



Effective methods for removal of antibiotic pollutants from wastewater: sources, pathways, distribution, and impacts

Pham Thi-Huong · Nguyen Lam Nhat Minh ·
Subhav Singh · Kim Jitae

Received: 31 December 2025 / Accepted: 12 March 2026
© The Author(s), under exclusive licence to Springer Nature B.V. 2026

Abstract The global reliance on antibiotics has led to the discharge of large amounts of their residues into rivers, lakes, and coastal waters. Antibiotic residues, even in small amounts, can damage ecosystems and human health. They can also lead to the development of antibiotic-resistant bacteria and genes. This review applies a source–impact–treatment framework to connect major antibiotic classes, usage patterns, and transport pathways with resistance-related

environmental and public health concerns. Unlike reviews that focus on a single technology or material, this work provides a decision-oriented comparison of the two most widely used removal strategies: adsorption and advanced oxidation processes (AOPs). Recent advances are summarized by highlighting key materials, processes, performance trends, mechanisms, and practical limitations. Adsorption and AOPs are evaluated using unified criteria, including treatment cost, operating conditions, mineralization and by-product formation, toxicity reduction, and implementation challenges. This framework supports context-specific selection for various wastewater matrices and regional requirements. Moreover, this work identifies research gaps and future directions, such as the development of robust, low-cost materials, enhancement of mineralization with reduced secondary risks. In addition, it emphasizes the need to integrate treated wastewater reuse to more effectively assess sustainability and real-world applicability.

Keywords Antibiotic resistance · Antibiotic pollutants · Advanced oxidation processes · Adsorption · Wastewater

P. Thi-Huong
Department of Materials Science and Engineering,
Gachon University, 1342 Seongnam-daero, Sujeong-gu,
Seongnam 13120, South Korea
e-mail: phambary@gachon.ac.kr

N. L. N. Minh
Da Nang University of Medical Technology and Pharmacy,
Da Nang, Vietnam

S. Singh
Centre of Research Impact and Outcome, Chitkara
University, Rajpura, Punjab 140417, India

S. Singh
Division of Research and Development, Lovely
Professional University, Phagwara, Punjab, India

K. Jitae (✉)
Institute of Research and Development, Duy Tan
University, Da Nang, Vietnam
e-mail: kimjitae@duytan.edu.vn

K. Jitae
School of Engineering and Technology, Duy Tan
University, Da Nang, Vietnam

Introduction

Antibiotics have significantly reduced infectious diseases and helped to protect human life. However, overuse of antibiotics in medicine has led to increased

antibiotic residues in the environment (Yang et al., 2023; Zhai et al., 2024; Zhang et al., 2023). Because antibiotics are not completely broken down in the body, they are excreted and end up in wastewater, which then flows into rivers, oceans, and soil. In recent years, the frequent detection of antibiotic residues in freshwater and surface water has raised concerns about the presence of antibiotic pollutants in the environment (Bonetta et al., 2023; Ogunlaja et al., 2022; Tiwari et al., 2025). However, even at low levels, antibiotic residues can have significant effects on ecosystems, particularly by increasing the growth of antibiotic-resistant bacteria and antibiotic resistance genes (Savin et al., 2021; Tiwari et al., 2025). These problems become serious for human health, as they can reduce the effectiveness of antibiotic treatments, lead to the emergence of new bacterial strains, and prolong patient recovery times. Most conventional wastewater treatment plants were designed to handle bulk pollutants, such as organic matter, nutrients, suspended solids, and certain metals, but not biologically active micropollutants, including antibiotics. Because of this, many antibiotics are not broken down well and often pass through treatment only partly removed. The treatment processes can convert antibiotics into by-products that persist longer or are more toxic, which can then accumulate in treated water, sediments, and biosolids. These findings indicate that current treatment systems are not yet able to effectively control antibiotic pollution under real-world conditions, raising concerns for ecosystems, biodiversity, and public health (Alsaedi et al., 2025; Behere et al., 2025; Izah et al., 2025; Tiwari et al., 2025). Figure 1 shows that the pharmaceutical industry is a major source of antibiotic pollution, while hospitals and healthcare systems also contribute, as they use large amounts of antibiotics to protect patients (Hassoun-Kheir et al., 2020; Omufere et al., 2022). When people take antibiotics, much of the medicine leaves their bodies either unchanged or as active by-products. If these substances enter sewer systems without proper controls or treatment, they can become point sources of pharmaceutical pollution (Abou-Jaoudeh et al., 2024; Gwenzi et al., 2020; Li et al., 2025; Liu et al., 2025; Merhi et al., 2023; Rodriguez-Mozaz et al., 2020). In many developing or low-income countries, people can easily obtain antibiotics, which increases antibiotic use and raises residue levels in sewage. If sewage systems are not

working properly, the remaining antibiotics can easily enter rivers, lakes, and soil (Abou-Jaoudeh et al., 2024; Okeke et al., 2025; Rani et al., 2024). Besides, antibiotics are commonly used in raising livestock, poultry, and fish to treat illness, prevent disease, and, in some places, promote growth. Animals break down only a small amount of these drugs, so most of the antibiotics are excreted in urine and feces. This waste becomes a major source of pollution. Moreover, in fish farming, medicated feed and treatments can rapidly introduce antibiotics into nearby water (Bonetta et al., 2023; Gwenzi et al., 2020; Li et al., 2025; Liu et al., 2025; Okeke et al., 2025; Sousa et al., 2025). Therefore, controlling antibiotic residues has become an urgent priority to mitigate their potential risks to human health and aquatic ecosystems (Izah et al., 2025; Savin et al., 2021). Recent review articles have improved our understanding of antibiotic pollutants, but the available information remains limited (Ben et al., 2019; Bhunia et al., 2025; Darby et al., 2023; Galgano et al., 2025; Hassoun-Kheir et al., 2020; Holmes et al., 2016; Karthikeyan & Meyer, 2006; Kawsar et al., 2026; Patel et al., 2019; Song et al., 2025; Thakur et al., 2024, 2025; Tiseo et al., 2020; Wang et al., 2024b; Watkinson et al., 2007; Zhang et al., 2024c). They mainly focus on environmental sources, such as hospitals, municipalities, and livestock, as well as how antibiotics are distributed over time and space, and what happens to them in water systems (Alsaedi et al., 2025; Aryee et al., 2022; Hamid & Khanday, 2026; Liu et al., 2025; Lyu et al., 2026; Merhi et al., 2023; Niu et al., 2024; Vinayagam et al., 2022). Other studies examine treatment technologies, ecological toxicity, and potential human health effects. However, the reviews usually focus on just one method, such as adsorption or a specific advanced oxidation process (Lyu et al., 2026; Niu et al., 2024). Thus, it is possible to find in-depth information on each topic, but it is hard to see the connections throughout the whole process. Some works present the source, pathway, impact, and control chain in a clear framework (Liu et al., 2025; Xu et al., 2021). However, they often do not fully integrate common antibiotic classes, their environmental relevance, how they transform during natural processes or treatment, or the combined risks to ecosystems and human health, especially the spread of antibiotic-resistant bacteria and resistance genes. Besides, comparisons of technologies are frequently descriptive and provide

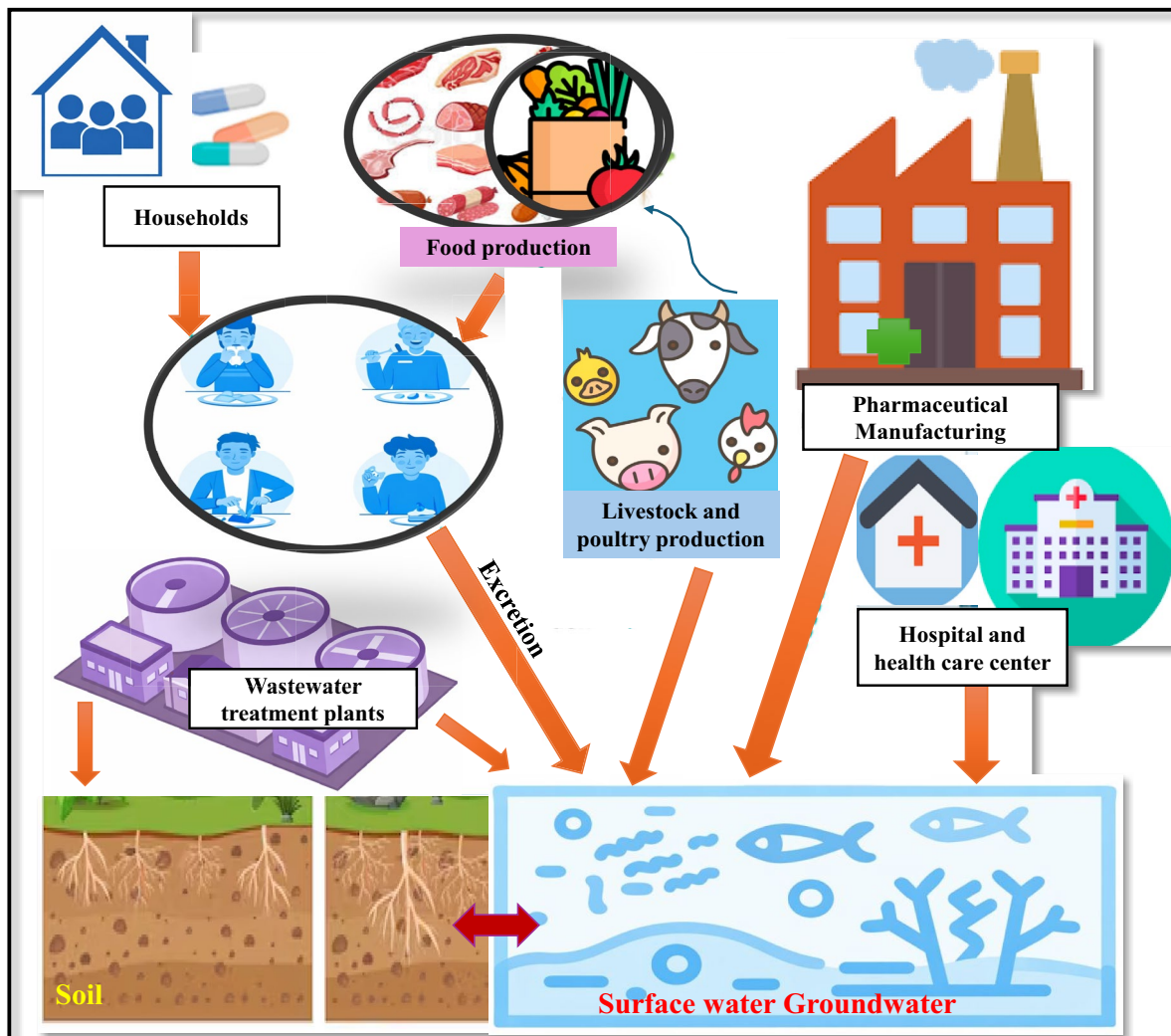


Fig. 1 Main sources of antibiotic residues released into the environment

little information on side-by-side evaluations. Key practical considerations, such as the removal performance of different antibiotic pollutants, toxicity reduction, and operational challenges (energy and chemical consumption, material stability, and by-product formation), remain limited.

This review covers both established and new methods for removing antibiotic residues from wastewater and aquatic environments. It begins by introducing antibiotics as emerging contaminants, describing their main sources, where they are found, and their key chemical properties. The review then examines how antibiotic residues move and accumulate in the environment and

discusses their effects on ecosystems and human health. It also assesses current treatment technologies, focusing on their efficacy, benefits, and limitations. Finally, this work highlights current challenges and suggests future research to develop more effective and sustainable approaches to managing antibiotic residues and mitigating their risks to people and the environment.

Types of antibiotics

Antibiotics divide into several main groups, including β -lactams, fluoroquinolones, tetracyclines,

sulfonamides, macrolides, and aminoglycosides (Bonetta et al., 2023; Hassoun-Kheir et al., 2020; Yang et al., 2023). Worldwide, β -lactam antibiotics such as penicillins and cephalosporins are most commonly used. Along with macrolides, fluoroquinolones, and tetracyclines, these represent the primary antibiotic classes in clinical practice (Hamad, 2010; Song et al., 2025). Previous studies show that penicillins and cephalosporins are the most commonly used systemic antibacterials in both community and hospital settings. Besides, quinolones, macrolides, and tetracyclines account for a large share of total antibiotic use. Each group has its own chemical structure and properties that influence how antibiotics move, degrade, and are removed during treatment (Hamad, 2010). For example, β -lactams break down more readily, while fluoroquinolones and tetracyclines bind strongly to sediments and sludge, resulting in long-term accumulation in aquatic environments and treatment system solids. As discussed above, antibiotic residues are found in many water systems, including hospital wastewater, sewage, rivers, lakes, groundwater, and even drinking water (Bonetta et al., 2023; Chen et al., 2024; Savin et al., 2021). Table 1 provides an overview of antibiotics identified in various wastewaters as reported in the literature. It shows a wide range of antibiotic residues found in wastewater, with maximum concentrations between 2.97 and 6900 ng L⁻¹. The detected compounds represent several major classes, including sulfonamides (such as sulfamethoxazole, sulfamethizole, and sulfaquinoxaline), fluoroquinolones (ciprofloxacin, ofloxacin, levofloxacin, norfloxacin, enrofloxacin), tetracyclines (tetracycline, oxytetracycline, doxycycline), β -lactams (ampicillin, amoxicillin, penicillin G/V, cloxacillin), as well as macrolides (erythromycin), nitroimidazoles (metronidazole), lincosamides (lincomycin), and ionophores (monensin). The highest concentrations were observed for fluoroquinolones and sulfonamides, specifically ciprofloxacin (6900 ng L⁻¹), sulfamethoxazole (3400 ng L⁻¹), and ofloxacin (1651 ng L⁻¹), reflecting their widespread use. However, several β -lactams were detected at much lower concentrations, consistent with their lower environmental stability. The frequent detection of various antibiotic pollutants in wastewater at different concentrations raises concerns, as these compounds

Table 1 Summary of antibiotic pollutants detected in wastewater

Antibiotic pollutants	Maximum concentration detected (ng L ⁻¹)	References
Sulfamethoxazole	3400	Yang et al. (2011)
Erythromycin	480	Yang et al. (2011)
Ciprofloxacin	1100	Yang et al. (2011)
Levofloxacin	900	Yang et al. (2011)
Tetracycline	310	Yang et al. (2011)
Sulfaquinoxaline	98	Shao et al. (2009)
Ofloxacin	342	Shao et al. (2009)
Tetracycline	747	Shao et al. (2009)
Oxytetracycline	1481	Shao et al. (2009)
Norfloxacin	73	Shao et al. (2009)
Norfloxacin	33	Shao et al. (2009)
Ampicillin	160	Blair et al. (2015)
Norfloxacin	140	Blair et al. (2015)
Penicillin G	30	Blair et al. (2015)
Penicillin V	86	Blair et al. (2015)
Sulfamethizole	92	Blair et al. (2015)
Penicillin	2.97	Kleywegt et al. (2019)
Sulfamethoxazole	80	Patel et al. (2019)
Ciprofloxacin	591	Patel et al. (2019)
Tetracycline	22.8	Patel et al. (2019)
Ofloxacin	366	Patel et al. (2019)
Ciprofloxacin	5692	Rosal et al. (2010)
Erythromycin	760	Rosal et al. (2010)
Metronidazole	127	Rosal et al. (2010)
Ofloxacin	1651	Rosal et al. (2010)
Amoxicillin	280	Watkinson et al. (2007)
Penicillin V	10	Watkinson et al. (2007)
Norfloxacin	145	Watkinson et al. (2007)
Ciprofloxacin	6900	Watkinson et al. (2007)
Enrofloxacin	20	Watkinson et al. (2007)
Lincomycin	70	Watkinson et al. (2007)
Doxycycline	40	Watkinson et al. (2007)
Monensin	10	Watkinson et al. (2007)
Sulphamethoxazole	570	Watkinson et al. (2007)

Table 1 (continued)

Antibiotic pollutants	Maximum concentration detected (ng L ⁻¹)	References
Trimethoprim	480	Watkinson et al. (2007)
Amoxycillin	6.94	Watkinson et al. (2009)
Penicillin V	13.8	Watkinson et al. (2009)
Cloxacillin	4.6	Watkinson et al. (2009)

remain bioactive even at low levels. As a result, antibiotic residues can impose chronic selection pressure on wastewater and receiving-water microbiomes, selecting for increased abundance of antibiotic-resistant bacteria and antibiotic resistance genes (Karthikeyan & Meyer, 2006; Kawsar et al., 2026; Kleywegt et al., 2019; Patel et al., 2019; Shao et al., 2009; Thakur et al., 2025; Tiseo et al., 2020; Watkinson et al., 2007). Long-term exposure to antibiotics and their mixtures can change the structure and function of microbial communities in aquatic ecosystems, especially when several antibiotics are present at the same time. The main concern for human health is the indirect risk of antimicrobial resistance. There is also a risk of low-level exposure when reclaimed water is used for irrigation, aquaculture, or as a drinking-water source if treatment is not effective (Thakur et al., 2025; Watkinson et al., 2009). Therefore, it is important to know the basic properties of antibiotics, such as their main components, structure, and uses. This knowledge helps us assess environmental risks and find ways to manage them (Fig. 2). For example, tetracycline antibiotics reduce the risk and severity of respiratory infections such as bronchitis and pneumonia. They can also be used for skin conditions such as dermatitis, bacterial intestinal infections, and diseases such as malaria. Penicillin antibiotics are widely used to treat serious bacterial infections such as meningitis and certain sexually transmitted diseases. Doctors often give them before or after surgery to help prevent infections and improve recovery. In farming, penicillin-type antibiotics help keep livestock healthy and productive by controlling infections (Alsaedi

et al., 2025; Hassoun-Kheir et al., 2020; Lyu et al., 2026). Sulfamethoxazole is another widely used antibiotic used for gastrointestinal infections and certain forms of gastroenteritis. In addition, sulfonamides, such as sulfamethoxazole and sulfadiazine, are commonly prescribed for community infections and are often combined with trimethoprim to improve their effectiveness (Alsaedi et al., 2025; Hamid & Khanday, 2026). Macrolides, including erythromycin, azithromycin, and clarithromycin, are key drugs for controlling infections caused by unusual bacteria. Minoglycosides (gentamicin, streptomycin, and kanamycin) are primarily used for severe or complicated infections, particularly in hospitals (Zhang et al., 2024c).

