatography – mass spectrometry and gas chromatography with electron capture detection. Science of the Total Environment, 441, 77–88. https://doi.org/10.1016/j.scitotenv.2012.09.043

Mirzaei, R., Yunesian, M., Nasseri, S., Gholami, M., & Jalilzadeh, E. (2018). Occurrence and fate of most prescribed antibiotics in different water environments of Tehran , Iran. Science of the Total Environment, 619–620, 446–459. https://doi.org/10.1016/j.scitotenv.2017.07.272

Mohammadi, Z., Kelishami, A. R., & Ashrafi, A. (2021). Application of Ni0.5Zn0.5Fe2O4 magnetic nanoparticles for diclofenac adsorption: isotherm, kinetic and thermodynamic investigation. Water Science & Technology, 1265–1277. https://doi.org/10.2166/wst.2021.049

Mohapatra, S., Huang, C., Mukherji, S., & Padhye, L. P. (2016). Occurrence and fate of pharmaceuticals in WWTPs in India and comparison with a similar study in the United States. Chemosphere, 159, 526–535. https://doi.org/10.1016/j.chemosphere.2016.06.047

Mostafaloo, R., Asadi-Ghalhari, M., Izanloo, H., & Zayadi, A. (2020). Photocatalytic degradation of ciprofloxacin antibiotic from aqueous solution by BiFeO3 nanocomposites using response surface methodology. Global Journal of Environmental Science and Management, 6(2), 191–202. https://doi.org/10.22034/gjesm.2020.02.05

Murata, A., Takada, H., Mutoh, K., Hosoda, H., Harada, A., & Nakada, N. (2011). Nationwide monitoring of selected antibiotics: Distribution and sources of sulfonamides, trimethoprim, and macrolides in Japanese rivers. Science of the Total Environment, 409(24), 5305–5312. https://doi.org/10.1016/j.scitotenv.2011.09.014

Mylon, S. E., Chen, K. L., & Elimelech, M. (2004). Influence of natural organic matter and ionic composition on the kinetics and structure of hematite colloid aggregation: Implications to iron depletion in estuaries. Langmuir, 20(21). https://doi.org/10.1021/la049153g

Nantaba, F., Wasswa, J., Kylin, H., Palm, W., Bouwman, H., & Kümmerer, K. (2020). Occurrence , distribution , and ecotoxicological risk assessment of selected pharmaceutical compounds in water from Lake Victoria , Uganda. Chemosphere, 239, 1–11. https://doi.org/10.1016/j.chemosphere.2019.124642

Nasiri, A., Malakootian, M., Shiri, M. A., & Yazdanpanah, G. (2021). CoFe 2 O 4 @ methylcellulose synthesized as a new magnetic nanocomposite to tetracycline adsorption : modeling , analysis , and optimization by response surface methodology. Journal of Polymer Research, 28, 192–216. https://doi.org/10.1007/s10965-021-02540-y

Nasiri, A., Tamaddon, F., Hossein, M. M., Amiri Gharaghani, M., & Asadipour, A. (2019). Magnetic nano-biocomposite CuFe2 O4 @methylcellulose (MC) prepared as a new nano-photocatalyst for degradation of ciprofloxacin from aqueous solution. Environmental Health Engineering and Management, 6(1), 41–51. https://doi.org/10.15171/ehem.2019.05

Nasiri, A., Tamaddon, F., Mosslemin, M. H., & Faraji, M. (2019). A microwave assisted method to synthesize nanoCoFe2O4@methyl cellulose as a novel metal-organic framework for antibiotic degradation. MethodsX, 6, 1557–1563. https://doi.org/10.1016/j.mex.2019.06.017

Nawaz, M., Shahzad, A., Tahir, K., Kim, J., Moztahida, M., Jang, J., Alam, M. B., Lee, S. H., Jung, H. Y., & Lee, D. S. (2019). Photo-Fenton reaction for the degradation of sulfamethoxazole using a multi-walled carbon nanotube-NiFe2O4 composite. Chemical Engineering Journal, 382, 1–12. https://doi.org/10.1016/j.cej.2019.123053