Pathways and environmental distribution of antibiotic pollutants

Figure 3 shows that antibiotic residues enter the environment in several ways, with wastewater treatment plants as the main source. When people or animals take antibiotics, some of the drug and its by-products are excreted and enter wastewater treatment plants (Hamid & Khanday, 2026; Liu et al., 2025; Zhang et al., 2024c). However, wastewater treatment plants are not designed to remove small amounts (trace levels) and by-product pollutants, so they often remain in the treated water and sewage sludge. The remaining antibiotic residues are discharged into receiving waters, including rivers, lakes, and coastal areas. The concentrations of these residues depend on factors such as dilution and hydrology, but the remaining contaminants are still present (Galgano et al., 2025). Moreover, discharges from wastewater treatment plants consistently introduce antibiotics into the environment. Therefore, the amount of contaminants increases, resulting in various negative effects on both human health and the ecosystem (Huang et al., 2026; Kawsar et al., 2026). Besides, some antibiotics may also be formed, regenerated, or produced during treatment because wastewater contains a mixture of parent compounds and transformation products. This means that, even if the target compound is partly removed earlier, it can be replenished later or transformed into other, potentially more toxic compounds. In general, when studies report removal efficiency based on the disappearance of the target antibiotic, the reported

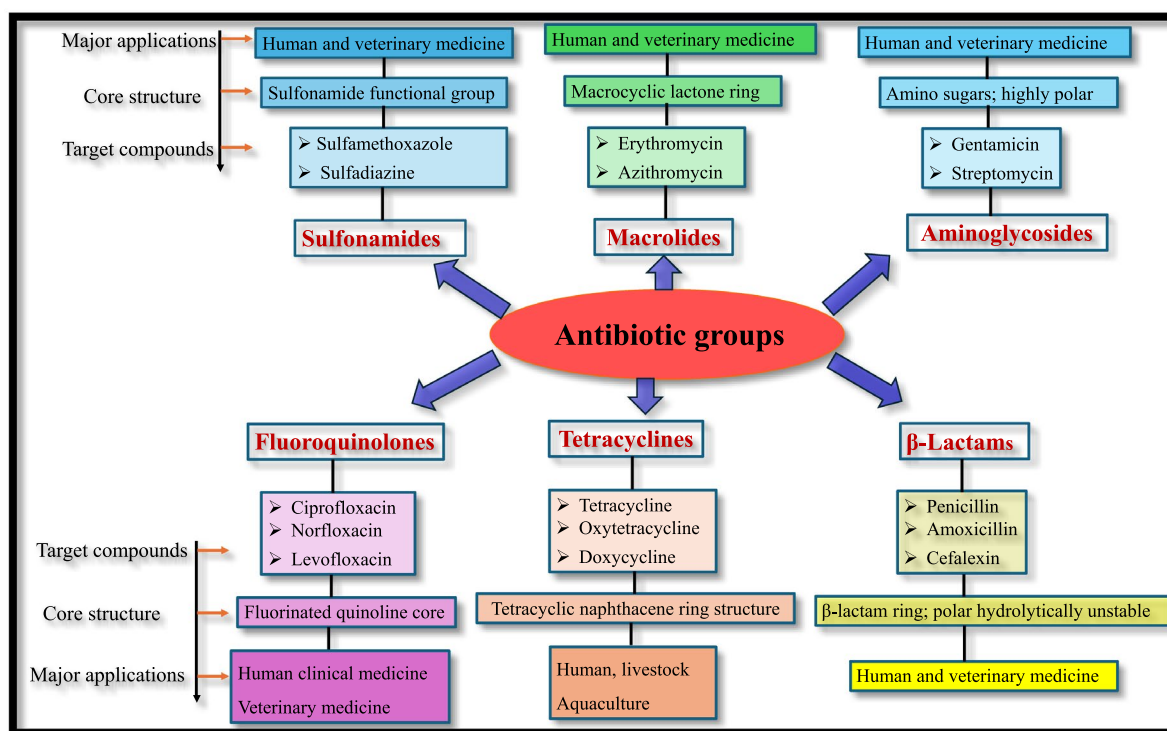


Fig. 2 Common antibiotics classified by chemical structure and applications

value may overestimate true elimination because the compound may be converted into other chemical forms (transformation products or bound residues) rather than fully mineralized to CO_2 , H_2O , and inorganic ions (Míguez González et al., 2025; Thakur et al., 2025). This distinction is important for environmental release: transformation products are often more polar and can pass through secondary treatment into the final effluent, while compounds sorbed to sludge can later desorb or undergo further transformations during sludge handling, potentially reintroducing antibiotic residues (Galgano et al., 2025; Karthikeyan & Meyer, 2006; Tiseo et al., 2020).

Further, antibiotics with a strong affinity for solids can partition into activated sludge and accumulate in waste sludge or biosolids. When sludge or biosolids are used as soil amendments, antibiotics can later reach surface waters through runoff and erosion, or seep into groundwater, depending on the soil and rainfall (Holmes et al., 2016; Thakur et al., 2025). Also, using treated effluent for irrigation or industrial purposes can spread antibiotic residues to soils and crops (Abou-Jaoudeh et al., 2024; Liu et al.,

2025). Antibiotic residues can reach groundwater in several ways. After being released into rivers and canals, these residues can move through riverbeds and enter nearby aquifers. When manure or biosolids are spread on land, or when reclaimed water is used for irrigation, antibiotics are added to the soil. More mobile compounds may then leach into the groundwater, depending on factors such as rainfall, soil type, organic carbon content, and the depth to the water table (Holmes et al., 2016; Kawsar et al., 2026; Rosal et al., 2010; Thakur et al., 2025; Watkinson et al., 2009).

On the other hand, antibiotics that strongly attach to solids, like fluoroquinolones and tetracyclines, usually stick to suspended particles, sludge, and sediments by bonding with minerals or organic matter (Huang et al., 2026; Karthikeyan & Meyer, 2006; Tiseo et al., 2020). This process limits their movement in water for a short time but causes them to build up in sludge and sediments over the long term, creating secondary reservoirs. These reservoirs can later release antibiotics back into the environment if conditions change, such as shifts in pH, salt levels,

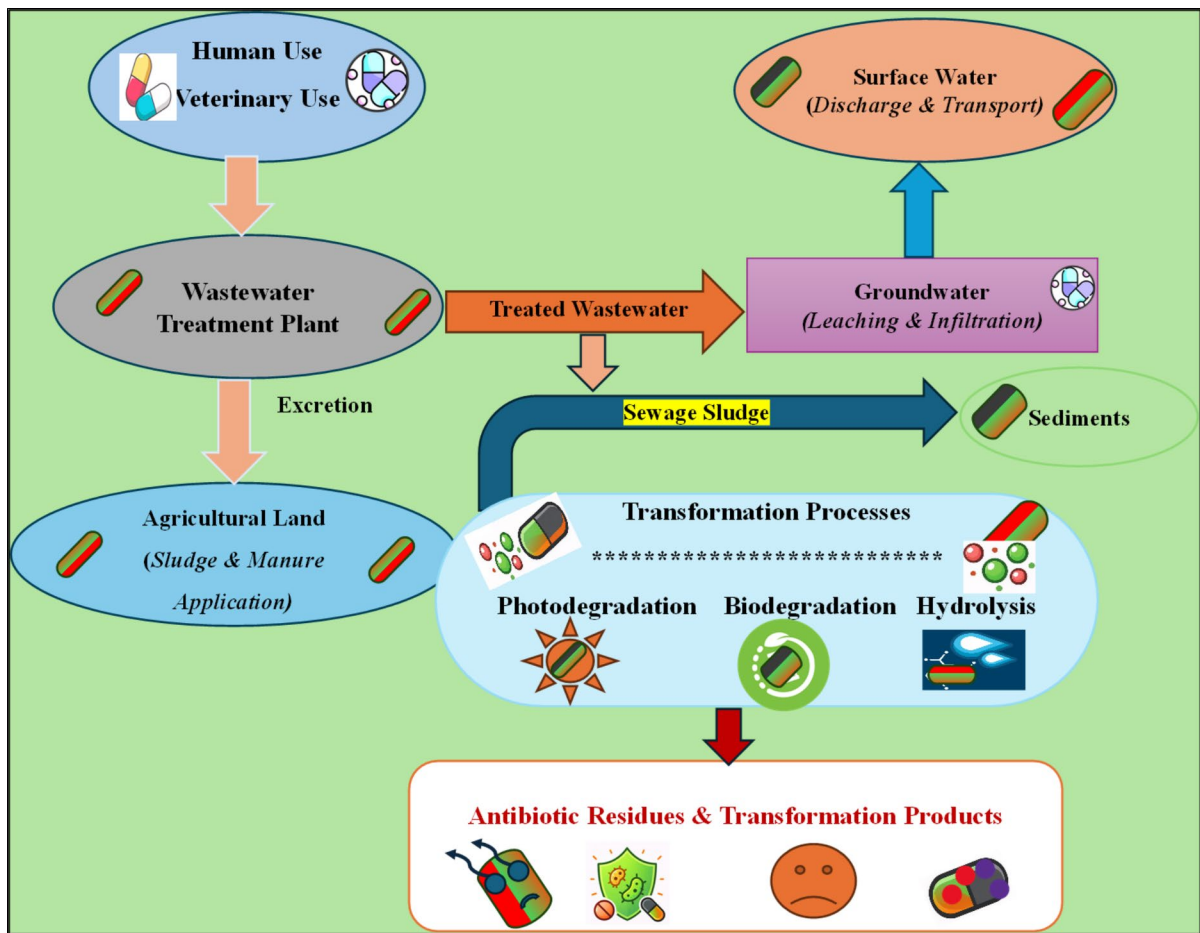


Fig. 3 Pathway and environment distribution of antibiotic residues

or during storms, which keeps exposure going even when water concentrations change (Miao et al., 2025; Zhang et al., 2023). When antibiotics enter natural systems, they can break down through photolysis, biodegradation, and hydrolysis. However, these processes are often slow, depend on the specific compound, and are strongly influenced by environmental factors such as sunlight, temperature, redox conditions, the microbial community, and water chemistry (Miao et al., 2025; Thakur et al., 2025). It is important to note that breaking down antibiotics does not always make them harmless. Partial breakdown can create new products that may last, stay active, or have different toxicity and movement compared to the original compound. Because of this, antibiotics in the environment are better described as being redistributed among water, sediment, and living organisms, and turned into various by-products, rather than being

completely removed. This helps explain why traces of antibiotics can remain in rivers, sediments, and groundwater affected by wastewater for long periods (Abou-Jaoudeh et al., 2024; Zhang et al., 2024c).

Impacts of antibiotics

Antibiotic pollutants are recognized as emerging contaminants because they can impact ecosystems and human health even at low concentrations (Galvano et al., 2025; Thakur et al., 2025; Tiseo et al., 2020). In water and soil environments, antibiotic pollutants can disrupt local microbial communities, reduce the number of sensitive microorganisms, and help resistant strains grow (Holmes et al., 2016). Besides, antibiotic pollutants often co-occur with other pharmaceuticals and organic and inorganic

compounds, further increasing their negative impact on the ecosystem. In particular, they contribute to ecological stress by producing mixture effects and improving persistence and transfer into sludge, sediments, and soils (Darby et al., 2023; Galgano et al., 2025; Huang et al., 2026; Kawsar et al., 2026; Thakur et al., 2025).

One of the most serious issues associated with antibiotic pollution is the increasing spread of antibiotic-resistant bacteria and antibiotic resistance genes, linking environmental contamination to human health (Akhter et al., 2024; Savin et al., 2021; Tiwari et al., 2025). The mechanisms for the spread of antibiotic-resistant bacteria and antibiotic resistance genes have been widely proposed in previous studies (Darby et al., 2023; Galgano et al., 2025; Holmes et al., 2016; Kawsar et al., 2026; Thakur et al., 2025). The spread of antibiotic-resistant bacteria and antibiotic resistance genes occurs due to the selective pressure exerted by residual antibiotics. These bacteria and genes disseminate rapidly through various mechanisms of genetic material exchange, particularly in environments with frequent antibiotic exposure. They persist and are transported through wastewater, rainwater runoff, reclaimed water used for irrigation, and food chains, enabling prolonged environmental presence and increasing the likelihood of human exposure (Darby et al., 2023; Galgano et al., 2025; Holmes et al., 2016; Tiseo et al., 2020).

In detail, places like wastewater treatment plants, rivers below effluent outfalls, sediments, and farm soils treated with sludge or manure often provide favorable conditions for the development of resistant bacteria (Matubber et al., 2025; Ogunlaja et al., 2022). When bacteria are often exposed to small amounts of antibiotics, those that can survive will thrive. Over time, these resistant strains become more prevalent than other strains (Izah et al., 2025; Savin et al., 2021; Tiwari et al., 2025). In addition, resistance genes can move between microbes by gene transfer, which makes them spread for long periods to different species and environments (Akhter et al., 2024; Savin et al., 2021; Tiwari et al., 2025). Resistant bacteria from the environment can re-enter the human body through the food chains and drinking water (Behere et al., 2025; Merhi et al., 2023). When these resistance traits transfer to humans, they reduce the effectiveness of the main antibiotics, increase healthcare costs, and increase mortality (Izah et al.,

2025). Moreover, the presence of antibiotic residues and transformation products in water sources also raises concerns about global public health (Izah et al., 2025; Okeke et al., 2025; Rodriguez-Mozaz et al., 2020). Figure 4 shows that when antibiotic residues enter water and soil, they disrupt natural microbial communities. Therefore, antibiotic resistance can reduce biodiversity and nutrient cycling. They also harm aquatic and soil organisms, which further impacts humans through the food chain. One major concern is that antibiotic-resistant bacteria can persist in the environment, turning rivers, sediments, and soils into long-term sources of resistance (Abou-Jaoudeh et al., 2024; Okeke et al., 2025).

Figure 4 also displays several direct and indirect risks to human health from antibiotic pollution (Akhter et al., 2024; Behere et al., 2025; Izah et al., 2025). Ongoing exposure to antibiotic residues and resistant microorganisms raises the chances of antibiotic-resistant infections, which are harder and more expensive to treat. The movement of resistance genes from environmental bacteria to human pathogens, facilitated by horizontal gene transfer, is a major concern because it can reduce the effectiveness of current antibiotics (Okeke et al., 2025; Zhong et al., 2022).

Therefore, evaluating and managing antibiotic pollutants should focus on reducing exposure routes (contaminated drinking-water sources, water reuse and irrigation, aquaculture, and food chains), controlling the original pollutants and their transformation products, and monitoring microbial functional indicators (Galgano et al., 2025; Patel et al., 2019; Thakur et al., 2025; Tiseo et al., 2020; Watkinson et al., 2007).

Methods used to remove antibiotic residues

Conventional wastewater treatment methods are widely used in municipal and industrial plants and effectively reduce organic matter, nutrients, and pathogens. However, these systems were not designed to remove trace-level micropollutants such as antibiotics, resulting in limited and inconsistent removal. Biological treatment, physical separation, and chemical oxidation each offer specific removal methods but have limitations when addressing antibiotics in wastewater (Alsaeedi et al., 2025; Hamid & Khanday, 2026; Lyu et al., 2026; Niu et al., 2024; Peng et al.,

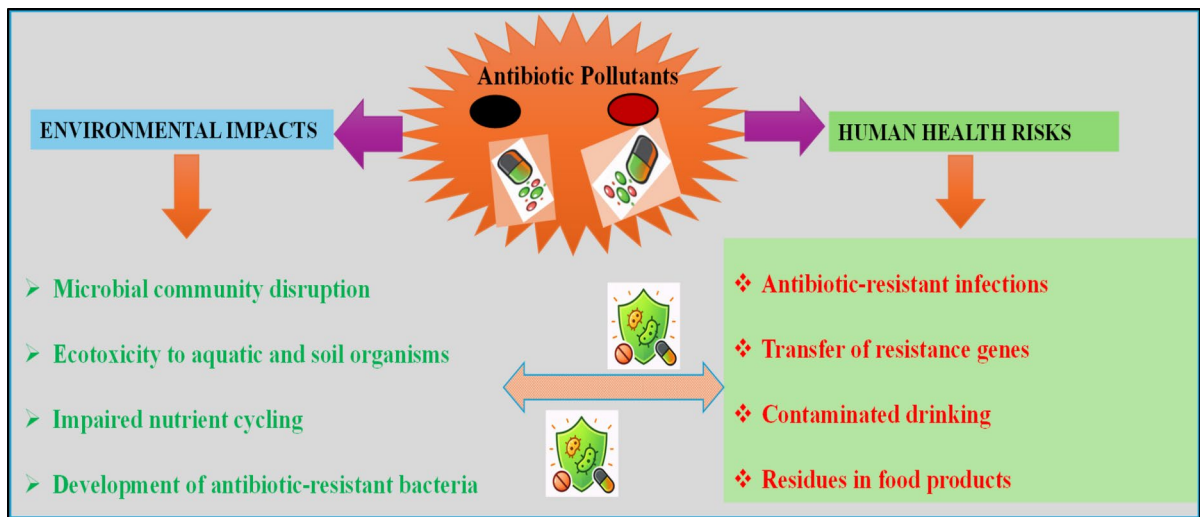


Fig. 4 Impact of antibiotic pollutants on humans and the environment

2024). Biological treatment methods like activated sludge, trickling filters, and nutrient removal systems use microbes to break down organic pollutants. Physical separation processes, including sedimentation, filtration, and membrane-based technologies, remove antibiotics primarily through adsorption onto suspended solids or by size exclusion (Hamid & Khanday, 2026). Primary and secondary clarifiers partially eliminate antibiotics that bind to particulates, such as tetracyclines and fluoroquinolones. Membrane fouling, high operational costs, and concentrated waste streams also challenge large-scale use, especially in resource-limited settings (Li et al., 2023; Niu et al., 2024; Sompornpailin et al., 2024; Yu et al., 2024; Zhang et al., 2024d). Chemical oxidation methods, such as chlorination and ozonation can degrade or alter certain antibiotics. These methods work well for disinfection and reducing some contaminants, but many antibiotics resist mild oxidants under normal conditions. Chlorination can produce by-products that retain biological effects or may be more toxic. Ozonation is more effective at removing antibiotics but consumes substantial energy and requires careful management to avoid the formation of harmful by-products (2024d; Zhang et al., 2024c). The success of chemical oxidation also depends on factors such as wastewater complexity, pH, and the amount of other organic material present (Farkas et al., 2024; Hamid & Khanday, 2026; Zheng et al., 2023). Limitations of conventional wastewater treatment have driven research into advanced technologies that more

effectively remove antibiotic residues from complex water sources. These methods seek to improve removal efficiency, minimize secondary pollution, reduce antimicrobial activity, and enhance sustainability. Adsorption-based methods and advanced oxidation processes are among the most promising strategies (Gahrouei et al., 2024; Stylianou et al., 2021). This study evaluates the effectiveness of adsorption-based methods and AOPs, their applicability, and their principal limitations. The main goal is to find effective ways to lower antibiotic levels, reduce the risk of resistance, and protect both the environment and public health (Hamid & Khanday, 2026).

Adsorption process

Benefits and limitations

Adsorption is a common method for removing a wide range of water contaminants. It works for both inorganic substances, such as heavy metals, phosphates, nitrates, and organic micropollutants, including pharmaceuticals, dyes, pesticides, and antibiotic residues. In this process, dissolved pollutants attach to the adsorbent surface, enter its micropores, or bind to its active sites. This transfers contaminants from water to a solid medium, which can then be separated and treated (Wang et al., 2025). Adsorption is also effective for many antibiotics and for water sources. It removes a wide range of compounds and can be added to existing treatment systems to help manage changes

in incoming water quality and sudden increases in contaminants (Alsaedi et al., 2025; Hamid & Khanday, 2026; Wang et al., 2024b). Another important advantage is that adsorption can be adjusted to remove specific substances. By modifying the surface chemistry, such as by adding $-\text{COOH}$, $-\text{OH}$, $-\text{NH}_2$, sulfonic groups, or metal-binding sites, it is possible to direct adsorption toward specific antibiotics in complex mixtures (Hamid & Khanday, 2026; Wang et al., 2024b). However, it still has various limitations, particularly regarding antibiotic risk mitigation. Adsorption only transforms pollutants from the liquid to the solid phase and does not destroy antibiotic molecules. As a result, the toxicity and biological activity of the antibiotics remain (Alsaedi et al., 2025). Improper regeneration or disposal of the adsorbent can allow antibiotics to desorb and re-enter the environment (Hamid & Khanday, 2026). Advanced adsorbents such as carbon nanotubes, graphene oxide, and metal–organic framework-based materials have high processing costs, which limit their practicality for treating large volumes of wastewater. Even lower-cost alternatives like biochar, agricultural waste-derived carbons, and clays can pose challenges, including inconsistent performance and sensitivity to water composition (Wang et al., 2024b; Xiang et al., 2020). Third, adsorbents need to be regenerated using thermal, chemical, solvent-based, or electrochemical methods, or they must be safely disposed. This

step is important for sorbents containing antibiotics, as incomplete regeneration or improper disposal can lead to toxicity and the re-release of pollutants (Wang et al., 2024b). The advantages and disadvantages of the adsorption process are shown in Fig. 5. As discussed earlier, adsorption is a strong option for controlling antibiotic pollutants because it is simple, adaptable, and effective for removing trace organics, particularly as a final step in standard treatment systems. Still, its main drawback is clear: adsorption mainly moves pollutants rather than breaking them down (Wang et al., 2024b; Yeo et al., 2025).

Removal of antibiotic pollutants using adsorption process

Various adsorbents have been studied for removing antibiotic pollutants from water, highlighting the urgent issue of antibiotic contamination in water and wastewater (Mahdavi et al., 2025; Wang et al., 2024b). These materials include traditional carbon-based sorbents and advanced porous frameworks, such as granular activated carbon (GAC), Fe-MCM-41 molecular sieves, biochar from organic waste, iron-modified biochar, bentonite–alginate composites, mesoporous silica, and metal–organic framework (Chen et al., 2025b; Wang et al., 2024b; Xiang et al., 2020; Yang et al., 2025; Yeo et al., 2025; Zhang et al., 2025a). Together, the adsorbents offer different

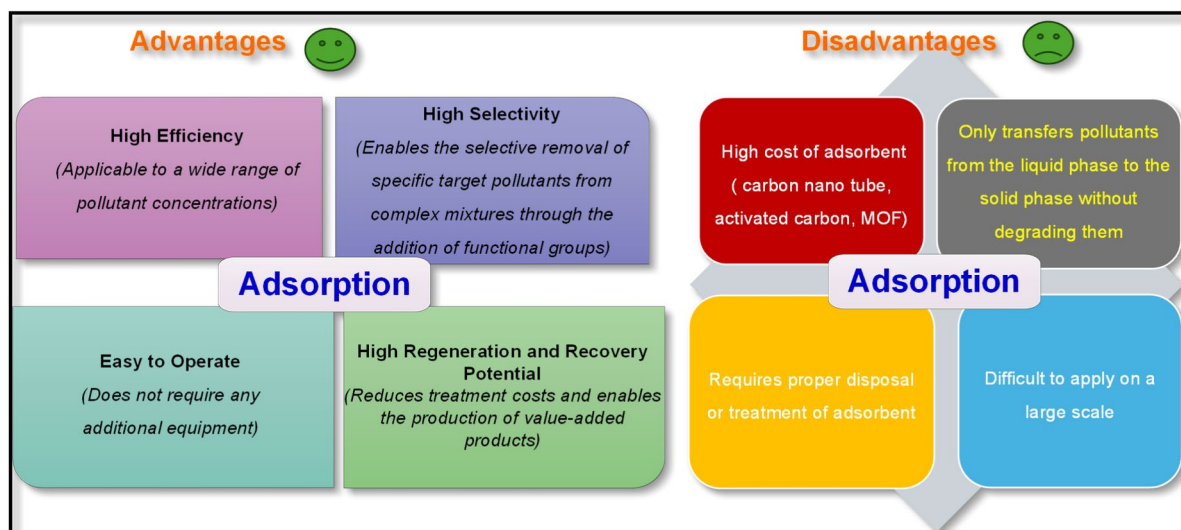


Fig. 5 Advantages and disadvantages of adsorption process

ways to remove antibiotics by combining large surface areas and pore spaces with adjustable surface chemistry, such as electrostatic attraction, hydrogen bonding, π - π interactions, and surface complexation (Chen et al., 2025b; Vamsi et al., 2024; Yang et al., 2025). Table 2 summarizes key adsorbents and their performance for the removal of different types of antibiotic pollutants (Gao et al., 2019; Hao et al., 2021; Khanday et al., 2025; Li et al., 2018). The adsorption of antibiotic pollutants depends on the interaction between adsorbent properties and antibiotic characteristics. For the adsorbent, factors such as surface area and pore structure affect the number of available adsorption sites and their accessibility. Surface charge and the surface functional groups influence the strength of electrostatic forces, hydrogen bonds, and surface complexation. For the antibiotic, important factors include its size, aromaticity, polarity, and acid-base behavior (as determined by pKa). These properties determine the form of the antibiotic at specific pH levels and its ability to enter pores and bind to active sites (Rana et al., 2025; Vamsi et al., 2024; Xiang et al., 2020; Yang et al., 2025; Yeo et al., 2025; Zhang et al., 2025a). Table 2 shows that adsorption has been studied for many types of antibiotics, including tetracyclines (tetracycline, doxycycline), β -lactams (amoxicillin, cefixime), fluoroquinolones (ciprofloxacin, norfloxacin, ofloxacin), sulfonamides (sulfamethoxazole), nitroimidazoles (ornidazole, metronidazole), and other residues. The variability in reported adsorption capacities indicates that this process depends on multiple interactions, which are influenced by the type of adsorbent and the properties of the water or wastewater (Wang et al., 2024b; Zhang et al., 2025a). Several high-performing materials show how careful adsorbent design can greatly improve uptake. For example, magnetic Ni@ZIF-8 has very high adsorption capacities for tetracycline (770.2 mg g⁻¹) and cefixime (428.2 mg g⁻¹). This is due to its porous structure, which offers many sites for adsorption, and its surface chemistry, which allows strong binding. The magnetic property also makes it easier to separate and reuse. Acid-modified chitosan also performs well, with a high capacity for doxycycline (295.43 mg g⁻¹). This is because it has more sites that can interact with antibiotics and form stronger hydrogen bonds and electrostatic interactions. Carbon-based materials are also effective. Cotton-based activated carbon and iron-modified sludge

biochar have high tetracycline adsorption capacities (824 and 386.9 mg g⁻¹, respectively). This shows the value of a well-developed pore network and surface features, as well as extra interactions in metal-modified biochar. Similarly, biochar made from furfural residue binds well to norfloxacin (299.6 mg g⁻¹). Its aromatic domains and oxygen groups help bind fluoroquinolones via π - π interactions, hydrogen bonding, and electrostatic interactions (Chen et al., 2025b; Wang et al., 2024b; Xiang et al., 2020; Yeo et al., 2025). At the same time, sustainable adsorbents, including buckwheat hull biochar, bentonite-alginate composites, sludge biochar, iron/zinc- and phosphoric acid-modified sludge biochar, activated magnetic biochar, and hazelnut shell biochar, typically achieve moderate but meaningful capacities of about 50–100 mg g⁻¹. While these values are lower than those of advanced frameworks, these sorbents are often preferred for real-world applications due to their low-cost materials, simpler production methods, and scalability. In treating antibiotic-contaminated wastewater, the balance between maximum capacity and practical or economic considerations is often the deciding factor.

It also reveals that surface functional groups play a major role in the removal performance of antibiotic pollutants. Groups with oxygen and nitrogen, such as -OH, -COOH, -NH₂, and metal sites like Fe, Ni, or Zn, help form strong bonds through hydrogen bonding and complexation (Chen et al., 2025b; Minale et al., 2021; Vamsi et al., 2024; Yang et al., 2024; Yeo et al., 2025; Zhang et al., 2025b). This is most important for antibiotics with multiple heteroatoms, which are common in tetracyclines and fluoroquinolones. To enhance performance, researchers often incorporate functional groups into the surface or design composites. Methods include acid or alkali treatment to introduce more oxygen-containing groups, metal addition to create coordination sites, or the use of porous materials, such as MOFs or mesoporous silica, to increase the number of active sites (Zhang et al., 2025b).

Adsorption mechanisms

The adsorption of antibiotic pollutants onto solid sorbents involves multiple interaction pathways, as shown in Fig. 6. Antibiotics are captured through π - π interactions, hydrogen bonding, electrostatic

Table 2 Adsorption of antibiotic pollutants using various adsorbents

Adsorbent	Antibiotic pollutants	Adsorption capacity (mg g ⁻¹)	References
Cotton-based activated carbon	tetracycline hydrochloride	824	Chen et al. (2025b)
Iron-modified municipal sludge biochar	Tetracycline	386.9	Ma et al. (2019)
Chicken bone biochar	Tetracycline	98.9	Oladipo and Ifebajo (2018)
Pine sawdust biochar	Tetracycline hydrochloride	177.7	Liang et al. (2019)
Hazelnut shell biochar	Oxytetracycline	52.7	Hao et al. (2021)
zero-valent iron@hazelnut shell biochar	Chlortetracycline	42.5	Hao et al. (2021)
Date brown waste biochar/zerovalent iron	Chlortetracycline	89.1	Ahmad et al. (2019)
Iron loaded sludge biochar	Doxycycline	129.0	Wei et al. (2019)
CuZnFe ₂ O ₄ -biochar composite	Sulfamethoxazole	212.8	Heo et al. (2019)
magnetic biochar	Sulfamethoxazole	20	Reguyal and Sarmah (2018)
Activated magnetic biochar	Norfloxacin	7.25	Wang et al. (2017)
Magnetic biochar-based manganese oxide composite	Norfloxacin	6.94	Li et al. (2018)
Magnetic biochar-based manganese oxide composite	Ciprofloxacin	8.37	Li et al. (2018)
Magnetic biochar-based manganese oxide composite	Enrofloxacin	7.19	Li et al. (2018)
magnetic biochar derived from furfural residue	Norfloxacin	299.6	Li et al. (2019)
Iron/zinc and phosphoric acid modified sludge biochar	Ciprofloxacin	83.7	Ma et al. (2020)
Iron/zinc and phosphoric acid modified sludge biochar	Norfloxacin	39.3	Ma et al. (2020)
Iron/zinc and phosphoric acid modified sludge biochar	Ofloxacin	25.4	Ma et al. (2020)
manganese ferrite modified biochar	Pefloxacin	253	Xiang et al. (2020)
manganese ferrite modified biochar	Ciprofloxacin	133	Xiang et al. (2020)
sludge biochar	Tylosin	58	Cai et al. (2020)
Magnetic Ni@ZIF-8 composite	Tetracycline	770.2	Zhang et al. (2025a)
Magnetic Ni@ZIF-8 composite	Cefixime	428.2	Zhang et al. (2025a)
Phosphoric acid-impregnated chitosan	Amoxicillin	229.82	Khanday et al. (2025)
Phosphoric acid-impregnated chitosan	Doxycycline	295.43	Khanday et al. (2025)
Bentonite-alginate composite	Amoxicillin	42.32	Yeo et al. (2025)
Bentonite-alginate composite	Ampicillin	59.93	Yeo et al. (2025)
SBA-15-modified with polyaniline	Amoxicillin	34.2	Pandey et al. (2021)
Amino functional SBA-15 assisted NU-1000	Tetracycline	424	Yang et al. (2024)
Amino-Fe(III) functionalized mesoporous silica	Tetracycline	53.9	Zhang et al. (2015)
Cu-based hydrochar	Tetracycline	291.2	Zhang et al. (2025b)
buckwheat hull biochar	Metronidazole	29.56	Zhang et al. (2025c)
buckwheat hull biochar	Tinidazole	27.90	Zhang et al. (2025c)
buckwheat hull biochar	Ornidazole	27.97	Zhang et al. (2025c)
Activated carbon fiber	Metronidazole	2.03	Gao et al. (2019)
Soybean hulls biochar	Metronidazole	34.24	Schneider et al. (2024)
MIL-53(al)-NDC-MOF	Tinidazole	149	Li et al. (2022)

attraction or repulsion, pore filling, and surface complexation or chelation. In practice, both physisorption (including van der Waals forces, pore filling, and π - π stacking) and chemisorption (complexation with functional groups or metal sites) contribute to

the transfer of antibiotics from the aqueous phase to the adsorbent surface (Ahmad et al., 2019; Schneider et al., 2024; Wang et al., 2024b; Wei et al., 2019; Zhang et al., 2025b, 2025c).