Nguyen, C., Giang, D., Sebesvari, Z., Renaud, F., & Rosendahl, I. (2015). Occurrence and Dissipation of the Antibiotics Trimethoprim , and Enrofloxacin in the Mekong Delta , Vietnam. PLoS ONE, 10(7), 1–24. https://doi.org/10.1371/journal.pone.0131855

Niu, H., Zhang, D., Zhang, S., Zhang, X., Meng, Z., & Cai, Y. (2011). Humic acid coated Fe3O4 magnetic nanoparticles as highly efficient Fenton-like catalyst for complete mineralization of sulfathiazole. Journal of Hazardous Materials, 190(1–3), 559–565. https://doi.org/10.1016/j.jhazmat.2011.03.086

Nodeh, M. K. M., Radfard, M., Ali, L., Nodeh, & Rashidi, Z. & H. (2018). Enhanced removal of naproxen from wastewater using silica magnetic nanoparticles decorated onto graphene oxide ; parametric and equilibrium study. Separation Science and Technology, 1–10. https://doi.org/10.1080/01496395.2018.1457054

Noroozi, R., Gholami, M., Farzadkia, M., & Jonidi Jafari, A. (2020). Catalytic potential of CuFe2O4/GO for activation of peroxymonosulfate in metronidazole degradation: study of mechanisms. Journal of Environmental Health Science and Engineering, 18(2), 947–960. https://doi.org/10.1007/s40201-020-00518-4

Oliveira, V. L., Pereira, M. C., Aquino, S. F., Oliveira, L. C. A., Correa, S., Ramalho, T. C., Gurgel, L. V. A., & Silva, A. C. (2017). Adsorption of diclofenac on a magnetic adsorbent based on maghemite: experimental and theoretical studies. New Journal of Chemistry, 1–14. https://doi.org/10.1039/C7NJ03214E

Olusegun, S. J., Larrea, G., Osial, M., Jackowska, K., & Krysinski, P. (2021). Photocatalytic degradation of antibiotics by superparamagnetic iron oxide nanoparticles. Tetracycline case. Catalysts, 11(10), 1–17. https://doi.org/10.3390/catal11101243

Olusegun, S. J., & Mohallem, N. D. S. (2020). Comparative adsorption mechanism of doxycycline and Congo red using synthesized kaolinite supported CoFe 2 O 4 nanoparticles *. Environmental Pollution, 260, 1–11. https://doi.org/10.1016/j.envpol.2020.114019

Omar, T. F. T., Zaharin, A., Yusoff, F., & Mustafa, S. (2019). Occurrence and level of emerging organic contaminant in fi sh and mollusk from Klang River estuary , Malaysia and assessment on human health risk.