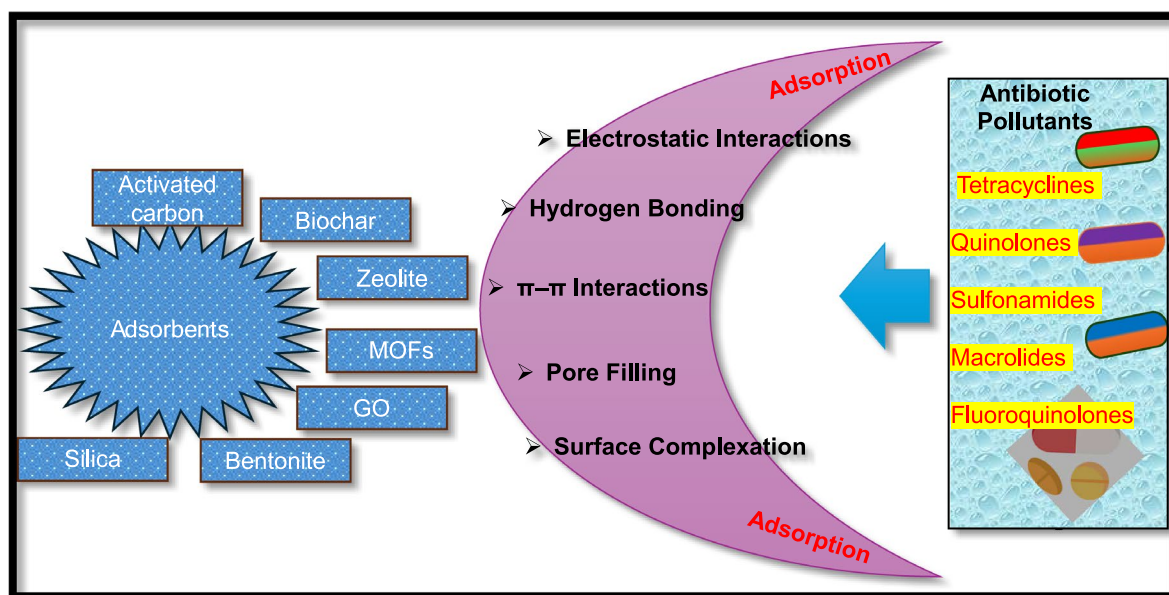


Fig. 6 Adsorption mechanism of antibiotic pollutants

Adsorption removes antibiotic molecules from water by trapping them on a solid material, which reduces pollutant concentration and limits environmental exposure (Chen et al., 2025b; Wang et al., 2024b; Xiang et al., 2020; Yang et al., 2025). When the adsorbent is added to contaminated water, antibiotic molecules move from the water to the surface of the adsorbent, enter its pores, and are held there by the interaction mechanisms shown in Fig. 5 (Chen et al., 2025b; Liang et al., 2019; Ma et al., 2019; Wang et al., 2025; Yeo et al., 2025). Removal efficiency depends on the physicochemical properties of the adsorbent, such as surface area, pore structure, and surface chemistry, as well as the characteristics of the antibiotic compounds.

Each adsorption pathway operates optimally under specific conditions. As a result, the same antibiotic may behave differently on various materials, and factors such as pH can significantly influence performance. Electrostatic adsorption happens when the surface charge of the adsorbent is opposite to the net charge of the pollutant (Chen et al., 2025b; Vamsi et al., 2024; Yang et al., 2024, 2025; Yeo et al., 2025; Zhang et al., 2025b). Since many antibiotics change charge with pH, shifting between cationic and anionic forms, the interaction can alternate between attraction and repulsion (Minale et al., 2021; Yang et al., 2024).

Moreover, adsorption through complexation or chemisorption becomes stronger when the adsorbent has functional groups like $-\text{COOH}$, $-\text{OH}$, or $-\text{NH}_2$, or metal sites that can coordinate with heteroatoms in antibiotics, such as oxygen or nitrogen. This leads to more stable inner-sphere interactions. π - π interactions are strongest for antibiotics with aromatic rings, which are common in fluoroquinolones and sulfonamides, when the adsorbent has graphitic or conjugated domains. Hydrogen bonding is particularly important in materials with numerous polar functional groups (Khanday et al., 2025; Minale et al., 2021; Wang et al., 2025; Yang et al., 2024). Based on the mechanisms described above, we can design and develop next-generation adsorbents for antibiotic control (Vamsi et al., 2024; Zhang et al., 2025b, 2025c). To achieve high adsorption capacity, it is important to use porous materials that support easy diffusion and pore filling, along with suitable surfaces that increase electrostatic attraction, hydrogen bonding, and complexation (Chen et al., 2025b; Wang et al., 2024b; Yang et al., 2025).

Removal of antibiotic pollutants using advanced oxidation processes

Unlike adsorption, which transfers antibiotics from water to a solid surface, advanced oxidation processes (AOPs) chemically transform antibiotic pollutants. AOPs achieve deep oxidation and mineralization, making them a modern and effective alternative or supplement to traditional wastewater treatments (García et al., 2020; Hamid & Khanday, 2026; Niu et al., 2024). They are particularly valuable for antibiotics that are persistent and contribute to antimicrobial resistance. The main advantage of AOPs is that they degrade antibiotic molecules, reduce their bioactivity, and convert organic carbon into harmless products such as CO_2 , H_2O , and inorganic ions (Farkas et al., 2024; Niu et al., 2024). As shown in Fig. 7, AOPs share a key feature: they use a precursor or activation step to create highly reactive species, including hydroxyl radicals ($\cdot\text{OH}$), sulfate radicals ($\text{SO}_4^{\cdot-}$), singlet oxygen ($^1\text{O}_2$), superoxide anion radicals ($\text{O}_2^{\cdot-}$), and ferryl ions (FeO_2^+) to oxidize

antibiotic molecules (Hamid & Khanday, 2026; Niu et al., 2024). These radicals target electron-rich sites in antibiotics, such as aromatic rings, heterocycles, double bonds, and nitrogen- or sulfur-containing groups. This process breaks open rings, cleaves chains, and gradually oxidizes molecules into smaller fragments. In practice, AOPs change antibiotics from difficult-to-remove micropollutants into products that are easier to break down or fully mineralized, making proper detoxification rather than simple removal from water. The formation rate, steady-state concentration, and lifetime of radicals are critical to the effectiveness of AOPs. Antibiotic degradation depends on kinetics: radicals are continuously generated but are rapidly consumed by reactions with antibiotics, organic matter, inorganic scavengers such as bicarbonate and chloride, and process activators (Hamid & Khanday, 2026; Niu et al., 2024). Systems that maintain a higher radical flux by optimizing precursor dosage, employing effective activation methods like UV light or catalysts, and minimizing scavenging typically achieve faster degradation and improved

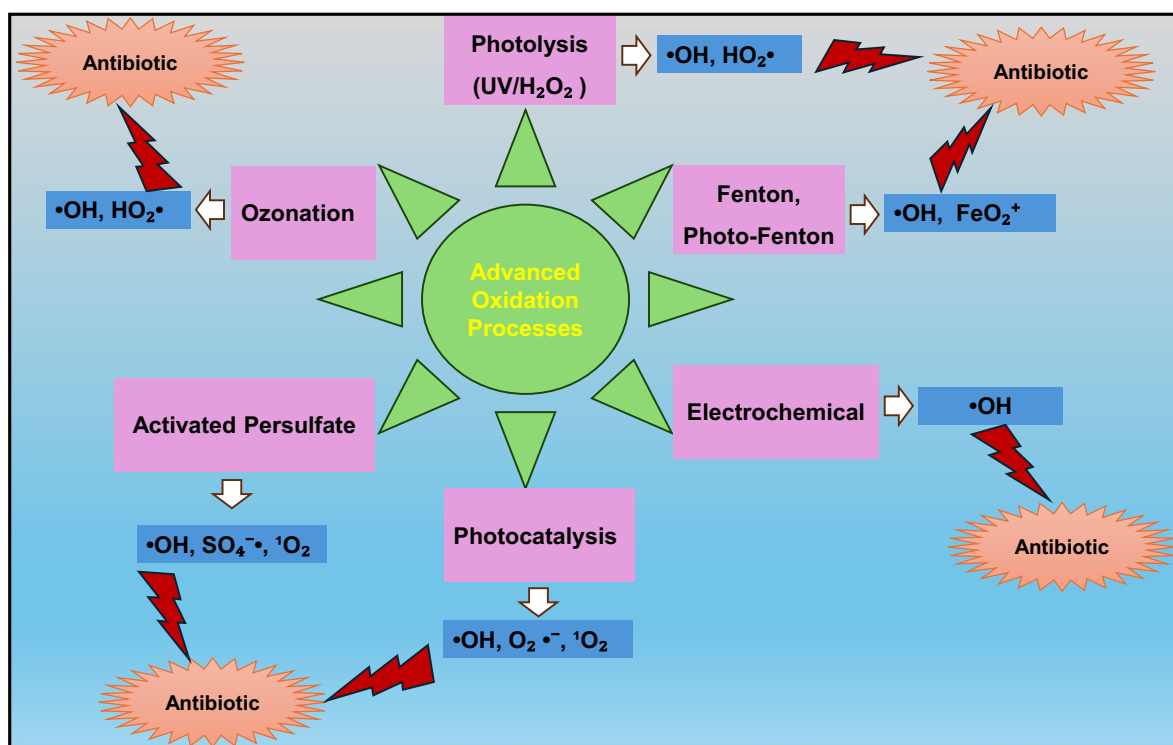


Fig. 7 Removal of antibiotic pollutants using advanced oxidation processes

mineralization. Therefore, AOP design prioritizes maximizing radical production and directing their reactions toward antibiotics rather than side reactions. When conditions are optimized, AOPs can achieve mineralization, fully breaking down antibiotics into harmless inorganic substances rather than merely transforming the parent compound. AOPs include several groups that all use radicals, but they differ in how these radicals are made. Common types are UV/ H_2O_2 , ozonation, Fenton and photo-Fenton systems ($\text{Fe}^{2+}/\text{H}_2\text{O}_2$), persulfate ($\text{SO}_4^{\cdot-}$), photocatalysis (TiO_2 , g- C_3N_4), and electrochemical (Chin et al., 2023; Dong et al., 2016; Li et al., 2023; Ma et al., 2023; Niu et al., 2024; Zhu et al., 2022). In each case, the process starts with a precursor like H_2O_2 , O_3 , persulfate/PMS, dissolved oxygen, or a catalyst-bound oxidizer, and the way this precursor is activated decides which radicals are most important. This is important for treating antibiotics because different radicals react

in different ways: $\cdot\text{OH}$ is generally very reactive, $\text{SO}_4^{\cdot-}$ can work better in certain ionic conditions and pH levels, and IO_2 may play a role in systems with catalysts or sensitizers. Choosing the right AOP for the specific water and antibiotics often makes the difference between only partial breakdown and complete mineralization.

Advantages and disadvantages of AOPs

Table 3 summarizes the benefits and drawbacks of AOPs for the removal of antibiotic pollutants. It describes how each method works and highlights their main disadvantages and practical limits, as reported in the literature (Gahrouei et al., 2024; Krishnan et al., 2023; Raj et al., 2021; Zhang et al., 2022, 2024a). AOPs offer significant advantages over adsorption, as they chemically degrade antibiotics rather than merely transferring them to another phase.

Table 3 Benefits and limitations of AOPs for antibiotic pollutant removal

Method	Benefits	Limitations
Photolysis (UV/ H_2O_2)	Effective degradation: Wide range of antibiotic pollutants No sludge formation Simple operation Easy to implement with (UV lamp + H_2O_2)	High energy demand: UV light High H_2O_2 Consumption: Requires hydrogen peroxide UV lamps degrade over time and need replacement to maintain efficiency Non-recovery H_2O_2
Fenton	High efficiency in $\cdot\text{OH}$ radical generation Cost-effective reagents (Fe^{2+} and H_2O_2) Simple and fast reaction	Requires acidic pH Generates iron sludge Limited regeneration of Fe^{2+}
Photo-Fenton	Enhanced $\cdot\text{OH}$ production using light (UV/solar) Faster degradation Reuses Fe^{3+} via photoreduction	Requires light source (infrastructure or sunlight) Produces iron sludge Higher operational costs than Fenton
Electrochemical	Precise control of radical generation No need for external chemicals Effective for wide range of pollutants	High energy consumption Electrode fouling and degradation over time Expensive electrode materials Limited scalability for large volumes
Photocatalysis	Utilizes solar or UV light (eco-friendly and energy-saving) Reusable and stable photocatalysts (e.g., TiO_2 , ZnO) Effective against persistent and low-concentration pollutants Produces minimal secondary pollution	Recombination of charge carriers reduce efficiency Poor light penetration in real wastewater Catalyst recovery and reuse can be challenging Require light, increasing energy cost
Activated persulfate	Generates strong oxidants ($\text{SO}_4^{\cdot-}$ and $\cdot\text{OH}$) Effective over a wide pH range Long-lived radicals for deeper oxidation Suitable for degrading a broad spectrum of antibiotics	Requires activation (heat, UV, transition metals, or base) Potential toxicity from by-products or sulfate residues High chemical cost (persulfate salts) May need post-treatment to remove residuals
Ozonation	Strong oxidizing power (O_3 and $\cdot\text{OH}$) Fast reaction kinetics with many antibiotics No chemical additives required No sludge generation	High cost of ozone Short ozone half-life; must be generated on-site Reduced efficiency in turbid or organic-rich water Potential formation of toxic by-products

Most AOPs act quickly, remain effective at low pollutant concentrations, and fully break down antibiotic molecules into less harmful or mineralized products. As a result, they are a more effective solution for reducing long-term environmental and health risks.

AOPs can help reduce secondary waste management and lower the risk of transferring pollution to other environmental compartments. The main exception is photo-Fenton systems, which produce iron hydroxide precipitate. In addition, AOPs use highly reactive radicals to break down antibiotic molecules, minimizing pollutant accumulation and uncontrolled release, which are common concerns in sorption-based methods. It also indicates that no single AOP performs best in all situations. However, each method has limitations that can make it difficult to apply on a large scale or for long-term use.

For example, photolysis-based systems, such as UV/H₂O₂, require ultraviolet light, which results in high costs for equipment, energy, and maintenance. In addition, hydrogen peroxide cannot be recovered or reused cost-effectively, and excessive use can increase costs or reduce efficiency (Dong et al., 2016; Farkas et al., 2024; Hamid & Khanday, 2026; Li et al., 2023; Ormeño-Cano & Radjenovic, 2024; Zhang et al., 2024d). Similarly, the electrochemical method requires a constant electrical supply to produce oxidizing species at the electrode surface. The systems allow precise control and on-demand oxidant production, but they often face challenges like high energy use and expensive electrode materials, especially when noble or stable anodes are needed for long-term use (Ormeño-Cano & Radjenovic, 2024; Zhang et al., 2022).

Selecting an AOP should fit with both the wastewater type and treatment objectives. Key factors such as antibiotic concentration, water composition, flow rate, available energy, and required mineralization influence the optimal choice. Rather than viewing these methods as competitors, recent evidence supports a context-specific or hybrid approach. This strategy leverages the strengths of each AOP while minimizing the limitations through combination or process enhancement (Farkas et al., 2024; Hamid & Khanday, 2026). By comparing advantages such as rapid degradation, high efficiency, low sludge production, and reduced secondary pollution with limitations like energy demand, chemical consumption, and activation requirements, researchers and practitioners

can select or combine advanced oxidation processes that best support effective, sustainable, and scalable removal of antibiotic residues from various wastewater systems (Hamid & Khanday, 2026).

Removal of antibiotic pollutants using AOPs

Table 4 summarizes case studies demonstrating the use of AOPs to remove common antibiotics from wastewater. The findings highlight current technologies and their limitations in practical applications. However, degradation performance depends strongly on oxidant activation, catalyst or electrode design, antibiotic type, and specific wastewater conditions (Farkas et al., 2024; Hamid & Khanday, 2026; Zheng et al., 2023).

The results in Table 4 show excellent removal performance of antibiotic pollutants by electrochemical oxidation. For example, an electrochemical system with an S-graphene sponge electrode removed 99.2% ofloxacin, 94.4% sulfamethoxazole, 95.9% erythromycin, and 92% roxithromycin. These results indicate that electrochemical AOPs generate reactive species directly at the electrode, enabling efficient oxidation across various antibiotics. The Ti/BTNAs electrode also achieved 86% removal of berberine hydrochloride. These findings suggest that electrode development can extend electrochemical treatment to a range of organic pollutants. Ozonation has been widely studied for antibiotics such as tetracycline, amoxicillin, sulfamethoxazole, ciprofloxacin, and chloramphenicol, with reported ozone-only efficiencies ranging from 20 to 55%. The results indicate that direct ozonation is less effective for removing antibiotic pollutant (Ahmadipour et al., 2024; Farkas et al., 2024; Hamid & Khanday, 2026; Ormeño-Cano & Radjenovic, 2024; Rodríguez-López et al., 2024; Siddhardhan et al., 2024; Zhang et al., 2024c, 2024d; Zheng et al., 2023). To improve the removal performance of antibiotic contaminants, several hybrid systems have been developed, such as O₃/PMS, activated carbon/O₃ (AC/O₃), silicate ore/O₃, Fe₃O₄/O₃, Fe₃O₄/Co₃O₄/O₃, and (Mn_xO_y/γ-Fe₂O₃)/O₃. Among them, Fe₃O₄/Co₃O₄/O₃ and (Mn_xO_y/γ-Fe₂O₃)/O₃ can completely remove sulfamethoxazole and sulfamethazine. The results show that catalytic ozonation enhances ozone utilization and increases radical generation. For example, Co-silicate ore/O₃ achieved 93.2% removal of tetracycline, while AC/O₃ degraded 85% of penicillin G,

Table 4 Degradation performance of antibiotic pollutants using advanced oxidation processes

Method	Antibiotic	Performance (%)	References
S-graphene sponge electrode	Ofloxacin	99.2	Ormeño-Cano and Radjenovic (2024)
S-graphene sponge electrode	Sulfamethoxazole	94.4	Ormeño-Cano and Radjenovic (2024)
S-graphene sponge electrode	Erythromycin	95.9	Ormeño-Cano and Radjenovic (2024)
S-graphene sponge electrode	Roxithromycin	92.0	Ormeño-Cano and Radjenovic (2024)
S-graphene sponge electrode	Trimethoprim	87.2	Ormeño-Cano and Radjenovic (2024)
Ti/BTNAs-electrochemical	Berberine hydrochloride	86	Li et al. (2024)
Fe ₃ O ₄ /ozonation	Sulfamethoxazole	85	Yin et al. (2016)
Fe ₃ O ₄ /Co ₃ O ₄ /Ozonation	Sulfamethoxazole	100	Chen and Wang (2019)
(MnxOy/γ-Fe ₂ O ₃)/Ozonation	Sulfamethazine	100	Liu et al. (2021)
Ozonation	Penicillin G	33.6	Hekmatshoar et al. (2022)
AC/ozonation	Penicillin G	85	Hekmatshoar et al. (2022)
Co-silicate ore/O ₃	Tetracycline hydrochloride	93.2	Luo et al. (2018)
Silicate ore/O ₃	Tetracycline hydrochloride	69.3	Luo et al. (2018)
Ozonation	Tetracycline hydrochloride	46.0	Luo et al. (2018)
Ozonation	Tetracycline, Amoxicillin, Sulfamethoxazole, Ciprofloxacin, Chloramphenicol	20–55	Zhang et al. (2024d)
O ₃ /PMS	Tetracycline, Amoxicillin, Sulfamethoxazole, Ciprofloxacin, Chloramphenicol	60–85	Zhang et al. (2024d)
CoMoO ₄ /g-C ₃ N ₄	Tetracycline	91.3	Jitae et al. (2025)
CoMoO ₄	Tetracycline	57.9	Jitae et al. (2025)
g-C ₃ N ₄	Tetracycline	68.7	Jitae et al. (2025)
Fe ₃ O ₄ /ZnO photocatalyst/UV light	Tetracycline	100	Panchakeaw et al. (2025)
ZnO/UV light	Tetracycline	74	Panchakeaw et al. (2025)
Fe ₃ O ₄ /UV light	Tetracycline	68	Panchakeaw et al. (2025)
AgCl/ZnO/g-C ₃ N ₄	Tetracycline hydrochloride	90	Ding et al. (2023)
BiVO ₄	Tetracycline	72	Hemavibool et al. (2022)
BiVO ₄	Oxytetracycline	83	Hemavibool et al. (2022)
Pd@Fe ₃ O ₄ /MMT	Tetracycline	84	Hou et al. (2024)
ZnO/N-g-C ₃ N ₄	Tetracycline,	80	Wang et al. (2022)
Cu ₂ O@Fe ₃ O ₄ /PMS	Tetracycline,	97.6	Wang et al. (2024a)
Magnetic Fe ₃ O ₄ -C@MoS ₂ /PMS	Tetracycline	97	Shan et al. (2024)
Fe ₃ O ₄ /g-C ₃ N ₄ /rGO	Tetracycline hydrochloride	86.7	Shan et al. (2023)
I-doped GCN	Tetracycline	99.8	Phoon et al. (2024)
ZnS-CdS/C	Levofloxacin	98.6	Yu et al. (2024)
ZnS-CdS/C	Enrofloxacin	92.1	Yu et al. (2024)
ZnS-CdS/C	Ciprofloxacin	95.4	Yu et al. (2024)
ZnS-CdS/C	Tetracycline	84.0	Yu et al. (2024)
CdZnS/BiOCl	Tetracycline hydrochloride	95	Zhang et al. (2024b)
Porous g-C ₃ N _{5-x} -O/PMS	Sulfamethoxazole	77.3	Huynh et al. (2024)

indicating that catalyst supports can enhance ozonation performance. Moreover, activated persulfate systems generate sulfate radicals with strong oxidizing capacity, which are effective at degrading antibiotic

pollutants. For example, g-C₃N_{5-x}-O/PMS achieved 77.3% degradation of sulfamethoxazole, while magnetic Fe₃O₄-C@MoS₂/PMS removed up to 97% of tetracycline (Feng et al., 2025; Jing et al., 2024; Tao

et al., 2025). However, among AOPs, photocatalysis is the most commonly used and rapidly growing method for antibiotic degradation. This is likely because it is simple, works with many materials, and can use solar energy. Table 4 demonstrates that a wide range of photocatalysts, including metal oxides (ZnO, TiO₂), non-metal semiconductors (g-C₃N₄, rGO), and multi-component composites (such as BiVO₄, ZnO/N-g-C₃N₄, Fe₃O₄/g-C₃N₄/rGO, ZnS–CdS/C, CdZnS/BiOCl), have achieved degradation rates up to 99.8%. For tetracycline, I-doped g-CN reached 99.8%, while CdZnS/BiOCl, CoMoO₄/g-C₃N₄, and AgCl/ZnO/g-C₃N₄ achieved 95%, 91.3%, and 90%, respectively (Ahmadipour et al., 2024; Aldrery et al., 2025; Baldez et al., 2024; Chen et al., 2025a; Chin et al., 2023; Jitae et al., 2025; Ma et al., 2023; senasu et al., 2023; Siddhardhan et al., 2024; Zhu et al., 2022). Conventional materials like ZnO, Fe₃O₄, and BiVO₄ provided lower but still significant removal rates of about 68–72%. These results indicate that catalyst optimization, including heterojunction formation, doping, cocatalysts, and conductive additives, is often crucial for achieving high degradation efficiency. Photocatalysis offers a practical and energy-efficient

way to treat water, using sunlight and common catalysts. When combined with scalable methods such as coated supports, magnetic recovery, or structured reactors, it achieves high removal efficiency, reduced secondary pollution, and simple operation. Therefore, advanced oxidation processes, especially photocatalysis, are among the best options for removing antibiotic residues from water and wastewater (Gahrouei et al., 2024; García et al., 2020; Panchakeaw et al., 2025; Tian et al., 2023; Zhang et al., 2024b).

Degradation mechanisms

Figure 8 presents the removal mechanisms of antibiotic pollutants using advanced oxidation processes. Unlike adsorption, which transfers antibiotics from water to a solid surface, AOPs destroy them through chemical oxidation. Reactive species such as hydroxyl radicals ($\cdot\text{OH}$), hydroperoxyl radicals ($\text{HO}_2\cdot$), sulfate radicals ($\text{SO}_4^{\cdot-}$), singlet oxygen ($^1\text{O}_2$), ferryl ions (FeO_2^+), and superoxide radicals ($\text{O}_2^{\cdot-}$) break down antibiotic molecules into non-toxic compounds (2024a; Chen & Wang, 2019; Hemavibool et al., 2022; Huynh et al., 2024; Liu et al., 2021;

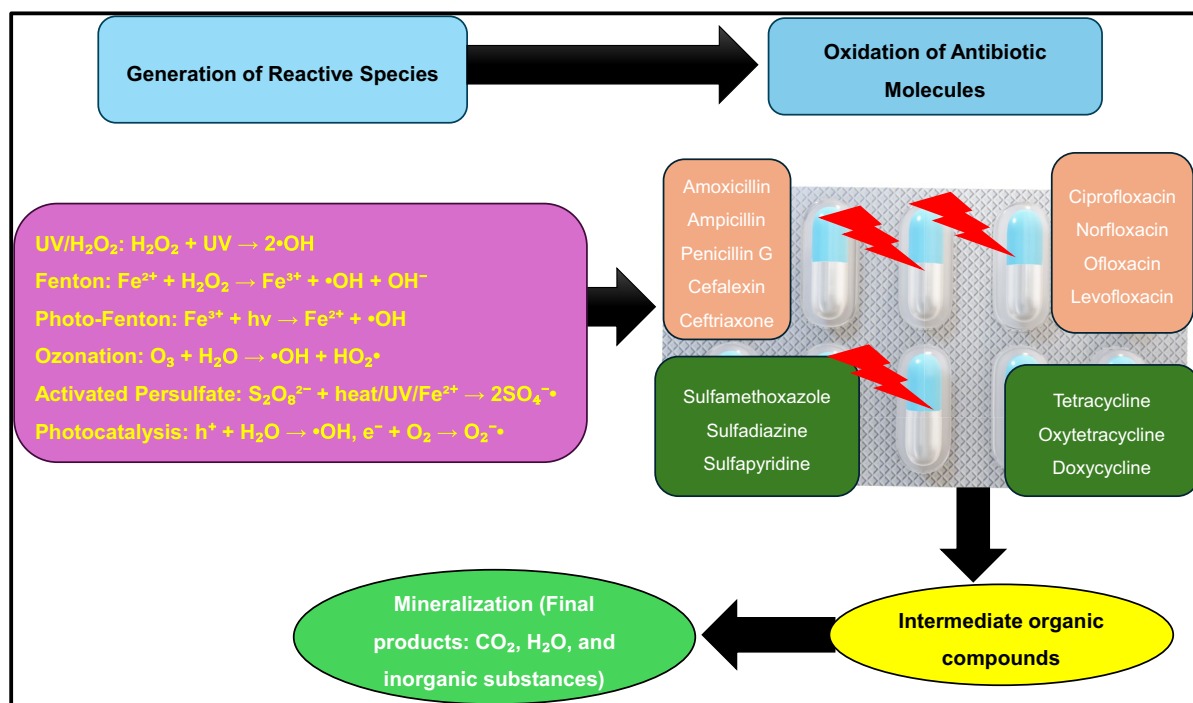


Fig. 8 Removal mechanism of antibiotic pollutants using advanced oxidation processes

Ormeño-Cano & Radjenovic, 2024; Panchakeaw et al., 2025; Shan et al., 2023; Wang et al., 2022; Yin et al., 2016; Zhang et al., 2024d). In detail, once these oxidizing species form, they quickly attack the most reactive parts of antibiotic molecules, such as aromatic rings, conjugated double bonds, heterocycles, and functional groups with nitrogen, sulfur, or oxygen. This first oxidation step usually produces several transformation intermediates through reactions like hydroxylation, dealkylation, ring opening, and side chain cleavage. Subsequently, the radicals continue to oxidize these intermediates, thereby degrading them into smaller compounds (Chin et al., 2023; Ma et al., 2023; Niu et al., 2024; Zhu et al., 2022). This process can lead to mineralization, in which the remaining organic carbon is converted to CO₂, H₂O, and inorganic ions. In this way, AOPs offer a clear mechanism for removing antibiotic residues and inhibiting their toxicity to humans and the environment (Aldrery et al., 2025; Baldez et al., 2024; Hamid & Khanday, 2026; Jitae et al., 2025; Li et al., 2024; Senasu et al., 2023; Zhang et al., 2024b).

Evaluation of technologies for removing antibiotic pollutants

To properly assess technologies for removing antibiotics, it is important to consider more than how well they remove contaminants. Factors such as energy use, costs, by-products, and scalability should also be considered. This evaluation helps identify treatment methods that perform not only in the laboratory but also in real-world wastewater treatment (Alsaedi et al., 2025; Hamid & Khanday, 2026; Hassoun-Kheir et al., 2020; Niu et al., 2024; Peng et al., 2024; Wang et al., 2024b). Figure 9 shows the advantages and limitations of different methods used to remove antibiotic pollutants. For example, adsorption and membrane processes often display high removal rates by trapping antibiotic molecules, but they do not destroy the contaminants and instead move them to another phase (Hamid & Khanday, 2026; Wang et al., 2024b). On the other hand, advanced oxidation processes, photocatalysis, and electrochemical treatments can degrade antibiotics, reducing both the parent compounds and their biological effects. Energy demand is a key limitation for advanced treatment technologies. Physical adsorption and natural treatment systems require little energy, making them suitable for decentralized or resource-limited settings.

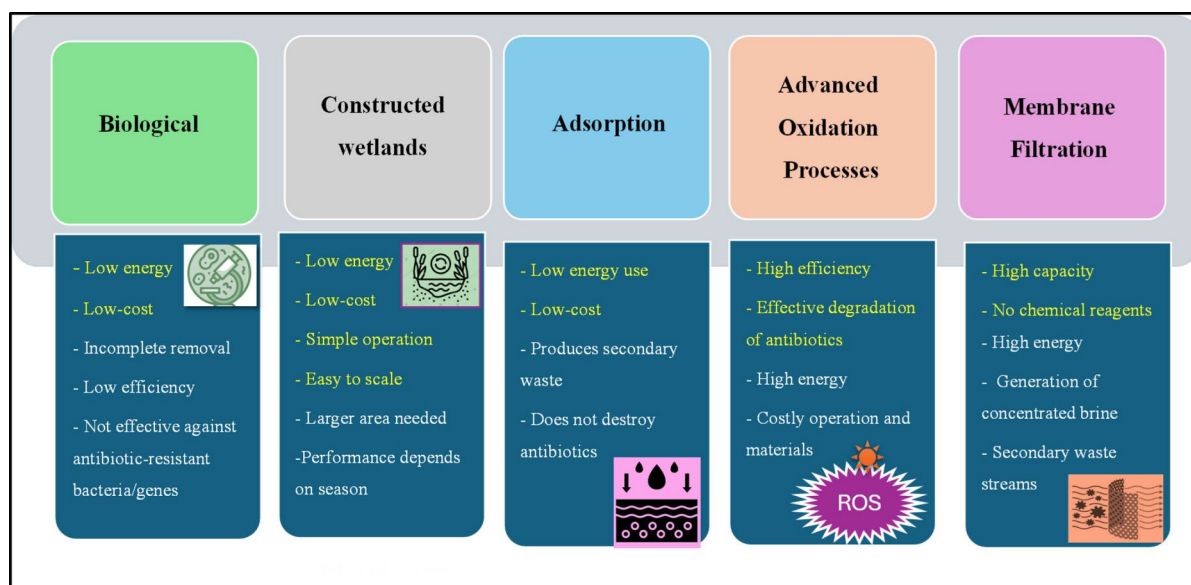


Fig. 9 Comparison of different technologies for antibiotic removal

However, AOPs need substantial energy to generate reactive species and maintain irradiation (Alsaedi et al., 2025; Lyu et al., 2026; Niu et al., 2024).

Cost is an important factor when choosing and using new technologies. Low-cost adsorbents made from biomass, industrial by-products, or natural systems are often more affordable, especially in developing regions. High-performance materials, membranes, and advanced reactors perform well but can be expensive to purchase and operate, as they may require chemicals, new electrodes, or catalyst regeneration. Increasingly, life-cycle cost analyses indicate that hybrid systems, which combine low-cost pretreatment with advanced processes, can reduce total treatment costs while achieving strong removal performance (Alsaedi et al., 2025; Hamid & Khanday, 2026).

By-product generation is often overlooked but remains critically important. Physical separation processes create secondary waste streams, including spent adsorbents, sludge, and concentrated brines, all of which require safe handling and disposal. Chemical and oxidative treatments can produce transformation products that retain antimicrobial activity or have unknown toxicity, raising concerns about incomplete mineralization. Comprehensive evaluation of transformation pathways and post-treatment toxicity is essential to ensure removal technologies do not substitute one environmental risk for another (Alsaedi et al., 2025; Hamid & Khanday, 2026; Lyu et al., 2026; Niu et al., 2024). Scalability and operational robustness are key to the practical relevance of removal technologies. While many advanced methods perform well at laboratory or pilot scale, they often encounter challenges with reactor design, maintenance, and long-term stability during scale-up. Adsorption units and nature-based systems are typically more scalable and easier to integrate into existing infrastructure. In contrast, energy-intensive processes demand precise engineering and operational oversight. As a result, integrated and hybrid treatment configurations are increasingly preferred, as they combine the strengths of multiple technologies and address individual limitations (Alsaedi et al., 2025; Hamid & Khanday, 2026; Lyu et al., 2026; Niu et al., 2024; Wang et al., 2024b; Zhang et al., 2024c).

Remaining challenges

Recently, various methods have been developed to control antibiotic pollutants, but they still remain several challenges related to treatment costs, safety issues, and scale-up in field applications (Fig. 10).

For safety reasons, a major problem is that some methods can reduce antibiotic levels but do not fully break them down into harmless substances, such as CO₂ and H₂O, or into other inorganic compounds. Therefore, by-products still remain, and some of them may be more toxic than the original antibiotics. Another major challenge is controlling antibiotic-resistant bacteria and the resistance genes that drive them. Destroying antibiotic molecules does not automatically remove the genetic material responsible for resistance (Alsaedi et al., 2025; Hamid & Khanday, 2026; Zhang et al., 2024c). Also, treatments that are not strong enough, especially in biological systems or partially oxidative processes, can unintentionally increase the pressure that selects resistance. To solve this problem, targeted approaches and often combined treatment strategies are needed, rather than relying only on conventional methods for removing chemical contaminants (Alsaedi et al., 2025; Hamid & Khanday, 2026). Besides, only a few studies have been done within the set timeframe. Most research has focused on short-term lab or controlled experiments that do not account for the complex nature of wastewater, changing loads, or seasonal variations (Alsaedi et al., 2025; Hamid & Khanday, 2026; Zhang et al., 2024c). Important practical issues, such as how long catalysts last, how well adsorbents can be reused, energy use over time, and efficiency declines, have not been studied enough. Without clear, data-based limits, it is difficult to assess how reliable, cost-effective, or sustainable the treatment process is. Finally, previous studies used different experimental designs, antibiotics, concentration ranges, water types, analytical methods, and performance measures. Thus, it is difficult to compare results or determine which technologies are most effective.