Environmental Pollution, 248, 763–773. https://doi.org/10.1016/j.envpol.2019.02.060
Omuferen, L. O., Maseko, B., Olowoyo, J. O., & Received: (2022). Occurrence of antibiotics in wastewater from hospital and convectional wastewater treatment plants and their impact on the effluent receiving rivers : current knowledge between 2010 and 2019. Environmental Monitoring and Assessment, 194, 306–331. https://doi.org/10.1007/s10661-022-09846-4
Papageorgiou, M., Kosma, C., & Lambropoulou, D. (2016). Seasonal occurrence , removal , mass loading and environmental risk assessment of 55 pharmaceuticals and personal care products in a municipal wastewater treatment plant in Central Greece. Science of the Total Environment, 543, 547–569. https://doi.org/10.1016/j.scitotenv.2015.11.047
Parashar, A., Sikarwar, S., & Jain, R. (2019). Removal of drug oxcarbazepine from wastewater at 3D porous NiFe 2 O 4 nanoparticles Removal of drug oxcarbazepine from wastewater at 3D porous NiFe 2 O 4 nanoparticles Arvind Parashar , Shalini Sikarwar & Rajeev Jain. Journal of Dispersion Science and Technology, 1–11. https://doi.org/10.1080/01932691.2019.1614030
Park, C. M., Heo, J., Wang, D., Su, C., & Yoon, Y. (2018). Heterogeneous activation of persulfate by reduced graphene oxide–elemental silver/magnetite nanohybrids for the oxidative degradation of pharmaceuticals and endocrine disrupting compounds in water. Applied Catalysis B: Environmental, 225, 91–99. https://doi.org/10.1016/j.apcatb.2017.11.058
Peralta, M. E., Mártire, D. O., Moreno, M. S., Parolo, M. E., & Carlos, L. (2021). Versatile nanoadsorbents based on magnetic mesostructured silica nanoparticles with tailored surface properties for organic pollutants removal. Journal of Environmental Chemical Engineering, 9(1). https://doi.org/10.1016/j.jece.2020.104841
Porwal, P., & Sharma, A. (2016). Improving Water Quality through Nanotechnology. International Journal of Applied Research and Technology, 1(2), 119–133.
Qu, X., Brame, J., Li, Q., & Alvarez, P. J. J. (2013). Nanotechnology for a safe and sustainable water supply: Enabling integrated water treatment and reuse. Accounts of Chemical Research, 46(3), 834–843. https://doi.org/10.1021/ar300029v
Rocha, L. S., Sousa, É. M. L., Gil, V., Oliveira, A. B. P., Otero, M., Esteves, V. I., & Calisto, V. (2021). Producing Magnetic Nanocomposites from Paper Sludge for the Adsorptive Removal of Pharmaceuticals from Water — A Fractional Factorial Design. Nanomaterials, 11, 1–20. https://doi.org/10.3390/nano11020287
Rosická, D., & Šembera, J. (2011). Influence of structure of iron nanoparticles in aggregates on their magnetic properties. Nanoscale Research Letters, 6(September), 1–9. https://doi.org/10.1186/1556-276x-6-527
Rosli, F. A., Ahmad, H., Jumbri, K., Abdullah, A. H., & Kamaruzaman, S. (2021). Efficient removal of pharmaceuticals from water using graphene nanoplatelets as adsorbent. Royal Society OPen Science, 8, 1–17. https://doi.org/10.1098/rsos.201076
Rossmann, J., Schubert, S., Gurke, R., Oertel, R., & Kirch, W. (2018). Simultaneous determination of most prescribed antibiotics in multiple urban wastewater by SPE-LC-MS / MS Simultaneous determination of most prescribed antibiotics in multiple urban wastewater by SPE-LC – MS / MS. Journal of Chromatography B, 969(August 2014), 162–170. https://doi.org/10.1016/j.jchromb.2014.08.008
Saeed, M., Usman, M., Muneer, M., Akram, N., Ul Haq, A., Tariq, M., & Akram, F. (2020). Synthesis of Ag-Fe3O4 nanoparticles for degradation of methylene blue in aqueous medium. Bulletin of the Chemical Society of Ethiopia, 34(1), 123–134. https://doi.org/10.4314/BCSE.V34I1.11
Sayadi, M. H., & Ahmadpour, N. (2021). Photocatalytic and Antibacterial Properties of Ag-CuFe2O4@WO3 Magnetic Nanocomposite. Nanomaterials, 11, 1–19. https://doi.org/10.3390/nano11020298
Senta, I., Terzic, S., & Ahel, M. (2012). Occurrence and fate of dissolved and particulate antimicrobials in municipal wastewater treatment. Water Research, 47(2), 705–714. https://doi.org/10.1016/j.watres.2012.10.041
Sharma, B., Thakur, S., Mamba, G., Prateek, Gupta, R. K., Gupta, V. K., & Thakur, V. K. (2021). Titania modified gum tragacanth based hydrogel nanocomposite for water remediation. Journal of Environmental Chemical Engineering, 9(1), 104608. https://doi.org/10.1016/j.jece.2020.104608
Sharma, V. K., McDonald, T. J., Kim, H., & Garg, V. K. (2015). Magnetic graphene-carbon nanotube iron nanocomposites as adsorbents and antibacterial agents for water purification. Advances in Colloid and Interface Science, 225, 229–240. https://doi.org/10.1016/j.cis.2015.10.006
Shehu, Z., & Lamayi, D. W. (2019). Recent Advances and Developments in Nanoparticles/ Nanocomposites as Nanoadsorbent for Adsorptive Removal of Lead in Wastewater: A Review. Nanomedicine & Nanotechnology Open Access, 4(3), 1–10. https://doi.org/10.23880/nnoa-16000165
Shehu, Z., William, G., Nyakairu, A., Tebandeke, E., & Nelson, O. (2022). Overview of African water resources contamination by contaminants of emerging concern. Science of the Total Environment, 852, 1–30. https://doi.org/10.1016/j.scitotenv.2022.158303