Conclusions and future perspectives

This review summarizes current approaches for removing antibiotic pollutants from water and wastewater, with a focus on reducing their toxicity and

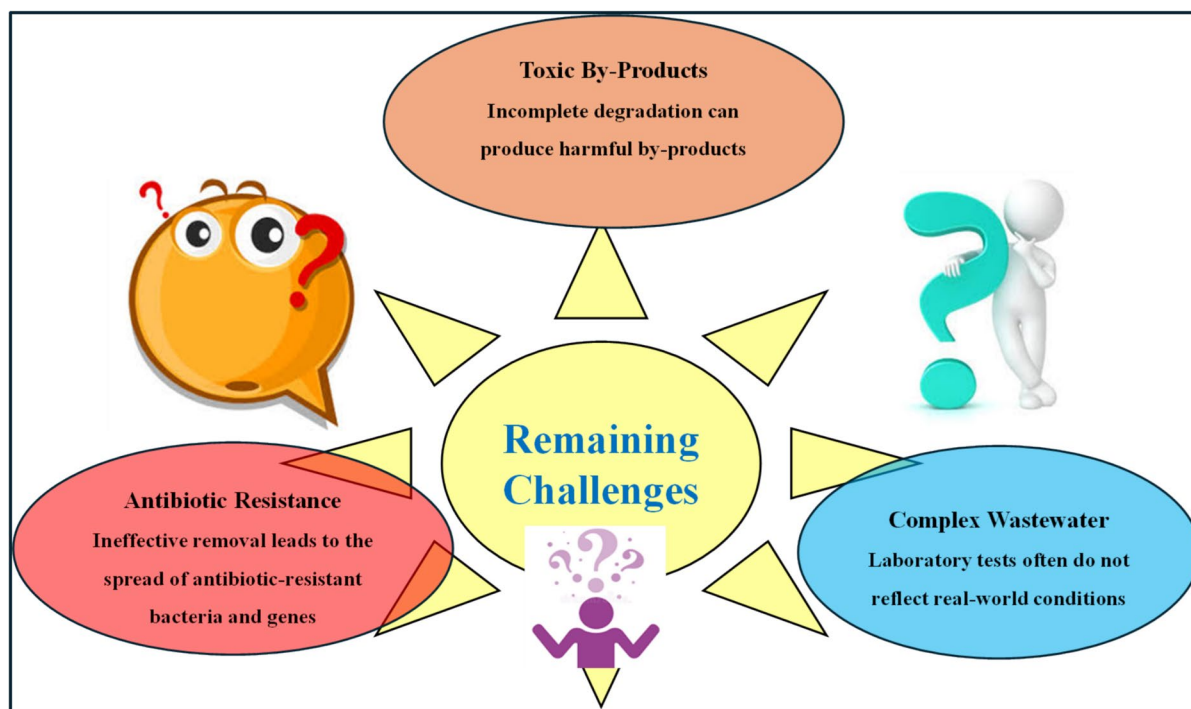


Fig. 10 Remaining challenges in controlling antibiotic pollutants

the spread of antibiotic-resistant bacteria and resistance genes. Among effective methods, adsorption and advanced oxidation processes are promising approaches for removing antibiotic residues. The adsorption process is a simple, low-cost operation that can be applied to different types of wastewaters. However, this method did not reduce the toxicity of antibiotic pollutants, and controlling the adsorbent after the treatment process remains challenging.

Besides, advanced oxidation processes can directly degrade antibiotic pollutants and reduce their toxicity by the reactive radicals. However, these processes require a high energy supply, large amounts of oxidants, and complex reactor systems. As antibiotic contamination increases, we need to develop low-cost, more sustainable treatment methods that can completely remove pollutants.

Therefore, future research should focus on developing materials/methods that reduce energy demand by utilizing renewable energy sources, improve reusability, and enhance the removal efficiency of antibiotic pollutants, particularly at trace levels.

On the other hand, the mineralization and reduced toxicity of antibiotics in real wastewater are

important factors that need to be carefully evaluated for further reuse of treated wastewater. The process also helps to reduce the development of antibiotic-resistant bacteria/genes that contribute to inhibiting their negative impacts on humans. Some treatment strategies combine advanced methods, such as adsorption with advanced oxidation processes or membrane with advanced oxidation processes. These approaches can improve pollutant removal efficiency and reduce pollutant toxicity.

These methods can be applied to various types of wastewaters containing different pollutants and can help reduce operating costs. Using natural sunlight as a renewable energy source should also be considered and developed to reduce treatment costs and create more sustainable wastewater management. To support sustainability, future antibiotic-control strategies need to match wastewater reuse goals. This means focusing on removing the main compounds, reducing toxicity, breaking down harmful byproducts, and managing antibiotic-resistant bacteria and antibiotic-resistance genes risks. When choosing technologies, it is important to consider energy and chemical use, the stability

and reusability of the materials, how to handle any leftover waste, and how well the treatment works.

Moreover, life cycle assessment should be included from the start of technology development. This approach helps control each process and makes it easier to develop sustainable methods before applying them in wastewater treatment plants.

Author contributions Pham Thi Huong: Investigation, methodology, writing—original draft, review editing. Nguyen Lam Nhat Minh: Conceptualization, methodology. Subhav Singh: Methodology, validation. Kim Jiatae: Investigation, supervision, review and editing.

Data availability The data that has been used is confidential.

Declarations

Conflict of interest The authors declare no competing interests.

Ethical approval Not applicable.

Consent to participate Not applicable.

Consent to publish Not applicable.

References

- Abou-Jaoudeh, C., Andary, J., & Abou-Khalil, R. (2024). Antibiotic residues in poultry products and bacterial resistance: A review in developing countries. *Journal of Infection and Public Health*. <https://doi.org/10.1016/j.jiph.2024.102592>
- Ahmad, M., Usman, A. R. A., Rafique, M. I., & Al-Wabel, M. I. (2019). Engineered biochar composites with zeolite, silica, and nano-zerovalent iron for the efficient scavenging of chlortetracycline from aqueous solutions. *Environmental Science and Pollution Research*, 26(15), 15136–15152. <https://doi.org/10.1007/s11356-019-04850-7>
- Ahmadipour, M., Rezaei Ardani, M., Chrouda, A., Pang, A. L., Mohd Razip Wee, M. F., & Satgunam, M. (2024). Removal of antibiotic sulfamethoxazole in water using rapid growing ZnO nanorod. *Ceramics International*. <https://doi.org/10.1016/j.ceramint.2024.04.405>
- Akhter, S., Bhat, M. A., Ahmed, S., & Siddiqui, W. A. (2024). Antibiotic residue contamination in the aquatic environment, sources and associated potential health risks. *Environmental Geochemistry and Health*. <https://doi.org/10.1007/s10653-024-02146-5>
- Aldrery, M., Alreshedi, F., El-Aassar, M. R., Ahmed, A., Aadil, M., Alazmi, A., El Jerry, A., Alrahili, M. R., & Amjad, A. (2025). Preparation and physicochemical characterization of highly efficient $ZrO_2/g-C_3N_4$ composite catalysts for visible-light-driven removal of tetracycline antibiotics. *Diamond and Related Materials*, 151, Article 111801. <https://doi.org/10.1016/j.diamond.2024.111801>
- Alsaeedi, S., Yan, B., Wang, Z., Chen, G., Song, Y., & Al-Hakeem, B. (2025). Current utilization technologies and products of antibiotic fermentation residues: A review. *Journal of Environmental Chemical Engineering*. <https://doi.org/10.1016/j.jece.2025.116182>
- Aryee, A. A., Han, R., & Qu, L. (2022). Occurrence, detection and removal of amoxicillin in wastewater: A review. *Journal of Cleaner Production*. <https://doi.org/10.1016/j.jclepro.2022.133140>
- Baldez, W. M., Santos, J. D., Santos, W. D., Aguilar-Pliego, J., Martin, N., Cabral, A. A., Paiva, A. E., Rodrigues, S. F., Teixeira, M. M., Alcântara, A. C., & Rojas, A. (2024). Enhanced photodegradation of ciprofloxacin antibiotic using ZnO@FAU composite: A promising material for contaminant removal. *Desalination and Water Treatment*, 318, Article 100356. <https://doi.org/10.1016/j.dwt.2024.100356>
- Behere, M., Thathola, P., Sahoo, T. P., Raval, I., & Haldar, S. (2025). Role of antibiotic residues in development of antibiotic resistance in coastal bacterial communities. *Regional Studies in Marine Science*, 89, Article 104340. <https://doi.org/10.1016/j.rsma.2025.104340>
- Ben, Y., Fu, C., Hu, M., Liu, L., Wong, M. H., & Zheng, C. (2019). Human health risk assessment of antibiotic resistance associated with antibiotic residues in the environment: A review. *Environmental Research*. <https://doi.org/10.1016/j.envres.2018.11.040>
- Bhunia, S., Mallick, S., Mondal, A. I., Saha, A., Ray, P., Roy, S., & Chakraborty, T. (2025). Exploring the scope of traditional Chinese medicinal plants in battle of antibiotic resistance—A comprehensive review. *Pharmacological Research - Modern Chinese Medicine*. <https://doi.org/10.1016/j.prmm.2025.100574>
- Blair, B., Nikolaus, A., Hedman, C., Klaper, R., & Grundl, T. (2015). Evaluating the degradation, sorption, and negative mass balances of pharmaceuticals and personal care products during wastewater treatment. *Chemosphere*, 134, 395–401. <https://doi.org/10.1016/j.chemosphere.2015.04.078>
- Bonetta, S., Di Cesare, A., Pignata, C., Sabatino, R., Macrì, M., Corno, G., Panizzolo, M., Bonetta, S., & Carraro, E. (2023). Occurrence of antibiotic-resistant bacteria and resistance genes in the urban water cycle. *Environmental Science and Pollution Research*, 30(12), 35294–35306. <https://doi.org/10.1007/s11356-022-24650-w>
- Cai, L., Sun, J., Cui, L., Jiang, Y., & Huang, Z. (2020). Stabilization of heavy metals in piggy wastewater sludge through coagulation-hydrothermal reaction-pyrolysis process and sludge biochar for tylosin removal. *Journal of Cleaner Production*, 260, Article 121165. <https://doi.org/10.1016/j.jclepro.2020.121165>
- Chen, A., Ji, H., Xu, Z., Wang, Z., & Zhang, L. (2025a). Rational design of S-scheme structure via the combination of Aurivillius oxides and TiO_2 for high-efficiency tetracycline antibiotics removal. *Journal of Alloys and Compounds*, 1010, Article 177577. <https://doi.org/10.1016/j.jallcom.2024.177577>
- Chen, A., Zhang, T., Cheng, F., Yang, H., Guo, Z., Zhao, S., Zhang, Y. N., & Qu, J. (2024). Comprehensive analysis

- and risk assessment of Antibiotic contaminants, antibiotic-resistant bacteria, and resistance genes: Patterns, drivers, and implications in the Songliao Basin. *Environmental Pollution*. <https://doi.org/10.1016/j.envpol.2024.124852>
- Chen, H., & Wang, J. (2019). Catalytic ozonation of sulfamethoxazole over $\text{Fe}_3\text{O}_4/\text{Co}_3\text{O}_4$ composites. *Chemosphere*, 234, 14–24. <https://doi.org/10.1016/j.chemosphere.2019.06.014>
- Chen, X., Li, M., He, J., Wu, Y., Sun, J., & Wen, X. (2025b). Waste cotton-based activated carbon with excellent adsorption performance towards dyes and antibiotics. *Chemosphere*, 376, Article 144292. <https://doi.org/10.1016/j.chemosphere.2025.144292>
- Chin, J. Y., Ahmad, A. L., & Low, S. C. (2023). Antibiotics oxytetracycline removal by photocatalyst titanium dioxide and graphitic carbon nitride in aquaculture wastewater. *Journal of Environmental Management*. <https://doi.org/10.1016/j.jenvman.2023.118231>
- Darby, E. M., Trampari, E., Siasat, P., Gaya, M. S., Alav, I., Webber, M. A., & Blair, J. M. A. (2023). Molecular mechanisms of antibiotic resistance revisited. *Nature Reviews Microbiology*. <https://doi.org/10.1038/s41579-022-00820-y>
- Ding, C., Zhu, Q., Yang, B., Petropoulos, E., Xue, L., Feng, Y., He, S., & Yang, L. (2023). Efficient photocatalysis of tetracycline hydrochloride (TC-HCl) from pharmaceutical wastewater using $\text{AgCl}/\text{ZnO}/\text{g-C}_3\text{N}_4$ composite under visible light: Process and mechanisms. *Journal of Environmental Sciences (China)*, 126, 249–262. <https://doi.org/10.1016/j.jes.2022.02.032>
- Dong, H., Yuan, X., Wang, W., & Qiang, Z. (2016). Occurrence and removal of antibiotics in ecological and conventional wastewater treatment processes: A field study. *Journal of Environmental Management*, 178, 11–19. <https://doi.org/10.1016/j.jenvman.2016.04.037>
- Farkas, L., Monzini, I., Takács, E., Wojnárovits, L., Vörös, M., Vágvolgyi, C., Janáky, C., & Alapi, T. (2024). Comparison of the effectiveness of UV, UV/VUV photolysis, ozonation, and ozone/UV processes for the removal of sulfonamide antibiotics. *Journal of Environmental Chemical Engineering*, 12(1), 1118454. <https://doi.org/10.1016/j.jece.2023.111845>
- Feng, F., Zhang, X., Xu, X., Huang, Q., Yin, H., Li, R., Wu, G., & Xing, W. (2025). Construction of 2D/3D biochar modified $\text{g-C}_3\text{N}_4$ for efficient removal of tetracycline hydrochloride via photocatalytic PMS activation. *Optical Materials*, 167, Article 117246. <https://doi.org/10.1016/j.optmat.2025.117246>
- Gahrouei, A. E., Vakili, S., Zandifar, A., & Pourebrahimi, S. (2024). From wastewater to clean water: Recent advances on the removal of metronidazole, ciprofloxacin, and sulfamethoxazole antibiotics from water through adsorption and advanced oxidation processes (AOPs). *Environmental Research*. <https://doi.org/10.1016/j.envres.2024.119029>
- Galgano, M., Pellegrini, F., Catalano, E., Capozzi, L., Del Sambro, L., Sposato, A., Lucente, M. S., Vasinioti, V. I., Catella, C., Odigie, A. E., & Tempesta, M. (2025). Acquired bacterial resistance to antibiotics and resistance genes: From past to future. *Antibiotics*. <https://doi.org/10.3390/antibiotics14030222>
- Gao, Y., Liu, Y., Zou, D., Guan, H., & Zou, D. (2019). Metronidazole in aqueous solution removal by activated carbon fiber adsorption of systems: Adsorption kinetics, adsorption isotherms and thermodynamics. *Desalination and Water Treatment*, 148, 162–169. <https://doi.org/10.5004/dwt.2019.23521>
- García, J., García-Galán, M. J., Day, J. W., Boopathy, R., White, J. R., Wallace, S., & Hunter, R. G. (2020). A review of emerging organic contaminants (EOCs), antibiotic resistant bacteria (ARB), and antibiotic resistance genes (ARGs) in the environment: Increasing removal with wetlands and reducing environmental impacts. *Bioresource Technology*. <https://doi.org/10.1016/j.biortech.2020.123228>
- Gwenzi, W., Musiyiwa, K., & Mangori, L. (2020). Sources, behaviour and health risks of antimicrobial resistance genes in wastewaters: A hotspot reservoir. *Journal of Environmental Chemical Engineering*. <https://doi.org/10.1016/j.jece.2018.02.028>
- Hamad, B. (2010). The antibiotics market. *Nature Reviews Drug Discovery*. <https://doi.org/10.1038/nrd3267>
- Hamid, I., & Khanday, W. A. (2026). Recent advances in antibiotic removal methods from wastewater: A comprehensive review. *Separation and Purification Technology*. <https://doi.org/10.1016/j.seppur.2025.135478>
- Hao, D., Chen, Y., Zhang, Y., & You, N. (2021). Nanocomposites of zero-valent iron@biochar derived from agricultural wastes for adsorptive removal of tetracyclines. *Chemosphere*, 284, Article 131342. <https://doi.org/10.1016/j.chemosphere.2021.131342>
- Hassoun-Kheir, N., Stabholz, Y., Kreft, J. U., de la Cruz, R., Romalde, J. L., Nesme, J., Sørensen, S. J., Smets, B. F., Graham, D., & Paul, M. (2020). Comparison of antibiotic-resistant bacteria and antibiotic resistance genes abundance in hospital and community wastewater: A systematic review. *Science of the Total Environment*. <https://doi.org/10.1016/j.scitotenv.2020.140804>
- Hekmatshoar, R., Khoramnejadian, S., Alahabadi, A., & Saghi, M. H. (2022). Potential of ammonium chloride-activated carbon for decomposition of penicillin G by catalytic ozonation process (COP). *International Journal of Environmental Science and Technology*, 19(3), 1131–1138. <https://doi.org/10.1007/s13762-021-03180-x>
- Hemavibool, K., Sansanya, T., & Nanan, S. (2022). Enhanced photocatalytic degradation of tetracycline and oxytetracycline antibiotics by BiVO_4 photocatalyst under visible light and solar light irradiation. *Antibiotics*. <https://doi.org/10.3390/antibiotics11060761>
- Heo, J., Yoon, Y., Lee, G., Kim, Y., Han, J., & Park, C. M. (2019). Enhanced adsorption of bisphenol A and sulfamethoxazole by a novel magnetic $\text{CuZnFe}_2\text{O}_4$ -biochar composite. *Bioresource Technology*, 281, 179–187. <https://doi.org/10.1016/j.biortech.2019.02.091>
- Holmes, A. H., Moore, L. S. P., Sundsfjord, A., Steinbakk, M., Regmi, S., Karkey, A., Guerin, P. J., & Piddock, L. J. (2016). Understanding the mechanisms and drivers of antimicrobial resistance. *The Lancet*. [https://doi.org/10.1016/S0140-6736\(15\)00473-0](https://doi.org/10.1016/S0140-6736(15)00473-0)