Sibeko, P. A., Naicker, D., Mdluli, P. S., Sibeko, P. A., Naicker, D., Mdluli, P. S., & Madikizela, L. M. (2019). Naproxen , ibuprofen , and diclofenac residues in river water , sediments and Eichhornia crassipes of Mbokodweni river in South Africa : An initial screening. Environmental Forensics, 1–8. https://doi.org/10.1080/15275922.2019.1597780

Silva, C. P., Pereira, D., Calisto, V., Martins, M. A., Otero, M., Esteves, V. I., & Lima, D. L. D. (2021). Biochar-TiO2 magnetic nanocomposites for photocatalytic solar-driven removal of antibiotics from aquaculture effluents. Journal of Environmental Management, 294(June). https://doi.org/10.1016/j.jenvman.2021.112937

Singh, H., Bhardwaj, N., Arya, S. K., & Khatri, M. (2020). Environmental impacts of oil spills and their remediation by magnetic nanomaterials. Environmental Nanotechnology, Monitoring and Management, 14(May), 100305. https://doi.org/10.1016/j.enmm.2020.100305

Singh, K. K., Singh, A., & Rai, S. (2021). A study on nanomaterials for water purification. Materials Today: Proceedings, 51(xxxx), 1157–1163. https://doi.org/10.1016/j.matpr.2021.07.116

Singh, N., Prajapati, S., Prateek, & Gupta, R. K. (2022). Investigation of Ag doping and ligand engineering on green synthesized CdS quantum dots for tuning their optical properties. Nanofabrication, 7, 89–103. https://doi.org/10.37819/nanofab.007.212

Soares, S. F., Fernandes, T., Trindade, T., & Daniel-da-silva, A. L. (2019). Trimethyl Chitosan/Siloxane-Hybrid Coated Fe3O4 Nanoparticles for the Uptake of Sulfamethoxazole from Water. Molecules, 24, 1–18.

Soares, V., Grando, M. C., Colpani, G. L., Silva, L. L., Maria, J., & Mello, M. De. (2019). Obtaining of Fe 3 O 4 @ C Core-Shell Nanoparticles as an Adsorbent of Tetracycline in Aqueous Solutions. Materials Research, 22(Suppl. 1), 1–11. https://doi.org/10.1590/1980-5373-MR-2018-0857

Solís, R. R., Dinc, Ö., Fang, G., Nadagouda, M. N., & Dionysiou, D. D. (2021). Activation of inorganic peroxides with magnetic graphene for the removal of antibiotics from wastewater. Environmental Science: Nano, 8(4), 960–977. https://doi.org/10.1039/d0en01280g

Stan, A. M., Lung, I., Soran, M., Leostean, C., Popa, A., Stefan, M., Diana, M., Opris, O., Silipas, T., & Sebastian, A. (2017). Removal of antibiotics from aqueous solutions by green synthesized magnetite nanoparticles with selected agro-waste extracts. Process Safety and Environmental Protection, 1–25. https://doi.org/10.1016/j.psep.2017.03.003

Styszko, K., Proctor, K., Castrignanò, E., & Kasprzyk-hordern, B. (2021). Occurrence of pharmaceutical residues , personal care products , lifestyle chemicals , illicit drugs and metabolites in wastewater and receiving surface waters of Krakow agglomeration in South Poland. Science of the Total Environment, 768, 1–18. https://doi.org/10.1016/j.scitotenv.2020.144360

Tamaddon, F., Nasiri, A., & Yazdanpanah, G. (2020). Photocatalytic degradation of ciprofloxacin using CuFe2O4@methyl cellulose based magnetic nanobiocomposite. MethodsX, 7, 74–81. https://doi.org/10.1016/j.mex.2019.12.005

Tang, J., & Wang, J. (2018). Metal Organic Framework with Coordinatively Unsaturated Sites as Efficient Fenton-like Catalyst for Enhanced Degradation of Sulfamethazine. Environmental Science and Technology, 52(9). https://doi.org/10.1021/acs.est.8b00092

Tran, N. H., Chen, H., Reinhard, M., Mao, F., & Gin, K. Y. (2016). Occurrence and removal of multiple classes of antibiotics and antimicrobial agents in biological wastewater treatment processes. Water Research, 104, 461–472. https://doi.org/10.1016/j.watres.2016.08.040

Vecchia, E. D., Coisson, M., Appino, C., Vinai, F., & Sethi, R. (2009). Magnetic characterization and interaction modeling of zerovalent iron nanoparticles for the remediation of contaminated aquifers. Journal of Nanoscience and Nanotechnology, 9(5), 3210–3218. https://doi.org/10.1166/jnn.2009.047

Verlicchi, P., Aukidy, M. Al, Galletti, A., Petrovic, M., & Barceló, D. (2012). Hospital ef fl uent : Investigation of the concentrations and distribution of pharmaceuticals and environmental risk assessment. Science of the Total Environment, The, 430, 109–118. https://doi.org/10.1016/j.scitotenv.2012.04.055

Verlicchi, P., Aukidy, M. Al, Jelic, A., Petrovi, M., & Barceló, D. (2014). Comparison of measured and predicted concentrations of selected pharmaceuticals in wastewater and surface water : A case study of a catchment area in the Po Valley (Italy). Science of the Total Environment, 471, 844–854. https://doi.org/10.1016/j.scitotenv.2013.10.026

Vicente-Martínez, Y., Caravaca, M., Soto-Meca, A., & Solana-González, R. (2020). Magnetic core-modified silver nanoparticles for ibuprofen removal: an emerging pollutant in waters. Scientific Reports, 10(1), 1–10. https://doi.org/10.1038/s41598-020-75223-1

Wan, Z., & Wang, J. (2017). Fenton-like degradation of sulfamethazine using Fe3O4/Mn3O4 nanocomposite catalyst: kinetics and catalytic mechanism. Environmental Science and Pollution Research, 24(1), 568–577. https://doi.org/10.1007/s11356-016-7768-9

Wang, J., & Chu, L. (2016). Irradiation treatment of pharmaceutical and personal care products (PPCPs) in water and wastewater: An overview. Radiation Physics and Chemistry, 125, 56–64. https://doi.org/10.1016/j.radphyschem.2016.03.012

Wang, J. L., & Xu, L. J. (2012). Advanced oxidation processes for wastewater treatment: Formation of hydroxyl radical and application. Critical Reviews in Environmental Science and Technology, 42(3), 251–325. https://doi.org/10.1080/10643389.2010.507698