- Hou, S., Gao, Y., Song, P., Zhao, J., Gong, B., Zhu, X., & Liu, Q. (2024). Synthesis of Pd-modified Fe_3O_4 loaded on montmorillonite catalyst for photocatalytic degradation of tetracycline. *Inorganic Chemistry Communications*, 159, Article 111745. <https://doi.org/10.1016/j.inoche.2023.111745>
- Huang, B., Bu, X., Wang, J., Chen, L., Su, B., Zhang, Q., & Zhou, S. (2026). Strategy selection for addressing antibiotic pollution in farmland soils based on the analysis of source apportionment and risk decomposition. *Journal of Hazardous Materials*, 505, Article 141522. <https://doi.org/10.1016/j.jhazmat.2026.141522>
- Huynh, N. D. T., Tran, H. T., Le, P. N. M., Ngo, T. H., Luan, V. H., & Le, M. V. (2024). Metal-free $\text{g-C}_3\text{N}_5$ photocatalysts with defect sites as efficient peroxymonosulfate activators for antibiotic removal in aqueous media. *Journal of Environmental Chemical Engineering*. <https://doi.org/10.1016/j.jece.2024.112860>
- Izah, S. C., Nurmahanova, A., Ogwu, M. C., Toktarbay, Z., Umirbayeva, Z., Ussen, K., Koibasova, L., Nazarbekova, S., Tynybekov, B., & Guo, Z. (2025). Public health risks associated with antibiotic residues in poultry food products. *Journal of Agriculture and Food Research*. <https://doi.org/10.1016/j.jafr.2025.101815>
- Jing, L., Xie, M., Xu, Y., Tong, C., Du, X., Zhao, H., Zhong, N., Li, H., & Hu, J. (2024). Advanced oxidation via the synergy of C-defective/ C–O band modified ultrathin porous $\text{g-C}_3\text{N}_4$ and PMS for efficient photothermal degradation of bisphenol pollutants and lignin derivatives. *Green Energy and Environment*, 9(7), 1159–1170. <https://doi.org/10.1016/j.jee.2023.01.006>
- Jitae, K., Nguyen, M. V., & Thi Huong, P. (2025). Visible light-driven $\text{CoMoO}_4/\text{g-C}_3\text{N}_4$ photocatalyst for removal of antibiotic contaminant from wastewater. *Materials Chemistry and Physics*. <https://doi.org/10.1016/j.matchemphys.2025.130433>
- Karthikeyan, K. G., & Meyer, M. T. (2006). Occurrence of antibiotics in wastewater treatment facilities in Wisconsin, USA. *Science of the Total Environment*, 361(1–3), 196–207. <https://doi.org/10.1016/j.scitotenv.2005.06.030>
- Kawsar, M. A., Shahriar, F., Adikari, D., Hasan, M. T., & Zhang, Y. (2026). Exploring antibiotics and antimicrobial resistance (AMR) in aquaculture: What have we learned from Bangladesh? *Water Biology and Security*. <https://doi.org/10.1016/j.watbs.2026.100586>
- Khanday, W. A., Ahmed, M. J., Okoye, P. U., & Hummadi, E. H. (2025). Single-step H_3PO_4 activation of chitosan for efficient adsorption of amoxicillin and doxycycline antibiotic pollutants. *Inorganic Chemistry Communications*. <https://doi.org/10.1016/j.inoche.2025.114189>
- Kleywegt, S., Payne, M., Ng, F., & Fletcher, T. (2019). Environmental loadings of active pharmaceutical ingredients from manufacturing facilities in Canada. *Science of the Total Environment*, 646, 257–264. <https://doi.org/10.1016/j.scitotenv.2018.07.240>
- Krishnan, R. Y., Manikandan, S., Subbaiya, R., Karmegam, N., Kim, W., & Govarthan, M. (2023). Recent approaches and advanced wastewater treatment technologies for mitigating emerging microplastics contamination—A critical review. *Science of the Total Environment*. <https://doi.org/10.1016/j.scitotenv.2022.159681>
- Li, C., Gao, Y., Li, A., Zhang, L., Ji, G., Zhu, K., Wang, X., & Zhang, Y. (2019). Synergistic effects of anionic surfactants on adsorption of norfloxacin by magnetic biochar derived from furfural residue. *Environmental Pollution*, 254, Article 113005. <https://doi.org/10.1016/j.envpol.2019.113005>
- Li, G., Zhao, H., Guo, P., & Liu, D. (2022). Effective removal of tinidazole by MIL-53(Al)-NDC metal–organic framework from aqueous solution. *Journal of Solid State Chemistry*, 310, Article 123066. <https://doi.org/10.1016/j.jssc.2022.123066>
- Li, R., Wang, Z., Zhao, X., Li, X., & Xie, X. (2018). Magnetic biochar-based manganese oxide composite for enhanced fluoroquinolone antibiotic removal from water. *Environmental Science and Pollution Research*, 25(31), 31136–31148. <https://doi.org/10.1007/s11356-018-3064-1>
- Li, S., Meng, D., Zhang, G., & Yang, F. (2024). Periodic polarity reversal triggered sequential electrochemical redox of blue TiO_2 nanotube arrays for efficient removal of antibiotics and inorganic nitrogen from actual mariculture wastewater. *Chemical Engineering Journal*, 499, Article 156651. <https://doi.org/10.1016/j.cej.2024.156651>
- Li, W., Wang, B., Wang, T., Li, J., Qi, J., Luo, J., Zhang, T., Xu, X., & Hou, L. A. (2025). A review of antibiotic resistance genes in major river basins in China: Distribution, drivers, and risk. *Environmental Pollution*. <https://doi.org/10.1016/j.envpol.2025.125920>
- Li, X., Liu, F., Xi, S., Xie, H., Li, J., & Liu, G. (2023). Removal of antibiotics and antibiotic resistance genes in the synthetic oxytetracycline wastewater by UASB-A/O(MBR) process. *Journal of Environmental Chemical Engineering*. <https://doi.org/10.1016/j.jece.2023.109699>
- Liang, J., Fang, Y., Luo, Y., Zeng, G., Deng, J., Tan, X., Tang, N., Li, X., He, X., Feng, C., & Ye, S. (2019). Magnetic nanoferromanganese oxides modified biochar derived from pine sawdust for adsorption of tetracycline hydrochloride. *Environmental Science and Pollution Research*, 26(6), 5892–5903. <https://doi.org/10.1007/s11356-018-4033-4>
- Liu, N., Zhang, L., Xue, H., Yang, Z., & Meng, F. (2025). Sources, dissemination, and risk assessment of antibiotic resistance in surface waters: A review. *Emerging Contaminants*. <https://doi.org/10.1016/j.emcon.2024.100455>
- Liu, X., Li, H., Fang, Y., & Yang, Z. (2021). Heterogeneous catalytic ozonation of sulfamethazine in aqueous solution using maghemite-supported manganese oxides. *Separation and Purification Technology*, 274, Article 118945. <https://doi.org/10.1016/j.seppur.2021.118945>
- Luo, L., Zou, D., Lu, D., Yu, F., Xin, B., & Ma, J. (2018). Study of catalytic ozonation for tetracycline hydrochloride degradation in water by silicate ore supported Co_3O_4 . *RSC Advances*, 8(72), 41109–41116. <https://doi.org/10.1039/c8ra08402e>
- Lyu, H., Zhang, X., Bai, C., Ren, Y., Zheng, T., Wang, X., Peng, W., & Jin, H. (2026). Coupled advanced oxidation process systems for enhanced degradation of antibiotics: A review. *Separation and Purification Technology*. <https://doi.org/10.1016/j.seppur.2025.135602>
- Ma, B., Zha, Y., Yu, P., Chen, G., Guo, Y., Lan, Y., Li, J., Xia, W., & Zhao, B. (2023). Hydrothermal nanoarchitectonics of Z-scheme $\text{g-C}_3\text{N}_4/\text{Bi}_2\text{WO}_6$ heterojunction

- with enhanced adsorption and photocatalytic activity for fluoroquinolone antibiotics removal: Kinetics, mechanism and degradation pathway. *Journal of Alloys and Compounds*, 952, Article 170061. <https://doi.org/10.1016/j.jallcom.2023.170061>
- Ma, J., Zhou, B., Zhang, H., Zhang, W., & Wang, Z. (2019). Activated municipal wasted sludge biochar supported by nanoscale Fe/Cu composites for tetracycline removal from water. *Chemical Engineering Research and Design*, 149, 209–219. <https://doi.org/10.1016/j.cherd.2019.07.013>
- Ma, Y., Li, P., Yang, L., Wu, L., He, L., Gao, F., Qi, X., & Zhang, Z. (2020). Iron/zinc and phosphoric acid modified sludge biochar as an efficient adsorbent for fluoroquinolones antibiotics removal. *Ecotoxicology and Environmental Safety*, 196, Article 110550. <https://doi.org/10.1016/j.ecoenv.2020.110550>
- Mahdavi, P., Siol, A., & Thöming, J. (2025). Adsorption-based removal of pharmaceutical from water: A critical review on adsorbent performance. *Journal of Environmental Chemical Engineering*, 13(5), Article 117520. <https://doi.org/10.1016/j.jece.2025.117520>
- Matubber, B., Rahman, S. M. E., Akter, S., Farzana, F., Rahman, M. A., Wang, J., & Oh, D. H. (2025). Prevalence of antibiotic resistance and residue in meats in southwest region of Bangladesh. *Food and Humanity*. <https://doi.org/10.1016/j.foohum.2025.100636>
- Merhi, A., Khatib, S. E., Haddad, J., & Hassan, H. F. (2023). A review of the antibiotic residues in food in the Arab countries. *Applied Food Research*, 3(2), Article 100332. <https://doi.org/10.1016/j.afres.2023.100332>
- Miao, Y., Liu, X., Liu, M., Huang, Y., Hu, Q., Zhang, Q., Xie, Z., & Li, Q. (2025). Vertical migration of antibiotics, ARGs, and pathogens in industrial multi-pollutant soils: Implications for environmental and public health. *Ecotoxicology and Environmental Safety*, 303, Article 118912. <https://doi.org/10.1016/j.ecoenv.2025.118912>
- Míguez González, A., Oliveira Rodrigues, A., Cela Dablanca, R., Barreiro, A., Álvarez-Rodríguez, E., Fernández-Sanjurjo, M. J., & Núñez-Delgado, A. (2025). Alternatives to face anticoccidial ionophore antibiotics as emerging environmental pollutants. *Current Opinion in Environmental Science and Health*. <https://doi.org/10.1016/j.coesh.2025.100629>
- Minale, M., Guadie, A., Li, Y., Meng, Y., Wang, X., & Zhao, J. (2021). Enhanced removal of oxytetracycline antibiotics from water using manganese dioxide impregnated hydrogel composite: Adsorption behavior and oxidative degradation pathways. *Chemosphere*, 280, Article 130926. <https://doi.org/10.1016/j.chemosphere.2021.130926>
- Niu, J., Yuan, R., Chen, H., Zhou, B., & Luo, S. (2024). Heterogeneous catalytic ozonation for the removal of antibiotics in water: A review. *Environmental Research*. <https://doi.org/10.1016/j.envres.2024.119889>
- Ogunlaja, A., Ogunlaja, O. O., Olukanni, O. D., Taylor, G. O., Olorunnisola, C. G., Dougnon, V. T., Mousse, W., Fatta-Kassinos, D., Msagati, T. A., & Unuabonah, E. (2022). Antibiotic resistomes and their chemical residues in aquatic environments in Africa. *Environmental Pollution*. <https://doi.org/10.1016/j.envpol.2022.119783>
- Okeke, E. S., Nwankwo, C. E. I., Ezeorba, T. P. C., Ogugor, M. O., & Nwuche, C. O. (2025). Antibiotic residues and antibiotic resistance genes in African water systems: Implications for safe drinking water, aquatic ecosystems, and sustainable development goals. *Journal of Water Process Engineering*. <https://doi.org/10.1016/j.jwpe.2024.106636>
- Oladipo, A. A., & Ifebajo, A. O. (2018). Highly efficient magnetic chicken bone biochar for removal of tetracycline and fluorescent dye from wastewater: Two-stage adsorber analysis. *Journal of Environmental Management*, 209, 9–16. <https://doi.org/10.1016/j.jenvman.2017.12.030>
- Omufere, L. O., Maseko, B., & Olowoyo, J. O. (2022). Occurrence of antibiotics in wastewater from hospital and conventional wastewater treatment plants and their impact on the effluent receiving rivers: Current knowledge between 2010 and 2019. *Environmental Monitoring and Assessment*. <https://doi.org/10.1007/s10661-022-09846-4>
- Ormeño-Cano, N., & Radjenovic, J. (2024). Electrochemical removal of antibiotics and multi-drug resistant bacteria using S-functionalized graphene sponge electrodes. *Journal of Cleaner Production*, 470, Article 143245. <https://doi.org/10.1016/j.jclepro.2024.143245>
- Panchakeaw, A., Nonthing, S., Dulyasucharit, R., & Nanan, S. (2025). Improved photocatalytic activity of magnetically separable Fe₃O₄/ZnO photocatalyst for complete sunlight-active removal of tetracycline antibiotic. *Chemical Physics Letters*, 862, Article 141868. <https://doi.org/10.1016/j.cplett.2025.141868>
- Pandey, P., Shankar, A., Biney, M., & Saini, V. K. (2021). Enhancement in amoxicillin adsorption and regeneration properties of SBA-15 after surface modification with polyaniline. *Colloids and Interface Science Communications*, 43, Article 100432. <https://doi.org/10.1016/j.colcom.2021.100432>
- Patel, M., Kumar, R., Kishor, K., Mlsna, T., Pittman, C. U., & Mohan, D. (2019). Pharmaceuticals of emerging concern in aquatic systems: Chemistry, occurrence, effects, and removal methods. *Chemical Reviews*. <https://doi.org/10.1021/acs.chemrev.8b00299>
- Peng, P., Yan, X., Zhou, X., Chen, L., Li, X., Miao, Y., & Zhao, F. (2024). Enhancing degradation of antibiotic-combined pollutants by a hybrid system containing advanced oxidation and microbial treatment, a review. *Journal of Hazardous Materials*. <https://doi.org/10.1016/j.jhazmat.2024.136300>
- Phoon, B. L., Lai, C. W., Chen, C. Y., Boonyuen, S., Tang, W. K., & Juan, J. C. (2024). Mesoporous I-doped-g-C₃N₄ with C vacancies as superior visible-light-driven photocatalyst for removal of tetracycline antibiotic. *Journal of Alloys and Compounds*. <https://doi.org/10.1016/j.jallcom.2024.176772>
- Raj, R., Tripathi, A., Das, S., & Ghangrekar, M. M. (2021). Removal of caffeine from wastewater using electrochemical advanced oxidation process: A mini review. *Case Studies in Chemical and Environmental Engineering*, 4, Article 100129. <https://doi.org/10.1016/j.csee.2021.100129>
- Rana, P., Soni, V., Sharma, S., Poonia, K., Patial, S., Singh, P., Selvasembian, R., Chaudhary, V., Hussain, C. M., & Raizada, P. (2025). Harnessing nitrogen doped