Wang, J., & Tang, J. (2021). Fe-based Fenton-like catalysts for water treatment: Preparation, characterization and modification. Chemosphere, 276, 130177. https://doi.org/10.1016/j.chemosphere.2021.130177

Wang, J., & Wang, S. (2016). Removal of pharmaceuticals and personal care products (PPCPs) from wastewater: A review. In Journal of Environmental Management (Vol. 182). https://doi.org/10.1016/j.jenvman.2016.07.049

Wang, J., & Wang, S. (2019). Preparation, modification and environmental application of biochar: A review. Journal of Cleaner Production, 227, 1002–1022. https://doi.org/10.1016/j.jclepro.2019.04.282

Wang, J., & Wang, S. (2022). A critical review on graphitic carbon nitride (g-C3N4)-based materials: Preparation, modification and environmental application. Coordination Chemistry Reviews, 453, 214338. https://doi.org/10.1016/j.ccr.2021.214338

Wang, J., & Zhuan, R. (2020). Degradation of antibiotics by advanced oxidation processes: An overview. Science of the Total Environment, 701, 135023. https://doi.org/10.1016/j.scitotenv.2019.135023

Wang, J., Zhuan, R., & Chu, L. (2019). The occurrence, distribution and degradation of antibiotics by ionizing radiation: An overview. Science of the Total Environment, 646, 1385–1397. https://doi.org/10.1016/j.scitotenv.2018.07.415

Wang, Z., Chen, X., Meng, Z., Zhao, M., & Zhan, H. (2020). A water resistance magnetic graphene-anchored zeolitic imidazolate framework for efficiently adsorption and removal of residual tetracyclines in wastewater. Water Science & Technology, 1–15. https://doi.org/10.2166/wst.2020.283

Wang, Z., Lai, C., Qin, L., Fu, Y., He, J., & Huang, D. (2020). ZIF-8-modi fi ed MnFe 2 O 4 with high crystallinity and superior photo-Fenton catalytic activity by Zn-O-Fe structure for TC degradation. Chemical Engineering Journal, 392(December 2019), 124851. https://doi.org/10.1016/j.cej.2020.124851

Wang, Z., Lai, C., Qin, L., Fu, Y., He, J., Huang, D., Li, B., Zhang, M., Liu, S., Li, L., Zhang, W., Yi, H., Liu, X., & Zhou, X. (2020). ZIF-8-modified MnFe2O4 with high crystallinity and superior photo-Fenton catalytic activity by Zn-O-Fe structure for TC degradation. Chemical Engineering Journal, 392. https://doi.org/10.1016/j.cej.2020.124851

Wei, H., Hu, D., Su, J., & Li, K. (2015). Intensification of levofloxacin sono-degradation in a US/H2O2 system with Fe3O4 magnetic nanoparticles. Chinese Journal of Chemical Engineering, 23(1), 296–302. https://doi.org/10.1016/j.cjche.2014.11.011

Wu, W., He, Q., & Jiang, C. (2008). Magnetic iron oxide nanoparticles: Synthesis and surface functionalization strategies. Nanoscale Research Letters, 3(11), 397–415. https://doi.org/10.1007/s11671-008-9174-9

Xiang, Y., Huang, Y., Xiao, B., Wu, X., & Zhang, G. (2020). Magnetic yolk-shell structure of ZnFe2O4 nanoparticles for enhanced visible light photo-Fenton degradation towards antibiotics and mechanism study. Applied Surface Science, 513, 1–12. https://doi.org/10.1016/j.apsusc.2020.145820

Xing, L., Madjeed, K., Emami, N., Nalchifard, F., Hussain, W., Jasem, H., Dawood, A. H., Toghraie, D., & Hekmatifar, M. (2020). Fabrication of HKUST-1/ZnO/SA nanocomposite for Doxycycline and Naproxen adsorption from contaminated water. Sustainable Chemistry and Pharmacy, 29, 1–15. https://doi.org/10.1016/j.scp.2022.100757

Ye, X., Li, Y., Lin, H., Chen, Y., & Liu, M. (2021). Lignin-Based Magnetic Nanoparticle Adsorbent for Diclofenac Sodium Removal: Adsorption Behavior and Mechanisms. Journal of Polymers and the Environment, 29(10), 3401–3411. https://doi.org/10.1007/s10924-021-02127-0

Yegane Badi, M., Azari, A., Pasalari, H., Esrafili, A., & Farzadkia, M. (2018). Modification of activated carbon with magnetic Fe3O4 nanoparticle composite for removal of ceftriaxone from aquatic solutions. Journal of Molecular Liquids, 261, 146–154. https://doi.org/10.1016/j.molliq.2018.04.019

Yu, X., Lin, X., Feng, W., & Li, W. (2019). Effective Removal of Tetracycline by Using Bio-Templated Synthesis of - TiO 2 / Fe 3 O 4 Heterojunctions as a UV – Fenton Catalyst. Catalysis Letters, 149(2), 552–560. https://doi.org/10.1007/s10562-018-2544-8

Zeng, X., Liu, J., & Zhao, J. (2018). Highly efficient degradation of pharmaceutical sludge by catalytic wet oxidation using CuO-CeO2 / γ -Al2O3 as a catalyst. PLoS ONE, 13(10), 1–10. https://doi.org/10.1371/journal.pone.0199520

Zhang, Y., Jiao, Z., Hu, Y., Lv, S., Fan, H., Zeng, Y., Hu, J., & Wang, M. (2017). Removal of tetracycline and oxytetracycline from water by magnetic Fe3O4@graphene. Environmental Science and Pollution Research, 24(3), 2987–2995. https://doi.org/10.1007/s11356-016-7964-7

Zhao, H., Cui, H.-J., & Fu, M.-L. (2014). Synthe sis of co ore-shell structured Fe3O4@α-M MnO2 micros pheres for efficiently ca atalytic d degradat tion of ciprofl loxacin Received. RSC Advances, 4, 39472–39475. https://doi.org/10.1039/C4RA06696K

Zhu, J., Zhang, G., Xian, G., Zhang, N., & Li, J. (2019). A High-Efficiency CuO / CeO 2 Catalyst for Diclofenac Degradation in Fenton-Like System. Frontiers in Chemistry, 7(796), 2–11. https://doi.org/10.3389/fchem.2019.00796

Zhuang, S., Chen, R., Liu, Y., & Wang, J. (2020). Magnetic COFs for the adsorptive removal of diclofenac and sulfamethazine from aqueous solution: Adsorption kinetics, isotherms study and DFT calculation. Journal of Hazardous Materials, 385, 121596. https://doi.org/10.1016/j.jhazmat.2019.121596

Zhuang, S., Cheng, R., & Wang, J. (2019). Adsorption of diclofenac from aqueous solution using UiO-66-type metal-organic frameworks. Chemical Engineering Journal, 359, 354–362. https://doi.org/10.1016/j.cej.2018.11.150

Zhuang, S., Liu, Y., & Wang, J. (2019). Mechanistic insight into the adsorption of diclofenac by MIL-100: Experiments and theoretical calculations. Environmental Pollution, 253, 616–624. https://doi.org/10.1016/j.envpol.2019.07.069

Zhuang, S., Liu, Y., & Wang, J. (2020). Covalent organic frameworks as efficient adsorbent for sulfamerazine removal from aqueous solution. Journal of Hazardous Materials, 383, 121126. https://doi.org/10.1016/j.jhazmat.2019.121126

Zhuang, S., Zhu, X., & Wang, J. (2020). Adsorptive removal of plasticizer (dimethyl phthalate) and antibiotic (sulfamethazine) from municipal wastewater by magnetic carbon nanotubes. Journal of Molecular Liquids, 319, 114267. https://doi.org/10.1016/j.molliq.2020.114267