- magnetic biochar for efficient antibiotic adsorption and degradation. *Journal of Industrial and Engineering Chemistry*. <https://doi.org/10.1016/j.jiec.2025.01.025>
- Rani, J., Saha, S., Ferdous, F., & Rahman, M. A. (2024). Assessment of the Bangladeshi antibiotic market: Implications of the WHO AWaRe classification and dosage form availability on antimicrobial resistance. *Journal of Infection and Public Health*. <https://doi.org/10.1016/j.jiph.2024.102587>
- Reguyal, F., & Sarmah, A. K. (2018). Adsorption of sulfamethoxazole by magnetic biochar: Effects of pH, ionic strength, natural organic matter and 17 α -ethinylestradiol. *Science of the Total Environment*, 628–629, 722–730. <https://doi.org/10.1016/j.scitotenv.2018.01.323>
- Rodríguez-López, L., Santás-Miguel, V., Cela-Dablanca, R., Núñez-Delgado, A., Álvarez-Rodríguez, E., Rodríguez-Seijo, A., & Arias-Estévez, M. (2024). Comparison of by-products as adsorbents for the removal of the antibiotics ciprofloxacin, trimethoprim and clarithromycin. *Journal of Environmental Management*, 370, Article 122842. <https://doi.org/10.1016/j.jenvman.2024.122842>
- Rodríguez-Mozaz, S., Vaz-Moreira, I., Della Giustina, S. V., Llorca, M., Barceló, D., Schubert, S., Berendonk, T. U., Michael-Kordatou, I., Fatta-Kassinos, D., Martínez, J. L., & Elpers, C. (2020). Antibiotic residues in final effluents of European wastewater treatment plants and their impact on the aquatic environment. *Environment International*. <https://doi.org/10.1016/j.envint.2020.105733>
- Rosal, R., Rodríguez, A., Perdigón-Melón, J. A., Petre, A., García-Calvo, E., Gómez, M. J., Agüera, A., & Fernández-Alba, A. R. (2010). Occurrence of emerging pollutants in urban wastewater and their removal through biological treatment followed by ozonation. *Water Research*, 44(2), 578–588. <https://doi.org/10.1016/j.watres.2009.07.004>
- Savin, M., Alexander, J., Bierbaum, G., Hammerl, J. A., Hembach, N., Schwartz, T., Schmithausen, R. M., Sib, E., Voigt, A., & Kreyenschmidt, J. (2021). Antibiotic-resistant bacteria, antibiotic resistance genes, and antibiotic residues in wastewater from a poultry slaughterhouse after conventional and advanced treatments. *Scientific Reports*, 11(1), 16622. <https://doi.org/10.1038/s41598-021-96169-y>
- Schneider, L. T., Módenes, A. N., Scheufele, F. B., Borba, C. E., Trigueros, D. E. G., & Alves, H. J. (2024). Soybean hulls activated carbon for metronidazole adsorption: Thermochemical conditions optimization for tailored and enhanced meso/microporosity. *Journal of Analytical and Applied Pyrolysis*. <https://doi.org/10.1016/j.jaap.2023.106339>
- Senasu, T., Lorwanishpaisarn, N., Hemavibool, K., Nijpanich, S., Chanlek, N., & Nanan, S. (2023). Construction of g-C₃N₄/BiOCl/CdS heterostructure photocatalyst for complete removal of oxytetracycline antibiotic in wastewater. *Separation and Purification Technology*. <https://doi.org/10.1016/j.seppur.2022.122735>
- Shan, J., Wu, X., Li, C., Hu, J., Zhang, Z., Liu, H., Xia, P., & Huang, X. (2023). Photocatalytic degradation of tetracycline hydrochloride by a Fe₃O₄/g-C₃N₄/rGO magnetic nanocomposite mechanism: Modeling and optimization. *Environmental Science and Pollution Research*, 30(3), 8098–8109. <https://doi.org/10.1007/s11356-022-22770-x>
- Shan, Y., Liu, Y., Feng, L., Yang, S., Tan, X., & Liu, Z. (2024). Magnetic Fe₃O₄-C@MoS₂ composites coordinated with peroxymonosulfate catalysis for enhanced tetracycline degradation. *Journal of Alloys and Compounds*, 989, Article 174318. <https://doi.org/10.1016/j.jallcom.2024.174318>
- Shao, B., Chen, D., Zhang, J., Wu, Y., & Sun, C. (2009). Determination of 76 pharmaceutical drugs by liquid chromatography–tandem mass spectrometry in slaughterhouse wastewater. *Journal of Chromatography A*, 1216(47), 8312–8318. <https://doi.org/10.1016/j.chroma.2009.08.038>
- Siddhardhan, E. V., Steephen, A., Jose, M., & Arumanayagam, T. (2024). Efficient removal of TC and CIP antibiotics by surface modified g-C₃N₄/CdS nanocomposite under sunlight irradiation. *Dyes and Pigments*. <https://doi.org/10.1016/j.dyepig.2024.112052>
- Sompornpailin, D., Pulgerd, P., Sangsanont, J., Thayanukul, P., & Punyapalakul, P. (2024). Removal of antibiotics, bacterial toxicity, and occurrence of antibiotic resistance genes in secondary hospital effluents treated with granular activated carbon and the impact of preceding chlorination. *Science of the Total Environment*, 927, Article 172095. <https://doi.org/10.1016/j.scitotenv.2024.172095>
- Song, Q., Li, J., Zhou, P., Chen, R., Liu, Z., Li, H., & Yin, X. (2025). Worldwide antibiotic prescription practices in primary care and associated factors: A systematic review and meta-analysis. *American Journal of Infection Control*. <https://doi.org/10.1016/j.ajic.2025.08.009>
- Sousa, M., Machado, I., Simões, L. C., & Simões, M. (2025). Biocides as drivers of antibiotic resistance: A critical review of environmental implications and public health risks. *Environmental Science and Ecotechnology*. <https://doi.org/10.1016/j.esc.2025.100557>
- Stylianou, M., Christou, A., Michael, C., Agapiou, A., Papanastasiou, P., & Fatta-Kassinos, D. (2021). Adsorption and removal of seven antibiotic compounds present in water with the use of biochar derived from the pyrolysis of organic waste feedstocks. *Journal of Environmental Chemical Engineering*, 9(5), Article 105868. <https://doi.org/10.1016/j.jece.2021.105868>
- Tao, Y., Duan, Y., Chen, Z., Ye, M., Wang, Z., Yi, J., Jiang, W., Gu, B., Yang, F., & Hu, Q. (2025). Synergistic heterogeneous catalysis: MoS₂/ α -FeOOH nanocomposites for pH-universal PMS activation and efficient antibiotic degradation. *Molecular Catalysis*. <https://doi.org/10.1016/j.mcat.2025.115150>
- Thakur, N., Thakur, N., Kumar, A., Thakur, V. K., Kalia, S., Arya, V., Kumar, A., Kumar, S., & Kyzas, G. Z. (2024). A critical review on the recent trends of photocatalytic, antibacterial, antioxidant and nanohybrid applications of anatase and rutile TiO₂ nanoparticles. *Science of the Total Environment*. <https://doi.org/10.1016/j.scitotenv.2023.169815>
- Thakur, R., Singh, A., Dhanwar, R., Kadam, S., Waghmare, U., Lodha, T., Lopes, B. S., & Prakash, O. (2025). Global perspectives on residual antibiotics: environmental challenges and trends. *Discover Sustainability*. <https://doi.org/10.1007/s43621-025-01048-5>

- Tian, Y., Wang, X., Liang, Y., Li, B., Liu, Y., Feng, L., Li, J., & Zhang, L. (2023). Removal of oxytetracycline and sulfamethoxazole in vertical down-up flow constructed wetlands: Efficiency, removal pathways, and occurrence of antibiotic resistance genes. *Journal of Water Process Engineering*. <https://doi.org/10.1016/j.jwpe.2023.104142>
- Tiseo, K., Huber, L., Gilbert, M., Robinson, T. P., & Van Boeckel, T. P. (2020). Global trends in antimicrobial use in food animals from 2017 to 2030. *Antibiotics*, 9(12), 1–14. <https://doi.org/10.3390/antibiotics9120918>
- Tiwari, A., Jaén-Gil, A., Karavaeva, A., Gomiero, A., Ásmundsdóttir, Á. M., Silva, M. J., Salmivirta, E., Tran, T. T., Sarekoski, A., Cook, J., & Lood, R. (2025). Antibiotic resistance genes, antibiotic residues, and microplastics in influent and effluent wastewater from treatment plants in Norway, Iceland, and Finland. *Environmental Research*. <https://doi.org/10.1016/j.envres.2025.122629>
- Vamsi, E. B., Reshma, M., & Devatha, C. P. (2024). Adsorption of ciprofloxacin antibiotic using chitosan graphene oxide hybrid beads. *Case Studies in Chemical and Environmental Engineering*. <https://doi.org/10.1016/j.cscee.2024.100982>
- Vinayagam, V., Murugan, S., Kumaresan, R., Narayanan, M., Sillanpää, M., Vo, D. V., Kushwaha, O. S., Jenis, P., Potdar, P., & Gadiya, S. (2022). Sustainable adsorbents for the removal of pharmaceuticals from wastewater: A review. *Chemosphere*, 300, Article 134597. <https://doi.org/10.1016/j.chemosphere.2022.134597>
- Wang, B., Gao, X., Qiu, R., Chen, Y., Gao, Y., Hu, G., & Yu, D. (2025). Adsorption of PFCs and antibiotics from water using mesoporous silica and amino-functionalized mesoporous silicon materials: A review. *Chemical Engineering Journal*. <https://doi.org/10.1016/j.cej.2025.159642>
- Wang, B., Jiang, Y., Li, F., & Yang, D. (2017). Preparation of biochar by simultaneous carbonization, magnetization and activation for norfloxacin removal in water. *Biore-source Technology*, 233, 159–165. <https://doi.org/10.1016/j.biortech.2017.02.103>
- Wang, F., Chen, Z., Zhu, Z., & Guo, J. (2022). Construction of visible light responsive ZnO/N-g-C₃N₄ composite membranes for antibiotics degradation. *Journal of Materials Research and Technology*, 17, 1696–1706. <https://doi.org/10.1016/j.jmrt.2022.01.140>
- Wang, J., Zhang, L., Zhang, H., Cai, R., Jin, H., Xu, M., Cao, X., & Yao, S. (2024a). Magnetically recyclable spherical Cu₂O@Fe₃O₄ S-scheme heterojunction for efficient tetracycline removal via visible light-activated peroxydisulfate. *RSC Advances*, 14(34), 24413–24423. <https://doi.org/10.1039/d4ra04174g>
- Wang, K., Guo, C., Li, J., Wang, K., Liang, S., Wang, W., & Wang, J. (2024b). A critical review of the adsorption-desorption characteristics of antibiotics on microplastics and their combined toxic effects. *Environmental Technology and Innovation*. <https://doi.org/10.1016/j.eti.2024.103729>
- Watkinson, A. J., Murby, E. J., & Costanzo, S. D. (2007). Removal of antibiotics in conventional and advanced wastewater treatment: Implications for environmental discharge and wastewater recycling. *Water Research*, 41(18), 4164–4176. <https://doi.org/10.1016/j.watres.2007.04.005>
- Watkinson, A. J., Murby, E. J., Kolpin, D. W., & Costanzo, S. D. (2009). The occurrence of antibiotics in an urban watershed: From wastewater to drinking water. *Science of the Total Environment*, 407(8), 2711–2723. <https://doi.org/10.1016/j.scitotenv.2008.11.059>
- Wei, J., Liu, Y., Li, J., Zhu, Y., Yu, H., & Peng, Y. (2019). Adsorption and co-adsorption of tetracycline and doxycycline by one-step synthesized iron loaded sludge biochar. *Chemosphere*, 236, Article 124254. <https://doi.org/10.1016/j.chemosphere.2019.06.224>
- Xiang, Y., Yang, X., Xu, Z., Hu, W., Zhou, Y., Wan, Z., Yang, Y., Wei, Y., Yang, J., & Tsang, D. C. (2020). Fabrication of sustainable manganese ferrite modified biochar from vinasse for enhanced adsorption of fluoroquinolone antibiotics: Effects and mechanisms. *Science of the Total Environment*, 709, Article 136079. <https://doi.org/10.1016/j.scitotenv.2019.136079>
- Xu, L., Zhang, H., Xiong, P., Zhu, Q., Liao, C., & Jiang, G. (2021). Occurrence, fate, and risk assessment of typical tetracycline antibiotics in the aquatic environment: A review. *Science of the Total Environment*. <https://doi.org/10.1016/j.scitotenv.2020.141975>
- Yang, H., Xu, M., Wang, L., Wang, X., Jeppesen, E., & Zhang, W. (2023). Metagenomic analysis to determine the characteristics of antibiotic resistance genes in typical antibiotic-contaminated sediments. *Journal of Environmental Sciences (China)*, 128, 12–25. <https://doi.org/10.1016/j.jes.2022.08.014>
- Yang, J., Wu, J., Gao, L., Duan, L. H., & Wang, J. (2024). Amino functional SBA-15 assisted NU-1000 for the rapid and efficient adsorption of tetracycline antibiotics. *New Journal of Chemistry*. <https://doi.org/10.1039/d4nj03736g>
- Yang, X., Flowers, R. C., Weinberg, H. S., & Singer, P. C. (2011). Occurrence and removal of pharmaceuticals and personal care products (PPCPs) in an advanced wastewater reclamation plant. *Water Research*, 45(16), 5218–5228. <https://doi.org/10.1016/j.watres.2011.07.026>
- Yang, X., Tian, X., Xue, Y., & Wang, C. (2025). Application of iron-modified biochar in the fields of adsorption and degradation of antibiotics. *Journal of Environmental Management*. <https://doi.org/10.1016/j.jenvman.2025.124875>
- Yeo, J. Y., Bergaoui, M., Nakhli, A., Khaerudini, D. S., Soetaredjo, F. E., Ismadji, S., Sunarso, J., Al-Hada, N. M., Al-Asbahi, B. A., & Khalfaoi, M. (2025). Exploring interface interactions in antibiotics adsorption on bentonite-alginate composite: Insights from advanced simulations and adsorption isotherms modeling. *Surfaces and Interfaces*, 60, Article 106038. <https://doi.org/10.1016/j.surf.2025.106038>
- Yin, R., Guo, W., Zhou, X., Zheng, H., Du, J., Wu, Q., Chang, J., & Ren, N. (2016). Enhanced sulfamethoxazole ozonation by noble metal-free catalysis based on magnetic Fe₃O₄ nanoparticles: Catalytic performance and degradation mechanism. *RSC Advances*, 6(23), 19265–19270. <https://doi.org/10.1039/c5ra25994k>
- Yu, P., Tan, J., Zhuang, R., Tang, J., Wang, Z., Zhang, C., Wang, Q., Xiao, X., & Huang, W. (2024). Valorization of heavy metals enriched ALB adsorbents as effective

- ZnS-CdS/C photocatalysts for antibiotics removal. *Journal of Alloys and Compounds*, 1002, Article 175447. <https://doi.org/10.1016/j.jallcom.2024.175447>
- Zhai, Y., Huang, Q., Huang, W., Dong, S., Zhang, Y., Qin, R., & How, Z. T. (2024). Transformation and toxicity studies of veterinary antibiotic-sulfachloropyridazine by ozonation in livestock wastewater. *Journal of Water Process Engineering*. <https://doi.org/10.1016/j.jwpe.2024.105823>
- Zhang, B., Hiramatsu, T., Hamano, S., Fujii, M., Alalm, M. G., Yoshikawa, S., Matsumoto, H., & Ookawara, S. (2022). Swiss-roll electrodes for efficient degradation of carbofuran by electrochemical advanced oxidation processes. *Journal of Environmental Chemical Engineering*, 10(6), Article 108801. <https://doi.org/10.1016/j.jece.2022.108801>
- Zhang, C., Cheng, X., Zhao, R., Fu, M., Wang, M., Chen, Z., Zhang, C., & Li, X. (2025a). Enhanced antibiotic removal via magnetic Ni@ZIF-8 composite nanotubes: Synergistic adsorption, facile recovery and adsorption mechanism. *Separation and Purification Technology*, 363, Article 131988. <https://doi.org/10.1016/j.seppur.2025.131988>
- Zhang, C., Xu, Y., Chu, B., & Sun, X. (2024a). Mechanism and toxicity assessment of carbofuran degradation by persulfate-based advanced oxidation process. *RSC Advances*, 14(42), 30582–30589. <https://doi.org/10.1039/d4ra05365f>
- Zhang, J., Sun, X., Zhu, W., Liu, G., Xian, T., & Yang, H. (2024b). Design of CdZnS/BiOCl heterostructure as a highly-efficient piezo-photocatalyst for removal of antibiotic. *Journal of Environmental Chemical Engineering*. <https://doi.org/10.1016/j.jece.2024.114405>
- Zhang, P., Liu, Q., Yao, H., Wang, T., Zeng, B., Zou, Y., Fu, S., Hu, K., & Guo, H. (2025b). Copper-functionalized hydrochar from swine manure with complexation sites for selective adsorption of tetracycline antibiotics. *Separation and Purification Technology*. <https://doi.org/10.1016/j.seppur.2024.130671>
- Zhang, S., Zhang, Y., Wang, Y., Liu, X., Li, M., Fang, H., & Kong, M. (2023). Effect of antibiotics, antibiotic-resistant bacteria, and extracellular antibiotic resistance genes on the fate of ARGs in marine sediments. *Science of the Total Environment*, 891, Article 164305. <https://doi.org/10.1016/j.scitotenv.2023.164305>
- Zhang, X., Cai, T., Zhang, S., Hou, J., Cheng, L., Chen, W., & Zhang, Q. (2024c). Contamination distribution and non-biological removal pathways of typical tetracycline antibiotics in the environment: A review. *Journal of Hazardous Materials*. <https://doi.org/10.1016/j.jhazmat.2023.132862>
- Zhang, X. Y., Liu, T. S., & Hu, J. Y. (2024d). Antibiotics removal and antimicrobial resistance control by ozone/peroxymonosulfate-biological activated carbon: A novel treatment process. *Water Research*, 261, Article 122069. <https://doi.org/10.1016/j.watres.2024.122069>
- Zhang, Z., Liu, H., Wu, L., Lan, H., & Qu, J. (2015). Preparation of amino-Fe(III) functionalized mesoporous silica for synergistic adsorption of tetracycline and copper. *Chemosphere*, 138, 625–632. <https://doi.org/10.1016/j.chemosphere.2015.07.014>
- Zhang, Z., Wei, H., Shi, L., Pan, F., Teng, R., Gao, M., & Ma, X. (2025c). Understanding the interaction mechanisms between nitroimidazole antibiotics and buckwheat hull biochar during adsorption process: Experiments and molecular dynamics simulations. *Journal of Molecular Liquids*, 418, Article 126629. <https://doi.org/10.1016/j.molliq.2024.126629>
- Zheng, Q., Zhang, Y., Zhang, Q., Wang, Y., & Yu, G. (2023). Removal of antibiotic resistant bacteria and plasmid-encoded antibiotic resistance genes in water by ozonation and electro-peroxone process. *Chemosphere*, 319, Article 138039. <https://doi.org/10.1016/j.chemosphere.2023.138039>
- Zhong, D., Zhou, Z., Ma, W., Ma, J., Feng, W., Li, J., & Du, X. (2022). Antibiotic enhances the spread of antibiotic resistance among chlorine-resistant bacteria in drinking water distribution system. *Environmental Research*, 211, Article 113045. <https://doi.org/10.1016/j.envres.2022.113045>
- Zhu, Y., Wang, L., Xu, W., Xu, Z., Yuan, J., & Zhang, G. (2022). ZnO/Cu₂O/g-C₃N₄ heterojunctions with enhanced photocatalytic activity for removal of hazardous antibiotics. *Heliyon*. <https://doi.org/10.1016/j.heliyon.2022.e12644>

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Springer Nature or its licensor (e.g. a society or other partner) holds exclusive rights to this article under a publishing agreement with the author(s) or other rightsholder(s); author self-archiving of the accepted manuscript version of this article is solely governed by the terms of such publishing agreement and applicable law.